PEER 1 - Conceptual Models Peer Review

Title: CONCEPTUAL MODELS PEER REVIEW PLAN

(Assistant Manager, Office of Regulatory Compliance, Carlsbad Area Office) 3/28/96 Date:

1. INTRODUCTION

This Conceptual Model Peer Review (CMPR) Plan describes the peer review and documentation the WIPP Project will use to ensure that the conceptual models used in performance assessment (PA) reasonably represent possible future states of the disposal system.

1.1 BACKGROUND

In accordance with the regulatory requirements, as specified in 40 CFR Part 191, and the criteria for the implementation of those requirements, as specified in 40 CFR Part 194, the Department of Energy (DOE) will conduct a peer review (PR) of the conceptual models used in the compliance certification application for the WIPP Project. Specifically, a PR will be conducted to determine whether the conceptual models developed and selected by DOE reasonably represent future states of the disposal system. Sandia National Laboratories (SNL) is responsible for the WIPP PA. SNL has determined which processes are significant and have developed conceptual models which represent possible future states of the disposal system and subsystems. To facilitate review of the conceptual models, they have been divided into the following three associated subsystems:

- Natural barriers (Salado and non-Salado flow and transport);
- Engineered barriers (rock mechanics and shaft/borehole seals); and
- Waste form and the disposal room.

SNL has developed a description of the conceptual models, the associated parameters, and parameter values, and is developing and implementing a process for the selection and assembly of data and other information which will be utilized to support PR of the conceptual models.

1.2 PURPOSE

The purpose of the WIPP PR process for conceptual models is to ensure that the conceptual models used in PA reasonably represent possible future states of the disposal system.

The requirement for conducting peer reviews is specified in sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. Specifically, a PR is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The PR shall be independent of the work being reviewed; independence from the work being reviewed means that the peer: a) was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed.

1.3 SCOPE

This CMPR Plan describes the peer review process that the DOE Carlsbad Area Office (CAO) will use for review of conceptual models. A PR is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of the conclusions drawn in the original work. This Plan defines the management approach, resources, schedule, and technical requirements for using peer reviews to confirm the adequacy of the conceptual models.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

The DOE-CAO has prepared this Conceptual Model Peer Review (CMPR) Plan to document the approach to conducting the PR process. The CMPR will be conducted using a rigorous proceduralized approach in accordance with NUREG-1297. The DOE-CAO has prepared a procedure for conducting peer reviews in accordance with sections 27 (a)(1) and 22 (b) of 40 CFR Part 194. The DOE-CAO procedure ensures that each PR will be a documented, critical review performed by qualified peers who are independent of the work being reviewed. SNL has prepared a procedure to provide the information necessary to support peer review of the conceptual models.

2.1.1 DESCRIPTION OF CONCEPTUAL MODELS TO BE REVIEWED

Section 23(a)(3)(v) of 40 CFR Part 194 requires that any compliance certification application shall include documentation that the conceptual models have undergone PR according to 40 CFR Part 194 section 27. SNL will provide a description of the conceptual models and other supporting information to the PR Manager for peer review. The following listed conceptual models have been identified to be reviewed:

CONTAINMENT SUB-SYSTEM	CONCEPTUAL MODELS
Natural Barriers (Flow & Transport)	Disposal System Geometry Culebra Repository Fluid Flow Salado Impure Halite Salado Interbeds Disturbed Rock Zone Actinide Transport (Salado) Units Above the Salado Dissolved Actinides (Culebra) Colloidal Actinides (Culebra) Exploration Boreholes Cutting/Cavings Spallings Blowout Castile & Brine Reservoir Multiple Intrusions Climate Change
Engineered Systems (Shaft Seals & Rock Mechanics)	Disposal Room Geometry Creep Closure Repository Fluid Flow Shafts & Shaft Seals Disturbed Rock Zone
Waste Form & Disposal Room (Disposal Room Closure & Chemistry)	Gas Generation Chemical Conditions Dissolved Actinide Source Term Colloidal Actinides Source Term

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The CMPR Panel will be composed of a minimum of three individuals who possess the subject matter technical expertise to a degree at least equivalent to that needed for the original work. It is currently planned to have panel members who are experts in Natural Barrier System (flow and transport), Engineered Barriers (shaft seals and rock mechanics) and Waste Form and Disposal Room Chemistry.

Through a formal orientation process, each panel member will be made familiar with the WIPP containment system and the basis of the conceptual models which describe the containment system. In addition they will be provided a basic description of how the conceptual models are represented in numerical models, algorithms, and codes. The peer reviewers will be made familiar with the parameter inputs to the PA codes and the results of prior PAs, sensitivity analyses, and critical comments from previous reviews. Each peer reviewer will be selected, oriented, and trained in accordance with approved procedures.

2.1.3 LOGISTICS AND MANAGEMENT

Not all information necessary to support peer review of conceptual models is currently available. Therefore, it is necessary to conduct the CMPR in a phased manner. The phasing dependens on information availability. The PR Manager, working closely with SNL, has developed a preliminary schedule that provides the necessary information on an "as available" basis. Flexibility is required by all supporting organizations (i.e., DOE-CAO, SNL, and the PR manager, staff and panel members) to accommodate schedule changes due to uncertainty in the timing of information availability.

2.2 SUGGESTED METHODS

The method to be used by the CMPR Panel for the adequacy and reasonableness of the conceptual models will be developed based on SNL requirements for the process of conducting PR. The methods the PR Panel uses to evaluate the subject matter shall include, as applicable, the adequacy criteria identified in section 2.3 below.

2.3 ADEQUACY CRITERIA

Conceptual models which have been selected and developed by the DOE must meet commonly accepted technical and scientific standards based on in-depth evaluation. The peer review panel will evaluate and report on, as applicable:

- Adequacy of requirements and criteria;
- Validity of assumptions;
- Alternate interpretations as appropriate;
- Uncertainty of results and consequences if wrong;
- Appropriateness and limitations of methodology and procedures;
- Adequacy of application;
- Accuracy of calculations; and
- Validity of conclusions.

Adequacy of the conceptual models will be determined based on whether or not they reasonably represent possible future states of the disposal system.

2.4 SCHEDULE

Based on the concept described in section 2.1.3, Attachment A presents a schedule of CMPR activities and milestones. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated and approved if appropriate. Revisions to the baseline schedule will not require revision to this Plan, but will be attached to the plan by reference.

2.5 DELIVERABLES

Monthly status reports addressing CMPR progress against schedule and expenditures against budget will be submitted by the CTAC Project Manager and will be incorporated in the CTAC monthly report to the DOE-CAO. Significant variances in progress or spend rates will be explained and will include the cause of the variance, impact to the overall CMPR schedule and recommended corrective actions. A draft and final report of this PR will be submitted to DOE-CAO.

2.6 RESOURCE REQUIREMENTS

To meet the CMPR schedule as outlined in section 2.4 an estimate of the resources which may be required and the allowed manpower support levels are specified in Attachment C.

3. QUALITY ASSURANCE

The CMPR process will be conducted in a controlled manner and in compliance with the CAO Quality Assurance Program Description, CAO-94-1012, and other applicable QA procedures.

4. RECORDS MANAGEMENT

Records generated as a result of PR activities defined in this peer review plan and designated as QA records will be identified in the PR Procedure. Conceptual Models PR records will be assembled and maintained in accordance with the PR Management Procedure and the PR Desk Instruction(s). Ultimately, PR records will be dispositioned in accordance with DOE-CAO records management requirements. SNL records will be managed in accordance with SNL Records Management Procedure, SNL QAP 17-1.

5. DOCUMENT CONTROL

All plans, procedures, and other Documents which require document control will be handled in accordance with applicable DOE-CAO controlled document procedures.

ATTACHMENT A

CONCEPTUAL MODEL PEER REVIEW (CMPR) SCHEDULE

ACTIVITY	DRAFT	FINAL
CMPR Plan	3/8	3/29
PR Panel Assigned	NA	3/29
Information Package to PR Manager	3/15	4/2
Initiate CMPR	NA	4/2
Complete CMPR	NA	6/28
Submit CMPR Report	6/21	7/1

ATTACHMENT B

ESTIMATED PEER REVIEW RESOURCE REQUIREMENTS

Support	**Hours**
Subject matter experts	1800
Technical Coordinator	300
Clerical Support	300

M

CONCEPTUAL MODELS

PEER REVIEW REPORT

Final

Waste Isolation Pilot Plant

Conceptual Models Peer Review Report

A Peer Review Conducted By

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Office of Regulatory Compliance

July 1996

FOREWORD

The U.S. Environmental Protection Agency promulgated "Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations Final Rule" in Code of Federal Regulations, Title 40, Part 194 (40 CFR Part 194) on February 9, 1996. The 40 CFR Part 194 regulation prescribes three specific peer reviews and also provides the opportunity for the Department of Energy to use peer reviews, conducted in accordance with NUREG 1297, as a means of qualifying data and information for use in the demonstration of compliance.

This report contains the results of a peer review of specific conceptual models to be used in the demonstration of WIPP compliance with 40 CFR Part 194. To ensure the independence of this review, the Department of Energy has directed the assignment of an independent contractor to administratively manage the peer review panel activities. Peer reviewers were selected based on their demonstrated independence from the work being reviewed and their technical expertise in the subject matter to be reviewed. The peer review panel members collectively possess an appropriate spectrum of knowledge and experience in the subject matter reviewed.

This peer review was conducted in full compliance with the quality assurance requirements as defined in 40 CFR Part 194.

CONTENTS

FIGURES

TABLES

ACRONYMS

WIPP	Waste Isolation Pilot Plant
DOE	U.S. Department of Energy
SNL	Sandia National Laboratories
WID	Waste Isolation Division (Westinghouse)
EPA	U.S. Environmental Protection Agency
EEG	Environmental Evaluation Group
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
TRU	transuranic (waste)
LWA	Land Withdrawal Act
CAO	Carlsbad Area Office
CTAC	Carlsbad Technical Assistance Contractor
ET	evapotranspiration
FEP	features, events, and processes
DRZ	disturbed rock zone
MB	marker bed
MDCF	multimechanism deformation coupled fracture
RM	reduced modules
FMT	fracture-matrix-transport
SIT	specific ion interaction

EXECUTIVE SUMMARY

This report presents the results of an independent technical peer review of the adequacy of 24 conceptual models representing features, processes, and events involved in assessing the long-term performance of the Waste Isolation Pilot Plant (WIPP). These models were identified by the U.S. Department of Energy (DOE) through its scientific advisor, Sandia National Laboratories (SNL). WIPP has been developed at a site near Carlsbad, New Mexico, by the DOE to become the nation's repository for geologic isolation of transuranic radioactive waste resulting from nuclear weapons programs. Westinghouse Electric Corporation, Waste Isolation Division (WID) is the operations contractor for the WIPP. SNL and WID have provided most of the information used in this review. This independent peer review is required by 40 Code of Federal Regulations (CFR) 194.27 as part of the compliance application prepared by the DOE. The U.S. Environmental Protection Agency (EPA) will use the peer review documentation to help ensure that an adequate scientific foundation exists for a national decision on whether to dispose of this waste at WIPP.

The independent review was conducted by a six-member interdisciplinary Review Panel (Panel) having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted at SNL in Albuquerque, New Mexico, from April through June 1996. The Panel was given access to conceptual model descriptions, scientific reports, briefings, and SNL scientists, and to the SNL Nuclear Waste Management Program Library. During meetings of the Panel, representatives of the EPA, DOE, and New Mexico Environmental Evaluation Group (EEG) observed the Panel's deliberations. The Panel also had access to reports of prior peer reviews and had the full cooperation of the DOE, SNL, and WID throughout the review.

A conceptual model is a statement of how important features, events, and processes such as fluid flow, chemical processes, or intrusion scenarios, are to be represented in performance assessment. To be used in performance assessment, the conceptual model must be successfully translated into analytical statements and mathematical analogs. The Panel reviewed in detail the 24 conceptual models against criteria of the EPA, including the scientific information used to develop the model, the assumptions, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall performance assessment model. The review process and review criteria are discussed in Section 2.

The Panel has applied the stringent assessment criteria provided in NUREG 1297 and has concluded that thirteen of the models are adequate for implementation. The remaining eleven models were not found to be adequate for use in performance assessment of the WIPP. Models were judged to be inadequate if they failed to convince the Panel of their adequacy in terms of nine criteria. These criteria addressed: adequacy of information; validity of assumptions; alternatives evaluated; uncertainties; adequacy of the model and its application, accuracy, results, and conclusions; and whether the model was ready for implementation in the performance assessment process. Following is a list of the 24 models and a statement of the Panel's conclusion.

Disposal System Geometry	Adequate
Culebra Hydrogeology	Not Adequate (no consequence)*
Repository Fluid Flow	Not Adequate
Salado	Adequate
Impure Halite	Adequate
Salado Interbeds	Not Adequate
Disturbed Rock Zone	Adequate
Actinide Transport in the Salado	Adequate
Units Above the Salado	Not Adequate (no consequence)*
Transport of Dissolved Actinides in the Culebra	Adequate
Transport of Colloidal Actinides in the Culebra	Not Adequate
Exploration Boreholes	Not Adequate
Cuttings/Cavings	Adequate
Spallings	Not Adequate
Direct Brine Release	Not Adequate
Castile and Brine Reservoir	Not Adequate
Multiple Intrusions	Adequate
Climate Change	Adequate
Creep Closure	Adequate
Shafts and Shaft Seals	Adequate
Gas Generation	Not Adequate
Chemical Conditions	Not Adequate
Dissolved Actinide Source Term	Adequate
Colloidal Actinide Source Term	Adequate

*Although the conceptual model was found to be inadequate, no consequence to performance assessment is anticipated.

Several of the issues raised by the Panel could have significant effects on performance assessment. The details of evaluations and issues raised for each model are contained in Section 3 of this report. The relationships among the models are described in Section 4, and a summary of the evaluations is contained in Section 5.

The Panel believes that careful resolution of the issues discussed in Section 3, and any resulting changes to the models, will help to improve the overall quality of the performance assessment and provide a firmer basis for a national decision on whether to emplace waste at WIPP.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) Conceptual Models Peer Review is one of several peer reviews being conducted by the U.S. Department of Energy (DOE). The Conceptual Models Peer Review focused on the conceptual models developed and selected by DOE through its scientific advisor, Sandia National Laboratories (SNL), to determine if they adequately and reasonably represent future states of the WIPP disposal system for use in performance assessment. This review was conducted in support of and meets the regulatory requirements of 40 Code of Federal Regulations (CFR) 191 and the implementation of those requirements by 40 CFR 194. In these regulations, this peer review of conceptual models is specifically identified by the U.S. Environmental Protection Agency (EPA) as an activity required to supplement the DOE's Compliance Certification Application (CCA) for the WIPP.

According to 40 CFR 194.27, the peer review is to be conducted in accordance with the Nuclear Regulatory Commission's document NUREG 1297, stipulating requirements for conducting peer reviews. The adequacy criteria set forth in NUREG 1297 were used by the Review Panel (Panel) as a baseline for reviewing DOE's conceptual models. To implement 40 CFR 194, DOE-Carlsbad Area Office (CAO) developed Team Procedure TP-10.5, which stipulates that a peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work.

This report documents the results of the Conceptual Models Peer Review, as determined in accordance with the aforementioned requirements. Section 2 of this report presents background information relating to the WIPP facility and review methodology. This includes a description of the repository, its geologic and hydrogeologic settings, the scenarios used, review methodology, and evaluation criteria. Section 3 presents the evaluation of each of the 24 models as assessed against a predetermined list of nine evaluation criteria. Section 4 discusses the integration of the 24 models into an overall conceptual model for the waste disposal system. Section 5 provides a summary of the evaluations. These sections are followed by appendices which include administrative information and professional biographies for each of the Panel members.

2.0 BACKGROUND

The DOE was authorized in 1979 (by Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes generated in national defense activities. The Land Withdrawal Act (LWA) of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. This facility, the WIPP, is located in southeastern New Mexico. The WIPP is operationally ready to receive waste and is being proposed by DOE for EPA approval as an operating radioactive waste disposal facility through the CCA process. The purpose of the (Compliance Certification Application (CCA) is to demonstrate through performance assessments the ability of the WIPP to successfully isolate radioactive waste from the accessible environment for the 10,000-year regulatory time frame. If regulatory compliance is demonstrated and a decision to start disposal of waste at the WIPP is made, following the provisions of the LWA, the WIPP will be used for the permanent disposal of TRU wastes, including TRU wastes containing hazardous constituents (TRU mixed waste).

2.1. WIPP Overview

The WIPP facility has been constructed in southeastern New Mexico (Figure 2-1), 26 miles east of Carlsbad, on Federal land. Prior to October 1992, this land was administered by the U.S. Department of the Interior, Bureau of Land Management. In October 1992, Congress transferred jurisdiction of the land through the LWA to the Secretary of Energy. The site encompasses 10,240 acres in a sparsely populated area, with fewer than 30 people living within 10 miles of the WIPP. The immediate surrounding land is used for livestock grazing, potash mining, and oil and gas production.

Surface structures, the planned and partially developed underground repository, and four connecting shafts make up the WIPP facility. The purpose of the surface structures is to provide security and safeguards and to accommodate routine operations, administrative activities, and further scientific studies.

The underground excavation is 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. It includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities, an area in which the waste will be emplaced for permanent disposal if the disposal site approval decision is made, and four major interconnecting tunnels used for ventilation and traffic. The subsurface waste-disposal area is to cover 100 acres and will contain eight separately excavated panels, each containing

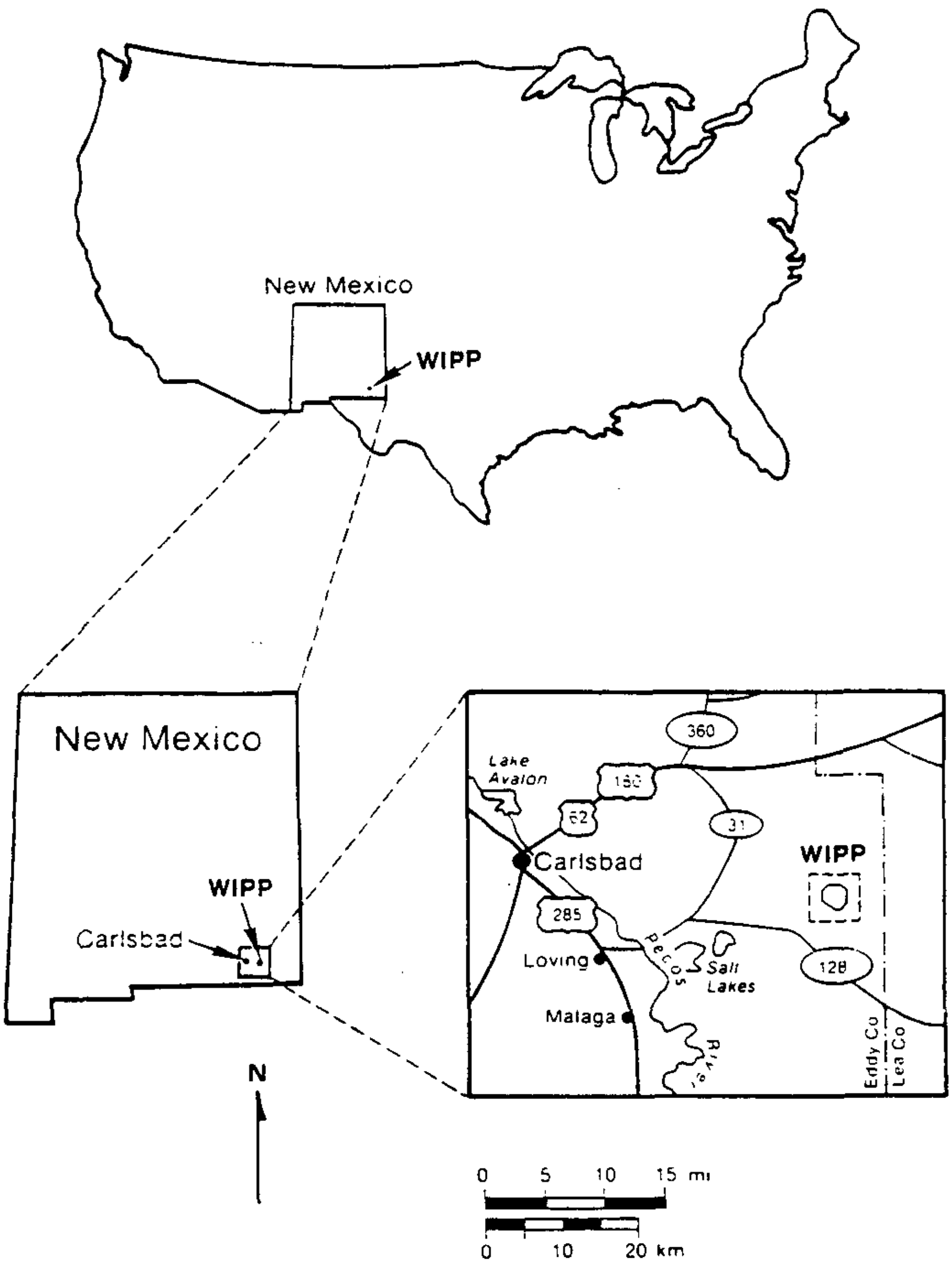


Figure 2-1. WIPP Facility Location

seven disposal rooms, and two additional panels in the area currently containing the drifts accessing the waste disposal area.

2.2. Peer Review Management

The Conceptual Models Peer Review was an independent review supported by the Office of Regulatory Compliance, DOE-CAO and delegated to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). CTAC commissioned Informatics Corporation, an independent firm, with the task of managing the peer reviews. The Conceptual Models Peer Review is the first of six peer reviews conducted between April 1 and August 15, 1996. The other peer reviews include: Engineered Systems Data Qualification Peer Review; Natural Barriers Data Qualification Peer Review; Waste Form and Disposal Room Data Qualification Peer Review; Passive Institutional Controls Peer Review; and Waste Characterization and Sensitivity Analyses Peer Review. Similar reviews are being conducted on engineered barrier evaluations by the WIPP operations contractor.

Each peer review was administered separately, with its own administrative coordinator and administrative assistant. Early in the review, a technical panel leader was selected from among the peer review members to serve as the focal point for the technical aspects of the review, analysis, and development of a report. The six panels shared access to an administrative document-gathering, recordkeeping, and document processing center comprised of several support staff.

The selection of panel members, training of coordinators and reviewers, and operation of the review process were governed by DOE-CAO's Team Procedure TP-10.5, the Conceptual Model Peer Review Plan, and Informatics' Desk Instruction IDI-1.0. Detailed information regarding the review process is further delineated in these documents and in the records of the Panel's review, both found in the SNL Records Center.

The Panel was requested to review the adequacy of the following 24 conceptual models that are being used by the DOE in assessing the future states of the geologic repository system.

1. Disposal System Geometry
2. Culebra Hydrogeology
3. Repository Fluid Flow
4. Salado
5. Impure Halite

6. Salado Interbeds
7. Disturbed Rock Zone
8. Actinide Transport in the Salado
9. Units Above the Salado
10. Transport of Dissolved Actinides in the Culebra
11. Transport Colloidal Actinides in the Culebra
12. Exploration Boreholes
13. Cuttings/Cavings
14. Spallings
15. Direct Brine Release
16. Castile and Brine Reservoir
17. Multiple Intrusions
18. Climate Change
19. Creep Closure
20. Shafts and Shaft Seals
21. Gas Generation
22. Chemical Conditions
23. Dissolved Actinide Source Term
24. The WIPP Colloidal Actinide Source Term

2.3. System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rocks, and the local and regional hydrologic system. Figure 2-2 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

2.3.1. Repository

The WIPP surface facilities, shafts, and underground workings are shown in Figure 2-3. The WIPP repository includes four shafts (exhaust shaft, waste shaft, salt handling shaft, and air intake shaft), an experimental area, an operations area, and a waste disposal area.

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed

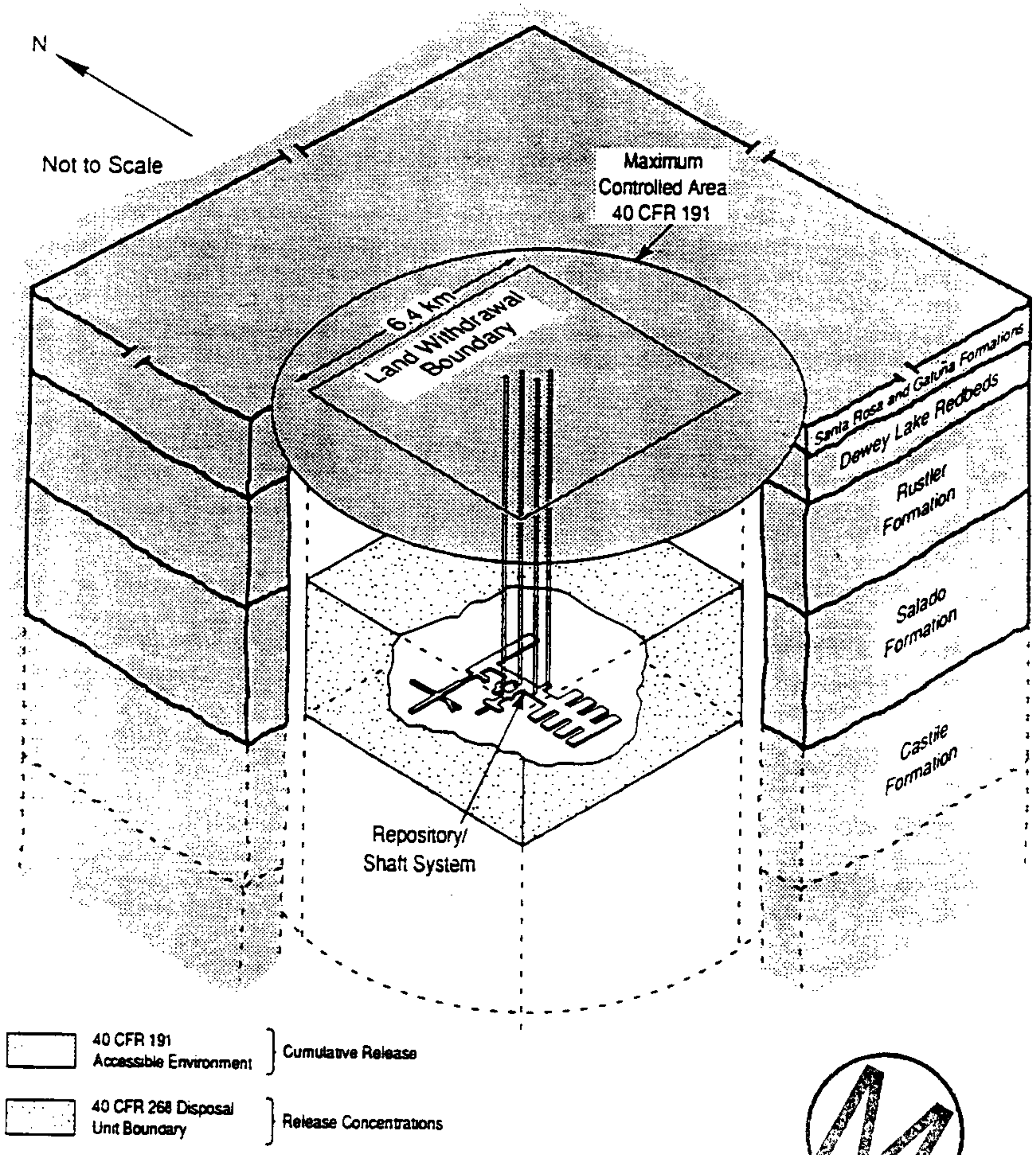


Figure 2-2. WIPP Controlled Area

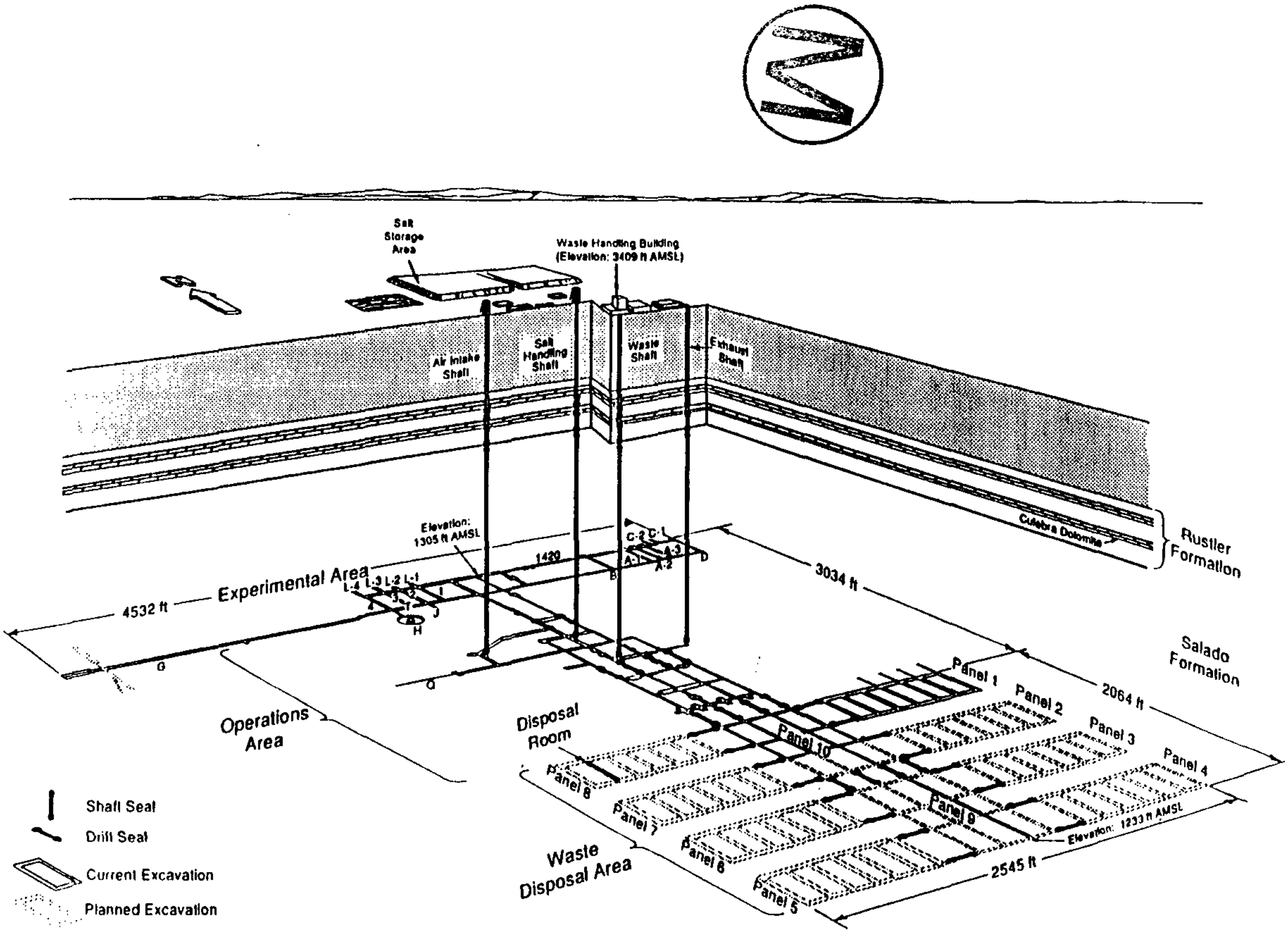


Figure 2-3. WIPP Facilities

permanently, each panel will be sealed, waste will be placed in the drifts between the panels, creating two additional panel volumes, and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by the creep closure of the salt.

2.3.2. Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA (DOE 1996) and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-4. The relevant geologic background setting for the peer review, however, includes specific formations and their lithologies. The Bell Canyon, Castile, Salado, Rustler, Dewey Lakes, Gatuna, and Santa Rosa Formations are the lithologic units within which the conceptual models represent processes and predictions of future states of the proposed disposal system.

The sandstones, siltstones, limestones and shales of the Bell Canyon Formation define the first extensive, continuous, transmissive unit below the WIPP repository and provide a source of groundwater that could migrate vertically into the repository. The halite and anhydrite beds of the Castile Formation separate the Bell Canyon from the Salado and contain pressurized brine reservoirs. Brine reservoirs are a repository performance concern expressed in human intrusion scenarios. The halite-dominated Salado Formation contains the proposed repository and provides the primary natural barrier for containing radionuclides. The laterally extensive Culebra Dolomite Member of the Rustler Formation is the closest stratigraphic unit above the Salado with the potential to transport a radionuclide release to the accessible environment. Studies conclude that transmissivities in the Culebra vary by six orders of magnitude across the WIPP site area. Fracturing and vuggy zones account for much of the variability in the physical/hydraulic properties of the Culebra.

While other stratigraphic members of the Rustler Formation, beds of anhydrite and polyhalite, clays, and other inclusions may be important as each of the conceptual models is reviewed, the four formations and units described above define the most important components of the geologic setting for the WIPP conceptual models review.

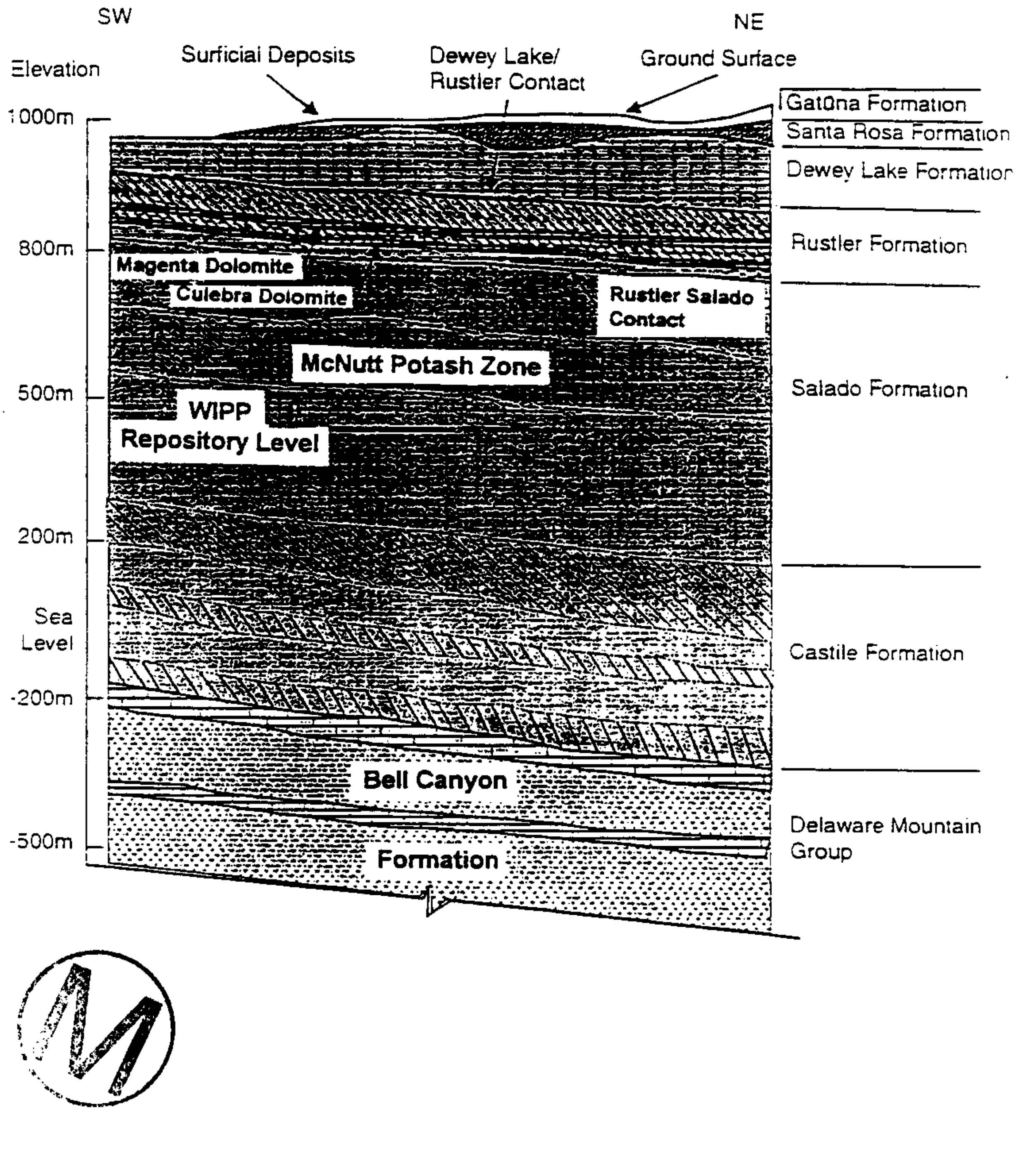


Figure 2-4. General Stratigraphy at the WIPP Site

2.3.3. Hydrologic Setting

2.3.3.1. Surface Water

The WIPP site is located within the Pecos River Basin. At its nearest point, the Pecos River flows approximately 12 miles southwest of the WIPP site boundary. There are no perennial streams at the WIPP site and in this semi-arid region, approximately 75% of annual precipitation results from intense, short-duration events between April and September. More than 90% of the mean annual precipitation is lost through evapotranspiration (ET) and on a mean annual basis, ET potential exceeds expected rainfall. EPA concluded in 1989 (EPA 1990a) that there were "no surface water features near the WIPP that could potentially affect repository performance in such a way as to influence the no-migration demonstration."

2.3.3.2. Groundwater

Extensive coring, logging and testing of boreholes in the vicinity of the WIPP site has provided data for the characterization of the hydrostratigraphy and hydrogeology important to the WIPP site region. While the deep Capitan Limestone, the Rustler-Salado contact zone near Nash Draw, and the shallower Dewey Lakes and Santa Rosa Formations are important in characterizing the WIPP region, the Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

As presented in the geologic setting, the Bell Canyon Formation is the first continuous, transmissive, water-bearing unit beneath the WIPP. This formation provides a source of groundwater below the WIPP repository that could migrate into the repository if a pathway were available. The Bell Canyon Formation exhibits hydraulic conductivities in the range of 10^{-7} to 10^{-12} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations and because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability, brine pressures exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole to the surface.

The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows range from extremely low to no flow when appreciable pressures are applied. The Salado contains the proposed repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area, but the Magenta is generally less transmissive than the Culebra. The Culebra is the first, most extensive, and most transmissive unit above the Salado at the WIPP site. As such, the Culebra provides the most direct pathway from the WIPP repository to the accessible environment and is the most important component of the hydrogeologic setting for the conceptual models peer review.

2.4. Peer Review Panel Methodology

The review of the conceptual models commenced after a training/orientation period and was conducted in accordance with management plans, the conceptual model peer review plan, desk instructions, and other relevant protocols. Panel member qualifications are detailed in Appendix A of this report.

The work of the Panel began following training/orientation on April 5, 1996 and was scheduled to terminate on June 28, 1996 with the submittal of this final report. The Conceptual Model Peer Review Panel employed six basic approaches in their overall method of conducting and accumulating information for the reviews: 1) extensive review of available, referenced, and "roadmapped" literature relevant to the Panel; 2) attendance at briefings on conceptual models and relevant aspects of the performance assessment process; 3) conduct conceptual model or issue-focused presentations/question-and-answer sessions with DOE scientists and engineers; 4) intensive review of literature/documents discovered through continued research and focused question-and-answer sessions; 5) conduct formal and informal discussions among Panel members; and 6) participate in a tour of WIPP facilities and the local area outside the WIPP site, and in presentations/discussions associated with the tour.

The Panel was provided a list of 24 conceptual models to be independently reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP. For the review, conceptual models are defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. Although such a definition could limit the scope of a review, the Panel evaluated the models in accordance with NUREG 1297 criteria, from conception to their integration with mathematical representations, and paid careful attention to alternative models and approaches. In addition, the Panel recognized that individual models may warrant varying levels of reviews of their mathematical representations, computerized representations, and results.

Individual Panel members were assigned lead responsibility for specific conceptual model reviews and preparation of subsequent sections for the report. The Panel members collectively assumed writing responsibilities for introductory and conclusionary sections in the report.

Early in the review process five Panel members visited the WIPP site to tour surface and subsurface facilities and to view nearby geological features. The purpose of the visit was to view first hand the site-specific features that have potential impact on the long-term behavior of the WIPP. When touring the underground facilities, the Panel members observed the Q Room experiment site, the horizons of the Salado halite visible within the repository, fractures within the repository disturbed rock zone, and collapse features in a room where a roof had fallen. Panel members also visited the WIPP core library and observed selected core samples representative of the geological formations that could not be seen underground. Geological features viewed by the Panel near the WIPP included outcrops of the Culebra and Magenta Dolomites, Dewey Lakes Redbeds, and the Gatuna Formation. Two Panel members visited the Western AG potash mine northwest of the WIPP, where ore zones and anhydrite marker beds not visible at WIPP were seen.

Due to the large volume of project literature required for review, the Panel adopted a process in which each member would work independently in getting pertinent information on a given topic. Group briefings were reserved for the broader topics. All information was freely disseminated for consensus-building among Panel members in the completed analysis. On learning that complete information was not available to complete the Panel's scope of work on time, the Panel requested DOE to provide specific information on an accelerated interim basis. This proved to be highly beneficial to the timeliness of model reviews. It was recognized that much of this input had not been reviewed in accordance with SNL procedures and that some of the information reflected the current status of an ongoing decision process. The Panel members are aware that errors can be made in understanding and accuracy when using information of this type, and used the full access provided by DOE to those personnel necessary to provide guidance and clarification to the answers sought.

In organizing its work, the Panel established limitations on its review and the content of this report. Panel members did not review or offer comments on regulations. The Panel confined its review to the suite of conceptual models identified by DOE (Section 2.2). Finally, to maintain independence, the Panel will not offer recommendations for specific methods and approaches to address its concerns. A cutoff date of June 7, 1996 was established for receiving new information for inclusion in the review. It was decided that if the Panel could not reach a conclusion due to a lack of information on a particular model, it would be so stated in the Panel's report.

Two additional activities were identified by DOE for the Panel. First, an overview of the Panel's finding would be presented to DOE, SNL, and observers, and the Panel would respond to questions raised to clarify the concerns identified in this report. The presentation is scheduled for July 1 and 2, 1996. Second, the Panel was requested to reconvene in August to review DOE's written responses to the Panel's findings, and prepare an addendum to this report, if necessary, indicating the adequacy with which the Panel's findings and concerns were resolved by SNL.

2.5. Criteria for Conceptual Model Review

The nine criteria used to review each of the 24 conceptual models are listed below along with a brief description of the way in which each was used by the Panel. Examples are provided where appropriate, to provide clarification. The nine criteria are based on the EPA regulation 40 CFR 194.27, NUREG 1297 Section IV.5, the EPA Compliance Application Guidance, and Panel discussions.

Information Used to Develop the Conceptual Model. This is an evaluation of data and information used to develop conceptual models and submodels. It includes attributes of the disposal system learned by DOE during site characterization activities, such as refinements to the room creep closure model or an improved understanding of disturbed rock zone characteristics.

Validity of Model Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the usefulness of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow in the various media, use of the ideal gas law at high pressures, or the method chosen to represent time-dependence of strain.

Evaluation of Alternatives. This section briefly identifies and assesses plausible alternative conceptual models or submodels seriously considered by DOE but not used, and the rationale why such alternative models were not used. Again, important features, events, and processes must be considered. The Panel does not expect the descriptions of alternative models to be as extensive as for the models chosen, but they should adequately document why the alternative models were not used. For example, the choice among matrix, dual porosity, or flow channeling in stratigraphic units, or the use of transmissivity fields versus uniform transmissivity, should be explained.

Uncertainties. This includes an evaluation of the key uncertainties in the selected conceptual models and a discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or process. For example, if elements of the particular models used to estimate the effect of pH on actinide solubility or the permeability of the disturbed rock zone around the shaft were flawed or incorrect, how significantly would this affect performance? This is not expected to be an exhaustive evaluation, but it should raise the reasonable question, "What if the model were wrong?"

Adequacy of the Conceptual Model. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual models and submodels represent a reasonable approximation of the actual disposal system elements.

Adequacy of Application. This is an assessment of whether it appears that the individual conceptual model is being adequately applied into an acceptable overall performance modeling system. This particular assessment does not cover the relationships among conceptual models, but whether the significant components of the individual conceptual models are appropriately implemented in support of performance assessment. For example, are the various geometrical systems and representations of the conceptual models adequately applied within the performance modeling system, or do there appear to be discontinuities between the conceptual model and its application? Also, are there apparently important alterations of key assumptions between the conceptual model and its implementation in performance modeling?

Accuracy of Results. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately simulate the physical and chemical processes represented. This could either be a subjective judgment (if analytical results were not available with any necessary caveats) or a more robust and useful judgment (if results of analyses were available). Review of key results could also improve the basis for the Panel's statements about adequacy of application, overall validity of outcome of analyses, and adequacy for implementation.

Typical results that could be useful in providing a basis for these improved judgments include reports of sensitivity studies among key intermediate parameters, such as: 1) mean and extreme values of expected brine inflows, 2) gas pressurizations, 3) likelihoods of marker bed fracture, 4) directions of brine flow in the undisturbed condition, 5) the effect of mining in the vicinity of waste panels, 6) relative amounts of waste released from intrusion scenario components (direct brine releases, cuttings, cavings and spallings), and 7) initial typical complementary cumulative distribution functions. Similar results from past performance assessments have provided a basis for improved judgments of models and modeling systems, and numerous improvements have been made in models since the 1992 performance assessment. A review of results is also desirable to facilitate making useful conclusions.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of conceptual models in the modeling framework. The key question is whether or not conclusions from model implementations appropriately relate to the expected goal of assessing the long-term performance of the disposal system. Again, a judgment in the absence of some key output information would need to be accompanied by appropriate explanations.

Adequacy for Implementation. This is an overall, bottom-line assessment of whether the conceptual models, as intended for use in the compliance application, represent a reasonable approximation of the actual disposal system based on the eight previous criteria.

3.0 MODEL EVALUATIONS

This section presents the results of the Panel's evaluations of the 24 individual conceptual models that the DOE requested the Panel to review. Each of these models is first described and then evaluated for adequacy in accordance with the nine criteria summarized in Section 2.5. Following each evaluation, space has been provided for dissenting views; however, no dissenting views were forwarded by any Panel member. An evaluation of the integration of these conceptual models into the WIPP performance assessment is provided in Section 4.

3.1. Disposal System Geometry

3.1.1. Model Description

The Disposal System Geometry conceptual model expresses the dimensionality of the engineered system and surrounding geologic/hydrogeologic formations. The parameters of dimensionality are length, width, and height, which are expressed in individual grid blocks and remain constant for all scenarios and realizations. The processes that rely on the geometric assumptions and parameters of dimensionality are represented across the overall performance assessment system through a finite difference mathematical model called BRAGFLO. The principal processes that depend on the conceptual model for disposal system geometry are fluid flow and actinide transport. The flow fields generated by BRAGFLO are based on the geometric representation of the repository and adjacent formations and the finite difference method, and are communicated to the NUTS code that determines the transport of actinides to the accessible environment.

3.1.2. Review of Criteria

3.1.2.1. Information Used To Develop the Conceptual Model

Numerous references accompany the various background, descriptive, and features, events, and processes (FEP) screening write-ups for the repository and disposal system geometries. Except for regulatory and guidance documents, all references are to internal (SNL) reports that characterize various aspects of and inputs to the modeling of the disposal system geometry. The reports present data and information used to develop the conceptual model and background references for specific applications, but no extensive reference list on "conceptual modeling" of disposal system geometry has been compiled by DOE.

Information concerning the effects of detailed stratigraphy and stratigraphic dip on brine and gas flow, and uncertainty and parameter sensitivity analyses for gas and brine migration, is presented in WIPP

(1992a and 1992b) and Christian-Frear and Webb (1996). Other reports (WIPP 1993, Rechard et al. 1990, and Marietta et al. 1989) explain the WIPP performance assessment aspects of characterizing the disposal system geometry, and FEP screening documents present modeling alternatives. Various sections of the Compliance Certification Application (DOE 1996) summarize disposal system, repository, and intrusion event geometries. The Disposal System Geometry conceptual model is the result of integrating other models that describe the physical and chemical conditions and processes expected in the repository into a characterization of the material properties of the repository and surrounding strata. As such, the conceptual model and its application are described in terms of a process that has evolved to its current structure, and has generally been developed after the mathematical models have been defined.

3.1.2.2. Validity of Model Assumptions

The Disposal Systems Geometry conceptual model must have assumptions that are internally consistent and consistent with the assumptions of other models that represent repository processes. Since the geometry by which processes are simulated is so closely tied to the processes themselves, it is difficult to review the conceptual model for disposal system geometry totally separate from other models.

As stated in Part 2.5, the validity of key conceptual modeling assumptions will be assessed in terms of how the assumptions could affect the usefulness of the conceptual model. While the assumptions that describe the repository-process conceptual models that are closely tied to the geometry (Creep Closure, Repository Fluid Flow, Gas Generation, Chemical Conditions, Dissolved and Colloidal Actinide Source Terms) are not reviewed in this section, they are reviewed individually in Section 3, and collectively in Section 4.

Assumptions key to the disposal system geometry conceptual model for undisturbed and disturbed conditions (disposal system, disposal room, adjacent disturbed rock zone (DRZ), and geologic systems) include: 1) the three-dimensional systems can be represented by two-dimensional simplifications; 2) the associations between and relationships across regions with varying material properties can be represented by the discretized grid blocks and by the finite difference method used in the computational model; 3) the four shafts can be represented by one shaft; 4) the entire repository can be represented by the simplified floor plan used in the computation model; 5) the intrusion borehole represents the concerns of the intrusion scenarios; and 6) effects of flow in the DRZ and intact rocks outside of the repository are represented by the divergent grid to the north and south away from the repository.

The representation of relevant systems by two-dimensional simplifications not only affects the usefulness of the conceptual model, it is intended to make the model useful. As stated in Section 3.1.2.1, the geometry followed the definition of the mathematical models. Early three-dimensional mathematical models were unwieldy and computationally inefficient with respect to time, cost, and overall management. The two-dimensional representation is efficient in terms of time, cost, and managing a large number of vectors. The BRAGFLO code, as simplified (BRAGFLO is a three-dimensional code), compared favorably with a three-dimensional alternative (TOUGH 28W) used for verification with respect to the relevant outputs. Two-dimensional simplifications appear to adequately represent the structural system through which fluid flow can be simulated to the shafts or intrusion boreholes. The two-dimensional representation may not be adequate, however, for simulating fluid movement across the repository and waste panel area to the anhydrite interbeds because such flow may be unrealistically impeded by the small depths and potentially low permeabilities assigned to the cells representing the shafts and boreholes in the model. This issue is further discussed in the Repository Fluid Flow conceptual model in Section 3.3.

The conceptual approach of characterizing varying material properties by discretized grid blocks, and using finite differences and partial differential equations to compute a flow field for a series of grid points, is useful and a standard method for hydraulic routing. It is beyond the scope of the conceptual model review to conduct a detailed analysis of the BRAGFLO code, and the finite difference method will be assumed to be of standard computational design. The usefulness of this method is well established in hydrogeology, considered valid for routing liquids, and is a valuable tool for sensitivity analysis.

It appears that the one-degree dip in the Salado, the important cross sectional areas (vertical and horizontal), and distances between key system features and pathways have been retained within modeling simplifications. As these characteristics are retained, the overall geometry conceptual model remains valid. Beyond the conceptual method, the panel makes no comment on the validity of the grid block densities or volumetric variation and whether or not they adequately represent material property maps and changes in properties and their distribution.

The representation of the four shafts by a single shaft of cross sectional area and volume equal to the sum of the four shafts, is a conservative representation and simplifies the mathematical representation of brine and gas flow to and in the shaft. The single shaft is located, geometrically, in the position of the waste handling shaft, which is the closest of all four shafts to the waste disposal regions. The Panel foresees no reasonable situation where such an assumption could compromise model usefulness and render the assumption invalid, but the presence of four sealed shafts presents four times the risk of failure of one shaft, and this may not have been taken into account. The four-shaft simplification assumption stimulates questions of reality, accuracy, and scientific credibility. While apparent conservatism, at least in the context of the scope of this review, answers most operational and performance questions, it would have been more credible, from a modeling perspective, to model the actual system.

The simplified repository floor plan represents a conservative view, and clearly provides fewer obstacles to flow in the repository than would actually be encountered by fluids. The simplifications and assigned high permeabilities answer operational and performance questions, since the conservatism and validity of the assumption was not refutable within the scope of this review. While the Panel is not satisfied that the simplifications for the sake of conservatism replace credible models of the actual systems, the assumptions remain valid.

The intrusion scenarios require assumptions about the intrusion borehole in terms of location, size, and how the brine and gas are conveyed to the borehole. The intrusion borehole is assumed to penetrate the repository and brine reservoir as appropriate to the scenario. During the intrusion scenario the represented waste panel is discretized to simulate radial flow of waste fluids to the borehole.

3.1.2.3. Evaluation of Alternatives

During the conceptual models review, information that indicated or described alternative conceptual models that were considered but not used was limited to FEP S-1 documents and unpublished informative write-ups provided by DOE (Larson 1996). Many grid configurations were experimented with in previous performance assessments, and sensitivity and uncertainty analyses (WIPP 1992a, 1992b) were conducted relative to the geometry model. Analyses that examined how detailed stratigraphy and stratigraphic dip affected brine and gas migration were reported in Christian-Frear and Webb (1996) and Webb and Larson (1996). Through all of the analyses and experiments the basic concept of the grid as the geometric framework has not changed. The specific geometric framework suitable for modeling disposal system processes and interactions was developed after the mathematical/computational system was defined. Three-dimensional and two-dimensional models were evaluated, with the three-dimensional model described as computationally inefficient for the large number of vectors required for the WIPP performance assessment, and was considered costly in terms of time and resources.

With the selection of the two-dimensional approach and the simplified BRAGFLO code, FEP S-1 screening verified (justified) the two-dimensional WIPP grid with a three-dimensional model (TOUGH 28 W). Based on the favorable comparison of outputs from the models, the DOE selected the two-dimensional model for use in the WIPP performance assessment.

Intrusion scenarios are limited to those that penetrate the repository waste panels or repository and brine reservoir. No alternative borehole intrusion scenarios are considered that miss the repository but penetrate the adjacent DRZ or strata and impact the physical properties of the DRZ or strata.

3.1.2.4. Uncertainties

The key uncertainties associated with the disposal system geometry conceptual model are associated with the simplifications made for the sake of conservatism (as opposed to, for example, operational efficiency, cost, and resource constraints) and with the question of whether the computational mesh is representative of the geometry of the system. While the two-dimensional simplifications embody assumptions key to the conceptual model, verification screening illustrates that these simplifications result in outputs of sufficient quality for use in the WIPP performance assessment (FEP S-1 1992 and 1993).

As stated in Section 3.1.2.2, the Panel concludes that there is little uncertainty or confusion with the fundamental geometric framework of discretized grid blocks or the use of the finite difference method to compute flow fields over a series of grid points. The uncertainty that exists relates to the definition of the processes by the mathematical representations and the representativeness of the computational mesh.

3.1.2.5. Adequacy of the Conceptual Model

The conceptual/geometric framework and computational method selected to characterize the material properties of the disposal system and relevant physical and chemical processes is adequate. As stated in previous sections, the implementation of the conceptual model has not been evaluated within the scope of this review and cannot be commented on.

The two-dimensional simplifications, considered part of the conceptualization of the disposal system geometry, have been subjected to verification and are considered adequate for use in characterizing releases for the WIPP performance assessment.

3.1.2.6. Adequacy of Application

The Disposal System Geometry conceptual model provides an adequate framework, method, and set of assumptions, and appears to be applied as an acceptable performance element. There are no apparent compatibility problems between the geometry and process-related conceptual models in terms of assumptions or application method that would create misrepresentations. The overall adequacy of the application should be measured by how well material properties are represented and physical and chemical processes are simulated. These measures, in turn, depend on the relevant conceptual models and data relevant to those processes being modeled. Therefore, a more definitive assessment of the adequacy of application of the Disposal System Geometry conceptual model could be determined from analyses, outputs, and results generated by the relevant process-related conceptual models, which were not available to the Panel at the time of review.

3.1.2.7. Accuracy of Results

For evaluating the accuracy of the results of the Disposal System Geometry conceptual modeling activity, model formulation results, as well as model evaluation/application results, must be reviewed. Model formulation results are the description or descriptive write-up that presents the conceptual model. Model evaluation/application results are those that indicate the performance of the conceptual model through sensitivity analyses, verification studies, or results of performance modeling of all or intermediate parameters.

The conceptual model, as defined by the geometric framework, the proposed use of a finite difference method, two-dimensional computational simplifications, and disposal system simplifications, is accurately presented as formulated. The Panel was required to consult numerous documents to acquire a comprehensive view of the conceptual model and the formulation process, but the description of the conceptual model is complete and accurate.

As presented in Section 3.1.2.6, the Disposal System Geometry model evaluation results, or results of model applications, should be measured for accuracy within the models that have conceptualized the physical and chemical processes. While the simplifications of this conceptual model have been verified as to comparability of outputs with other models (FEP S-1 1992 and 1993), the Disposal System Geometry model itself only produces results, as it represents material properties and processes conceptualized in other models. Therefore, the Panel cannot attest to the overall accuracy of the model.

3.1.2.8. Validity of Conclusions

The Panel is not aware of any results of the implementation of the Disposal System Geometry conceptual model (see Section 3.1.2.7) and therefore, there are no conclusions to validate.

3.1.2.9. Adequacy for Implementation

The conceptual model for the Disposal System Geometry provides a suitable framework for modeling the important processes and their interactions in the disposal system. The mathematical representation of the conceptual model within the BRAGFLO code has not been reviewed and, as a result, the panel offers no conclusions on the representativeness of applications using the code. The concept that the spatial effects of processes and interactions can be represented in two dimensions is defensible. The simplification in the system representation and computational method to simulate the two dimensions are defensible and adequate for implementation. The basic grid framework for representing the material properties of the disposal system, adjacent DRZ, geologic formations, and intrusion scenarios is adequate, and the proposed use of a finite difference method to connect the nodes and generate flow fields is also defensible and adequate for implementation.

3.1.2.10. Dissenting Views

There were no dissenting views for this model.

3.2. Culebra Hydrogeology

3.2.1. Model Description

The Culebra is identified as a principal potential pathway for radionuclide release to the environment. The conceptual model should support the results of hydrologic testing and provide bases for population of the model in regions lacking data. The conceptual model should correlate the regional and site scale hydrogeology with the model boundaries and help shape hydrologic gradients and local field boundaries.

The Culebra hydrogeologic characterization framework has evolved from two fundamentally different regional flow models, several formulations explaining local flow conditions represented by hydrologic testing, and several hypotheses explaining the distribution of permeability regions in the Culebra. The regional flow models include the "confinement" model and the "groundwater basin" model. The confinement model depicts the Rustler Formation (of which the Culebra is a member) as a series of perfectly isolated layers which are hydrogeologically independent. The groundwater basin model depicts the Culebra as a layer within a series of interacting hydrologic units of varying properties which include all the hydrologic units between the ground surface and the Salado Formation. In the groundwater basin model, hydrologic gradients are thought to be vertical in the low permeability layers (Tamarisk, Forty-Niner, Unnamed Lower Member) and horizontal in the Culebra and Magenta Dolomites.

Observations in the field and shaft openings indicate that the Culebra is a dolomite averaging approximately 7 meters in thickness. Generally fine-grained, red brown in color, occasionally vuggy and fractured, the crudely layered dolomite appears to be typical of evaporite dolomites. The fractures tend to be disorderly in orientation and in some places polygonal, and the vugs are occasionally open. The MgO content of the dolomite varies greatly vertically and areally within the Culebra member. These lithologic characteristics and the sedimentological setting imply that the Culebra is a reflux dolomite, deposited originally as a calcite sediment and subsequently altered by infiltration of MgO-rich evaporite brine. The variability of MgO content, texture, and fracture distribution are most probably due to variability in volume changes due to timing, rate, and degree of dolomitization of the original calcite sediment.

Hydrologic testing of the Culebra has indicated that the hydrologic properties of the unit (principally permeability and porosity) vary strongly both vertically and areally. At some localities, the test flow rates and interactions between wells have led to hypotheses that relatively low permeabilities resulting from flow through the rock matrix dominates the hydrogeology of the Culebra over regions many tens of meters in extent. Similar tests in other localities have implied high permeabilities over distances of several kilometers, which are hypothesized to be the result of the dominance of fracture permeability along interconnected fracture zones. Other localities show intermediate flow characteristics, which may be the result of combined effects of flow-through fractures and matrix. Multiple models that hypothesize the combined and singular effects of hydrologic sample intervals across regions of vertically varying modes and rates of flow have been proposed to explain some of the variability of test results. These models have been tested by varying sample intervals and pumping rates several times in the same stratigraphic interval. It appears that sample interval does not entirely explain the composite flows observed and that dual porosity flow models are appropriate. There are regional variations in hydrologic properties in the Culebra that are too large in magnitude to be explained by variation in sample interval or proportionality of flow mechanism, and that appear to be areally distributed within and around the repository area. These areal variations in the hydrogeologic nature of the Culebra have not been clearly associated with a conceptual model of the geology of the dolomite or of the Rustler Formation as a whole. The Culebra is the most extensively tested hydrogeologic unit in the WIPP region.

Jones (1974, 1975, 1978) and Snyder and Gard (1982) postulated that the hydrology of the Culebra was primarily related to the dissolution of halite within the Rustler Formation. Jones postulated the existence of dissolution "fronts," partly the consequence of Pleistocene climatological history, which are presently active at reduced rates based on halite distribution within the Rustler and at the Rustler-Salado contact. Subsidence of the Rustler related to dissolution was the postulated mechanism for locally increased aperture of preexisting fractures. Although dissolution is certainly a strong influence on the geology of the Rustler Formation in Nash Draw and isopac maps of the Rustler Formation members show erratic thickness changes in the soluble members (Brinster 1991), workers in the region remain divided about the role of dissolution in the hydrogeology of the Rustler Formation and of the included Culebra Member. Holt and Powers (1988) argue that variations in stratigraphic thickness within the Rustler are the result of depositional processes and that changes in overburden pressure due to erosion explain the variability of hydrologic properties. Bachman (1987) and Lambert (1987) argue that solution has been inactive since mid to late Pleistocene time. Chapman (1986) contends that Culebra waters contain significant amounts of meteoric water, while Lambert argues against the presence of any meteoric water. Corbet and Wallace (1993) argues that the filling of fractures and the removal of fracture fillings by dissolution explains gross regional variations in transmissivity.

Hydrologic testing has not resolved the questions raised by arguments about the origin of variability of hydraulic properties by simple correlation with geologic features. Some fundamental geologic variables, such as fracture distribution, aperture, and orientation, as well as patterns of variation in matrix permeability and porosity, have not been sufficiently characterized to make such correlations possible. Such characterization would require a large investment in angle hole nests and extensive three-dimensional modeling. The uncertainties in the hydrogeologic character of the Culebra has led to the abandonment of attempts to formulate a detailed hydrogeologic conceptual model and there have been several attempts to generate an acceptably predictive numerical hydrologic model exclusively from testing data. These attempts are summarized in Figure 3-1 and in Table 3.1. Recent multiwell tracer tests are presently being evaluated to more fully support transport modeling.

Chapman (1986), LaVenue (1990), Siegel (1991), and Beauheim (1989) have not been able to relate detailed hydrogeologic features, hydrogeochemical facies, radiogenic ages, flow constraints, or hydrologic testing results to a consistent, detailed hydrogeological conceptual model. Neither have they been able to uniquely explain water level changes observed in monitoring of the WIPP region over the last several decades. Groundwater flow directions in the Culebra member over the Los Medanos region,

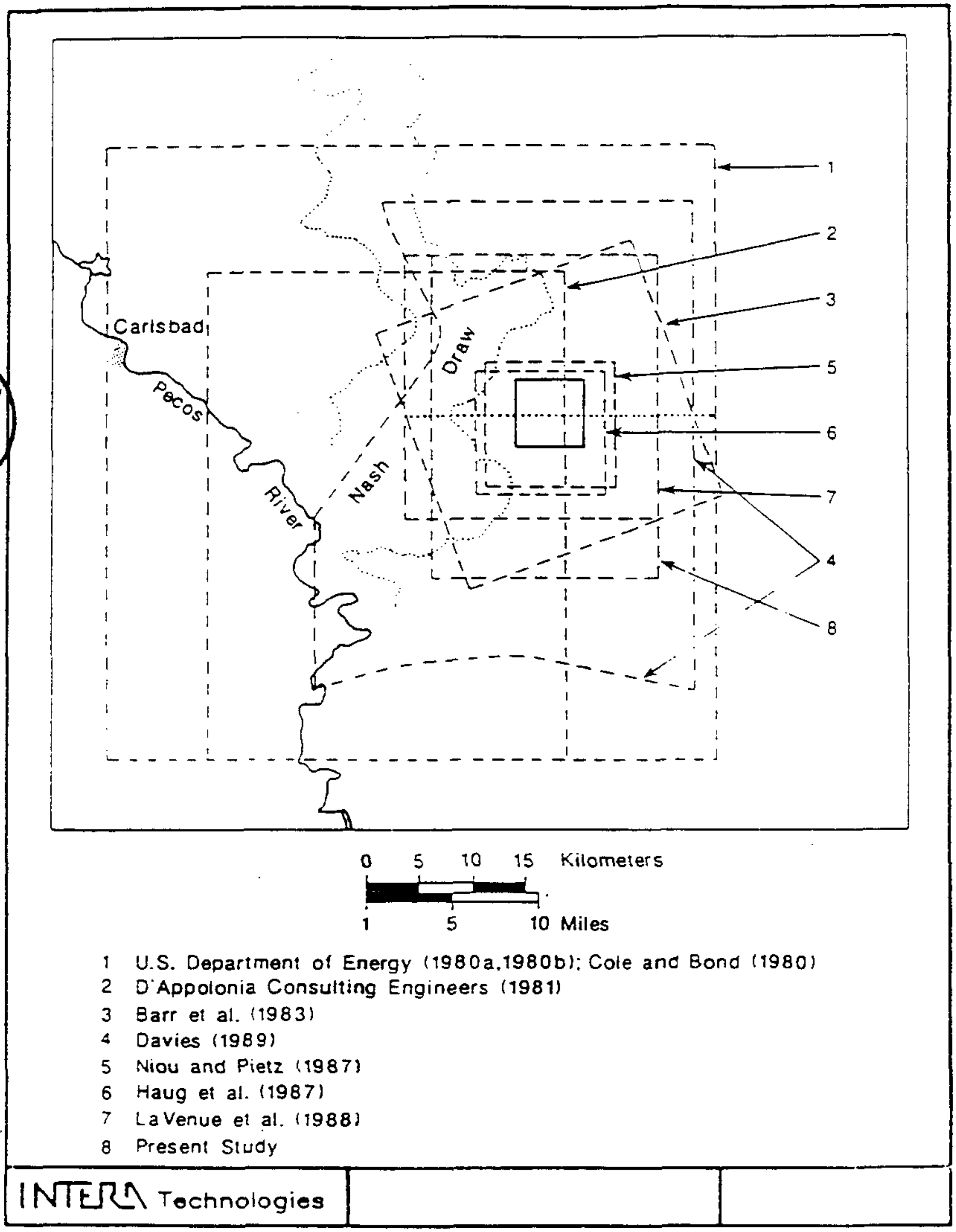


Figure 3.1. Approximate Boundaries of Groundwater Flow Models in the WIPP (after Lappin and Hunter 1989)

Table 3.1. Summary of Modeling Investigations of the Rustler Formation or Culebra Dolomite Member in the WIPP Site Region

Investigation	Hydrogeologic Unit Modeled	Head Calibration
DOE 1980	Rustler	Steady State
D'Appolonia 1981	Rustler	Steady State
Cole and Bond 1980	Rustler	Steady State
Barr et al. 1983	Culebra	Steady State
Davies 1989	Culebra	Steady State
Niou and Pietz 1987	Culebra	Transient
Haug et al. 1988	Culebra	Steady State
LaVenue et al. 1988	Culebra	Steady State
Present Study	Culebra	Combined Steady State/Transient

as well as in other members of the Rustler Formation, are reasonably well defined. The work synthesized by LaVenue (1990) and Brinster (1991) and the intervening single and multiwell and tracer testing in the Culebra, are an attempt to characterize the hydrology of the Culebra in a well-constrained area around the WIPP on the basis of a relatively large body of hydrologic test data by numerical modeling alone. If this effort is ultimately successful, perhaps a comparison of model results with the existing hydrogeologic characterization of the Culebra will allow the formulation of a hydrogeologic conceptual model that explains transmissivity variation at the site scale. None exists at this time. The large number of hydrologic tests within the repository area and in the Los Medanos region around the repository, the variety of types of testing, and the long period of monitoring suggest that a numerical flow model may be sufficient to answer most of the performance-related questions about the Culebra at the repository.

3.2.2. Review of Criteria

3.2.2.1. Information Used to Develop the Conceptual Model

Information used to develop the conceptual model included field geologic observations, logging of cores from borings, observations from shaft mapping, petrographic and mineralogic study, subsurface mapping, groundwater geochemistry and geochronology, and hydrologic testing and monitoring including multiwell pumping and tracer tests. Several hypotheses correlating detailed variations in the hydrologic properties and results of monitoring of the Culebra with groundwater geochemistry and geohydrological aspects of the formation were proposed and tested against existing information or information acquired specifically to test the hypotheses. All hypotheses failed to correlate the detailed hydrogeology of the Culebra with its tested hydrologic character. The information used to develop the conceptual model was insufficient to permit the formulation of the model at a sufficient scale.

The Culebra is a red-brown, fine grained dolomite, continuous over the WIPP area, which displays vugs and fractures that may be the primary sources of permeability and porosity. The lithologic aspect of the Culebra and the variability of its magnesium content suggest that it is a reflux dolomite formed by the gravity-driven infiltration of a calcite sediment by magnesium rich fluids, shortly after deposition in an evaporite sedimentological setting. The Culebra is bounded by two very low permeability anhydrite units. The hydrologic gradient in the Culebra is horizontal and generally southward over the repository area and the gradients in the adjacent beds are vertical. Some water-pressure measurements imply that the Culebra is underpressured. The transmissivity and gradient of the Culebra are capable of discharging more water than the formation is receiving in recharge, at least locally. There is more hydrologic test data for the Culebra than for any other hydrogeologic unit in the repository region. The model boundaries are defined by regional hydrogeologic features mapped and modeled by Corbett (1993). The information is inadequate to develop a conceptual model that explains hydraulic process and property variation at the site scale.

3.2.2.2. Validity of Model Assumptions

Since all detailed conceptual hydrogeologic hypotheses correlating the Culebra hydrogeology and geochemistry to the described hydrologic properties and the results of hydrogeologic testing and monitoring failed, no conceptual model was formed that could be linked to the computational flow model. No model assumptions, which have their origin in the conceptual model and impact performance assessment, exist for testing.

3.2.2.3. Evaluation of Alternatives

Alternative hydrogeologic models, which relied on apportioning fracture and matrix porosity and permeability within the Culebra as a result of: 1) solution of halite within the Rustler Formation; 2) solution of halite at the Rustler Salado interface; 3) variability of superincumbent load due to topography; and 4) dissolution due to gravity driven flow of brines of different density, were considered and discarded.

3.2.2.4. Uncertainties

Model uncertainties as a result of the conceptual model do not exist in this instance because of the absence of an accepted conceptual model at the appropriate level of detail. An alternative approach has been adopted which depends on the modeling of the hydrology of the Culebra entirely on the basis of the results of hydrologic testing. A detailed assessment of this numerical modeling effort is beyond the scope of this review.

Two sources of uncertainty are related to the absence of a conceptual model in this case. A conceptual model helps to explain the sources of variability observed in a data base derived from hydrologic testing and provides rational bases for populating the data-less areas in the model grid. Values are smoothed and gradients between varying clusters of data are shaped on the basis of hydrogeologic character. Absence of this influence on grid population reduces confidence in numerical model representativeness.

The second uncertainty is the absence of hydrogeologic bases for ruling out significant patterns of variance in the flow patterns and hydrologic properties in the Culebra hidden within data-less areas or areas of apparently incoherent variation in the testing area. The Culebra test results have exhibited relatively large, spatially dependent variations in hydraulic conductivity. The relatively dense testing data base and the ongoing multiwell and tracer testing are attempts to resolve this issue. Zones of relatively rapid fracture flow, without significant retardation of radionuclides by physical or geochemical processes, could cause accelerated transport in the Culebra. The existing transmissivity field models seem to cover the regions of greatest concern to site performance with what appears to be an adequate testing data distribution to rule out local variations in flow significant to performance of the site. The density of field testing data seems to be adequate.

The impact of ground subsidence due to repository closure on the hydrogeology of the Culebra is a source of uncertainty. Subsidence of nearby potash mines and an analysis by Westinghouse suggest a lowering of the ground surface of about .5 m and a small horizontal extensional strain in the Culebra (.007%). It has been asserted that the transmissivities represented by the two-dimensional flow model proposed for performance assessment are conservative enough to contain any enhancement of flow caused by subsidence of this scale. No conceptual arguments specific to Culebra hydrogeology or numerical analysis supporting the probable magnitude of enhancement of transmissivity or the sensitivity of the proposed model to that change have been presented.

3.2.2.5. Adequacy of the Conceptual Model

The conceptual model is not adequate to define variations in the transmissivity of the Culebra at the site scale. Its function has been replaced by an extensive hydrologic testing and modeling effort.

3.2.2.6. Adequacy of Application

See Section 3.2.2.5.

3.2.2.7. Accuracy of Results

No conceptual model is employed in performance assessment-related modeling. Assessment of the accuracy of the numerical flow modeling used in performance assessment is beyond the scope of this review.

3.2.2.8. Validity of Conclusions

The validity of the conclusions of numerical flow modeling is not impacted by the conceptual model in this case. Data distribution and density and geostatistical methods used to populate the model appear to be valid. The results make sense in a qualitative way.

3.2.2.9. Adequacy for Implementation

The conceptual model was not adequate for implementation. A numerical model based on an extensive hydrologic testing data base was substituted. The numerical model appears to meet the needs of the performance assessment, although the computational validity and accuracy of that model were not reviewed.

3.2.2.10. Dissenting Views

There were no dissenting views for this model.

3.3. Repository Fluid Flow

3.3.1. Model Description

The Repository Fluid Flow conceptual model addresses (1) fluid distribution in the waste, (2) long-term fluid flow to and from the Salado Formation and shafts, and (3) long-term fluid flow between the repository and intrusion boreholes. Related conceptual models include Disposal System Geometry, Disturbed Rock Zone, Creep Closure, Shafts and Shaft Seals, Gas Generation, Impure Halite, Salado, and Salado Interbeds, Castile and Brine Reservoirs, Exploration Boreholes, and Multiple Intrusions.

The Repository Fluid Flow conceptual model is a complex description of simultaneous, interacting hydrologic, chemical, geomechanical, engineering design, and human intrusion scenarios whose effects can be described separately, but require numerical modeling to identify the combined, integrated outcome. The conditions controlling repository fluid flow include brine inflow rates, halite creep rates, and gas generation from waste corrosion and degradation, which are themselves the objects of related but separately described conceptual models. The Repository Fluid Flow model accepts inputs from these related models and provides descriptions of pressures, flow rates, and flow directions for brine and gas within the excavated areas of the repository. A detailed description of the coupled processes in the conceptual model is presented in Freeze et al. (1995).

The layout of the waste repository is described in Section 2.3.1. The key elements of this layout pertaining to the Repository Fluid Flow conceptual model are the waste disposal area (the waste panels and access drifts), the panel seals, the operational area, the experimental area, the shafts, the WIPP site characterization boreholes in the vicinity of the repository, and any future exploration boreholes that are randomly determined to penetrate the repository. The waste panels in the disposal area will be sequentially filled to capacity with waste and isolated from the rest of the repository by 40-m long closure seals consisting of concrete plugs and crushed salt. The operations area is north of the disposal area and consists of four shafts and a network of interconnecting access drifts. Two additional sets of 40-m seals will be placed in the operations area between the waste and the shafts. The experimental area is north of the operations area and consists of a series of experimental rooms and access drifts.

In the current plan, waste will be placed in steel drums and waste boxes stacked to achieve efficient use of space. Magnesium oxide will be placed around the containers to absorb carbon dioxide gas generated during microbial decay of cellulosics in the waste. No structural backfill is planned for the repository. Analyses have indicated that decay and degradation of the waste are expected to generate little heat and the maximum repository-wide temperature excursion is expected to be about 5°C. The changes in density and viscosity for brine and gas at this temperature rise are small, and are not considered to be significant in performance assessment. Plans for shaft and borehole sealing are discussed in Sections 3.12 and 3.20. On repository closure, the Salado halite is expected to creep into the excavated rooms and crush the waste; however, some porosity will remain, resulting from the strength of the waste materials and from pressurized brine and gas in the waste. A discussion of the Creep Closure model is presented in Section 3.19.

In undisturbed scenarios, brine is expected to flow into the excavated entries of the repository at a slow rate both during and after closure. Brine will flow directly from the Salado halite, from higher conductivity anhydrite interbeds intersected by the excavations, from formations above the Salado by seepage through a DRZ around the shaft, and from brine squeezed from storage in clays in the impure halite. Flow into the repository through the halite is expected to be enhanced by a disturbed rock zone of higher permeability in the walls, floor, and back of the underground entries (see Section 3.7), from a series of 50-foot long site characterization boreholes drilled vertically upward and downward from the repository, and from rock bolt holes penetrating the back and walls of most entries. During the operational period, this inflow is expected to be removed by evaporation into the repository ventilation air. Under undisturbed conditions following closure, inflow is expected to continue at a low rate from the first three of these sources but not from the clay, which is expected to have been fully consolidated. The brine is expected to pool in low spots on the repository floor and to be wicked into the waste and magnesium oxide by capillary forces. Under disturbed conditions, additional inflows of brine may rapidly occur following closure if a borehole penetrating the repository also encounters pressurized brine in the underlying Castile Formation.

Both gas and brine will behave as fluids, filling pore volume in the repository. Gas and brine will be generated at the same time that the repository void spaces are being closed by halite creep, eventually reaching a state of equilibrium where the pressure of the gas and brine is balanced by the pressure of the halite on the remaining void spaces. Brine inflow into the remaining voids is expected to stop when the pressure of brine in the repository is the same as the pressure of brine in the halite. If gas production continues, the pressure of the gas will continue to rise, driving the brine back into the halite.

If the gas pressure exceeds the threshold pressure for its entry into the surrounding geologic media, the gas will enter the geologic media, increasing the available void volume. As the gas pressure approaches the lithostatic pressure, gas is expected to enter the anhydrite interbeds in the vicinity of the repository, increase the porosity in those interbeds by enlarging existing fractures along planes of weakness, and migrate laterally in the interbed away from the repository, until the increased pore volume sufficiently reduces gas pressure that the phenomenon stops (see Section 3.6). The lateral extent of such fracturing will depend on the rate of gas generation and the pressure and volume of gas present in the repository. Microfracturing of the intact halite from gas pressure buildup is expected to occur around the repository, but at a rate that is sufficiently slow that stress redistribution from halite creep will keep these fractures from developing into a size that would be of concern to performance assessment. More extensive fracturing is expected in anhydrite, which is more brittle and does not have the creep characteristics of halite.

The volume of gas produced will be limited primarily by the volume of source material (primarily steel and cellulosics) in the repository, and the rate of gas production will be limited primarily by the volume of brine present and in contact with the waste. Gas pressure can be relieved if the repository is penetrated by an exploration borehole, in which case releases of gas, contaminated brine, and repository waste materials could occur at the ground surface (see Sections 3.12 and 3.17). The void volume in the repository can also increase when the gas pressure exceeds the lithostatic pressure by reversing the creep process.

The conceptual model for repository fluid flow is implemented for performance assessment using two separate models developed from the BRAGFLO code. The first model, which for purposes of this review will be called BRAGFLO, is used for analyzing long-term flow through the repository under both disturbed and undisturbed conditions. The second model is used for calculating short-term, direct brine releases when the repository is penetrated by one or more boreholes, and will be called BRAGFLO-DBR. This second model is discussed under the Direct Brine Release conceptual model in Section 3.15.

The repository is represented in BRAGFLO in two-dimensional vertical section as a series of volumes, each with homogeneous, isotropic material properties and behaviors, and each representing a major repository feature. The slight 1° southerly dip of the bedding is incorporated into the model. The effective depth of each modeled feature (the third dimension normal to the plane of the model) is addressed through adjusting the cross section areas of the cells representing the feature. The model material numbers and the dimensions of each feature are summarized in Table 3.2. Ranges of depths are given for features with variable depths that are represented by multiple columns of model cells. The heights of the intrusion borehole and shaft are not given because they extend to the ground surface, have varying material properties and behaviors, and heights that are greater than the height of the repository excavations.

The effective depths of the model cells were varied to simulate the increasing hydraulic gradients that would occur into the repository, intrusion borehole, and shaft under radial flow conditions. The model depths used for the borehole and shaft approximate the effective diameters of these features. The model depth for the borehole is held constant whether or not an intrusion borehole is assumed to have been

Table 3.2. Model Material Numbers and Feature Dimensions

Feature	Material Number	Length (m)	Height (m)	Depth (m)
Single waste panel	23	112	4	4.8 to 126.2
Intrusion borehole	1	0.27	- -	0.27
Single panel closure	25	40	4	10
Rest of repository	24	695	4	141.6
Multiple panel closure	25	80	4	18.9
Operations area	26	333	4	18.9
Shaft	2 to 11	10	- -	9.5
Experimental area	27	560	4	20.5 to 53.1

drilled. BRAGFLO is configured assuming a single shaft with a vertical permeability of the four shafts (and their disturbed rock zones) combined, and assuming a single exploratory borehole that penetrates the center of one of the downdip waste panels. The borehole cells are assigned the properties of the undisturbed media until a borehole is randomly assumed to have been drilled. The borehole can be either an E1 type (penetrates a waste panel in the repository and encounters pressurized brine in the underlying Castile Formation) or an E2 type (penetrates a waste panel but does not encounter pressurized brine). Penetration of a waste panel by more than one borehole is also addressed by this version of BRAGFLO and is discussed in Section 3.17. The presence of existing site characterization borehole ERDA-9, very near the repository, is not addressed by BRAGFLO.

The waste is simulated in BRAGFLO in two areas: Material 23, which represents a single waste panel, and Material 24, which represents the rest of the repository. The waste itself is assumed to be distributed uniformly throughout the two areas. Between the waste materials, BRAGFLO simulates a 40-m long panel closure seal (Material 25) representing the seals in the two panel access drifts. In addition, an 80-m long panel closure seal (also Material 25) separates the rest of the repository from the operations area and represents the two groups of 40-m long seals that will be placed in the operations area. The remaining cells (Materials 26 and 27) represent the operations and experimental areas, respectively, and are located on either side of the shaft. Each of these material areas is three cells high in vertical dimension, allowing vertical variations in brine and gas saturations and the resulting varying rates of corrosion and waste decomposition to be simulated.

Gas production rates are estimated as a function of brine availability. Wicking of brine into the waste will increase gas production rates and is modeled by arbitrarily adding a randomly selected value, varying from zero to 1.0, to the brine saturation value in disposal area model cells containing brine (not to exceed a total brine saturation of 1.0). This value is called the wicking saturation. The additional brine is only used for chemical reaction purposes. The approach increases the volume of brine available for chemical reactions and increases the rate of corrosion and gas production. To simplify analysis of the mechanical effects of gas production and pressure buildup, all gases produced are assumed to have the properties of hydrogen and behave as ideal gases. Although this assumption would lead to underestimating the viscosity and overestimating the compressibility of the hydrogen-carbon dioxide mixture actually expected to be present, the error would be of no significance in view of the considerably larger uncertainties in other parameters in the model and the expected efficiency of the magnesium oxide in removing carbon dioxide from the system.

Repository closure through halite creep is modeled using the porosity surface approach discussed in Section 3.19. The waste disposal rooms are assumed to maintain a relatively high constant permeability, but a varying porosity during the creep closure process. The panel closure seals and the operations and experimental areas of the repository are assumed to have a constant permeability and porosity. BRAGFLO models the repository assuming two-phase Darcy porous medium flow throughout the closure process.

Material 22, representing disturbed halite, lies above and below the repository excavations and interconnects the repository with Marker Beds 138 and 139, and with Anhydrite Layers A and B. No disturbed halite is modeled in the walls of the excavations. The lateral outer boundaries of the model are over 2,000 m from the repository. All outer boundaries below the Rustler are assigned no-flow conditions.

3.3.2. Review of Criteria

3.3.2.1. Information Used to Develop the Conceptual Model

The conceptual model has relied greatly on the general Darcy model for flow in porous media, as amended for gas by considering the Klinkenberg effect, and for two-phase flow using a modified Brooks-Corey model that includes threshold pressures for gas entry into a brine-saturated medium. Brine salinity, density, compressibility, and viscosity are addressed in the model. Gas properties are given by the Redlich-Kwong-Soave equation of state, assuming behavior to be that of pure hydrogen. The principal basis for the conceptual model is not specific to WIPP, but was developed from the general state of knowledge of two-phase, isothermal flow of liquids and gases in porous media. This general behavioral information was supplemented by site-specific studies that included measurements of the coupled hydromechanical properties of brine, intact salt, crushed salt, gas, and sealing materials. Although site-specific parameters for two-phase flow in the waste are lacking in the data base, representative values for these parameters would be difficult to obtain because of the expected heterogeneity of the waste. Surrogate parameters from other media are instead used for two-phase flow, and the uncertainties are compensated for by random sampling over ranges of values. Detailed modeling sensitivity studies of repository fluid flow and other coupled phenomena are summarized in Freeze et al. (1995) and Christian-Frear and Webb (1996). The information and concepts used were appropriate for developing the conceptual model.

3.3.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.3.1 and are critically reviewed here. Most assumptions are reasonable and appropriate and include the assumption of isothermal conditions for fluid flow calculations, the assumption of Darcy flow, the incorporation of two-phase flow, the treatment of wicking, and the phase stratification from gravity effects. The assumed lack of a DRZ in the walls of the modeled repository rooms is not expected to significantly affect the Repository Fluid Flow model, but would change the frequency of borehole penetration by increasing the target area. This issue is further addressed in Section 3.15. Certain aspects of the principal model assumptions were reviewed more closely and are addressed in the following paragraphs.

The two-dimensional representation of the repository in BRAGFLO is necessary to feasibly perform the many repeated model runs needed for probabilistic analysis. The effect of more explicitly representing the detailed stratigraphy was evaluated in Christian-Frear and Webb (1996), and the sensitivity of a more rigorous evaluation of coupled repository processes was reviewed in Freeze et al. (1995). The results of these studies identified key parameters and processes and support the two-dimensional approach used in BRAGFLO.

BRAGFLO uses the Brooks-Corey relative permeability model for two-phase flow within all media except the anhydrite interbeds. Although site-specific parameters are not available to support this model, the use of surrogate media and the practice of incorporating uncertainty through random sampling from a range of values is considered appropriate. The sensitivity of pressure buildup to the alternative van Genuchten-Parker two-phase model was documented in Christian-Frear and Webb (1996) and found to be relatively low. Although the Brooks-Corey model calculates slightly higher repository fluid pressures than the van Genuchten-Parker model because of the reduced fluid mobility, the impact of this assumption was found to be small in the repository, where the porosities are high and the threshold pressures are low.

The depth of the model cells increases in a stepwise manner away from the repository to simulate radial flow into the repository, shaft, and borehole. While this is appropriate for flow to or from the shaft or borehole, it creates narrow constrictions in the two-dimensional flow field when considering flow across the shaft or borehole within the repository. The significant decrease in model depth in the vicinity of the borehole and shaft creates artificial constrictions for horizontal flow across the model. Model results were reviewed and have shown that the pressure drop across these constrictions is negligible under an undisturbed flow condition and that fluid movement is not unduly restricted. The lack of a significant pressure drop is expected to be related to the very low rates of flow and the relative mobility of the gas phase. However, this model configuration may restrict the rate of equilibration of brine saturation within the repository following an E1 borehole intrusion and the movement of brine from the "rest of the repository" to the anhydrite beds to the south.

Site characterization boreholes drilled by WIPP in the vicinity of the site are not addressed in BRAGFLO. ERDA-9, for example, penetrates the repository horizon within several meters of a drift wall in the operations area, but does not penetrate the repository excavation. The disposition of these boreholes is not addressed by DOE in the documents provided to the Panel. Unless properly sealed with a low permeability material such as a continuous concrete plug, such boreholes represent potential release pathways.

The permeabilities used in BRAGFLO for the waste materials and the panel closure seals are constants, but in reality are expected to change over time due to repository room closure. These parameters are important to repository fluid flow. The values chosen for permeability are in the high end of the range, and while they are conservative for late times, they underestimate permeabilities for early times. Both the closure seals and the waste may be highly permeable at early times, when the ability of the closure seals to effectively isolate waste panels may be in question. While the operations and experimental areas also are assigned constant permeabilities, the assigned value of 1×10^{-11} m^2 is considered conservatively high and therefore adequate for performance assessment purposes.

The permeability used in BRAGFLO for the DRZ is constant, but in reality is expected to change over time due to repository creep closure and to ultimately approach that of undisturbed halite as the fractures in that zone heal. The actual permeability will be determined not only by the stress-induced fracturing, but also by the roof falls expected after closure and by the numerous test, characterization, and rock bolt boreholes that penetrate the zone from inside the repository and may not be sealed before closure. The permeability of 1×10^{-15} m^2 assigned to the DRZ has apparently been selected to not impede fluid flow from the repository to the anhydrite interbeds, but has not been based on an analysis to determine what the actual permeability would be. The value chosen for permeability is expected to be in the high end of the range, and while it would be conservative for late times, it may underestimate the permeability at early times.

The evaluation of the panel closure seals in restricting the effects of borehole intrusions to the penetrated waste panels suggests that the design, placement, and performance of these seals is important. The assigned constant permeability of 1×10^{-15} m^2 is equal to that of the disturbed rock zone, yet the crushed salt and concrete to be used in the seal will have considerably different and time-variant properties, depending on the seal design, methods of emplacement, and creep closure rates and pressures. The permeability of the concrete will increase over time due to degradation, while that of the crushed salt will decrease due to consolidation. The panel closures do not appear to have been formally designed and an engineering evaluation of their performance over time does not appear to have been performed.

3.3.2.3. Evaluation of Alternatives

The overall conceptual model for repository fluid flow has evolved over time and has been the subject of detailed review in which alternatives were evaluated and led to refinements in the numerical representation of the model in BRAGFLO (see, for example, Christian-Frear and Webb [1996] and Freeze et al. [1995]). The alternatives evaluated included three-dimensional versus two-dimensional representation, including and excluding gravity effects, and varying configurations of the two-dimensional representation. Based on these studies, the overall conceptual model, as configured for use in performance assessment, has been shown to be adequate; however, the validity of certain assumptions regarding components of this model has been questioned, as described in Section 3.3.2.2. These assumptions include alternative depths for model cells in BRAGFLO, committing to sealing the ERDA-9 borehole prior to repository closure, providing variable permeabilities for the waste, panel closure materials, and the DRZ, and providing an engineering design and performance evaluation of the panel closures.

3.3.2.4. Uncertainties

The principal uncertainties in the model results are expected to stem from uncertainties in the modeling theory and in the parametric data base. Emphasis in this review has been on identifying uncertainties that would lead to underestimating radionuclide releases. While the theoretical basis for the model may contain inaccuracies, it closely represents the state-of-the-art and with the exceptions noted above, does not appear to bias the results toward underestimating releases. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in the aforementioned reports Freeze et al. (1995) and Christian-Frear and Webb (1996). Material properties with high degrees of uncertainty are generally treated as distributed variables. The properties of the panel seals, however, are not distributed variables and in the absence of a more thorough analysis of the seal design and its long-term performance, the ability of these seals to successfully isolate waste panels must be considered uncertain. Another uncertainty stems from the lack of a DRZ in the repository walls and the potential for waste releases through exploratory boreholes that penetrate the walls rather than the waste itself. The consequence of uncertainties in the models or data base is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are considered adequate for performance assessment.

3.3.2.5. Adequacy of the Conceptual Model

The conceptual model for repository fluid flow is fundamentally sound and represents an appropriate effort to simulate the complex, strongly coupled fluid flow processes occurring within the repository during periods of simultaneous gas generation and creep closure. The appropriateness of the model was supported by the results of more detailed modeling reported in Freeze et al. (1995) and Christian-Frear and Webb (1996). The issues raised regarding the validity of the model assumptions (Section 3.3.2.2) are associated with specific, but potentially significant, details of the model. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.3.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.3.2.2 regarding model assumptions, the application of the conceptual model in the numerical model is adequate. Principal concerns are related to the model cell depths, the treatment of material properties that vary over time, the disposition of the ERDA-9 borehole, and a more thorough evaluation of the long-term performance of panel closures as repository seals.

3.3.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although many simplifying assumptions are made, they are generally demonstrably conservative and are appropriate in view of the need to make the probabilistic modeling effort tractable, and in view of the relatively high degrees of uncertainty in both input parameters and the occurrence of future events. Selected modeling results were reviewed (specifically, repository pressure differences across borehole and shaft cells and at model boundaries) and were found to be reasonable. Although the accuracy of the BRAGFLO results is expected to be adequate and appropriate for performance assessment modeling, provided that the issues raised in Section 3.3.2.3 are appropriately addressed, a final determination of model accuracy cannot be made in the absence of modeling results.

3.3.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The sensitivity of modeling results to the depths of the cells in BRAGFLO representing the borehole and shaft does not appear to have been evaluated for a variety of flow conditions to determine if the model configuration unrealistically restricts brine movement within the waste panel area or to the anhydrite beds at the southern end of the repository. If modeling results are found to be sensitive to this model configuration, alternative configurations might be considered.

- A commitment to effectively seal the ERDA-9 borehole with a continuous concrete plug does not appear to have been made by DOE. Such a commitment is expected to be provided in Chapter 3 of the CCA; however, this chapter was not available to the Panel for review.

- The sensitivity of model results to the constant permeabilities assigned to the waste materials and panel seals does not appear to have been evaluated. Higher permeabilities at early times could lead to underestimating radionuclide releases.

- The basis for the permeability value assigned to the repository DRZ has not been adequately supported, and the sensitivity of model results to the selection of a constant value for this parameter does not appear to have been evaluated for the current performance assessment model. The presence of open, unsealed boreholes within this DRZ and the likelihood of massive fracturing during roof failure suggest that the permeability of this zone may approach that of the waste.

- The waste panel closures do not appear to have been formally designed and their long-term performance does not appear to have been evaluated in the same rigorous manner as shaft and borehole seals.

3.3.2.9. Adequacy for Implementation

The Repository Fluid Flow conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.3.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.3.2.10. Dissenting Views

There were no dissenting views for this model.

3.4. Salado

3.4.1. Model Description

The Salado Formation is the principle barrier between the waste and the environment and is the primary source of brine flowing into the repository. The conceptual model supports estimates of hydrologic processes and properties, as well as mechanical behavior of the halite-rich rocks of the Salado Formation. A simplified stratigraphy for hydrologic modeling is proposed and supported. The modeling of the anhydrite interbeds is discussed elsewhere.

The Salado Formation was deposited by cyclical evaporation of marine water in an imperfectly closed sub-basin of the Permian Basin. The sub-basin, called the Delaware Basin, contains the Los Medanos region in which the WIPP site is located. The cyclical nature of deposition is represented by variations in the details of the mineralogy and geochemistry of the halite, by the presence of interbeds composed mostly of anhydrite, and by the presence of clay seams. Individual depositional cycles are a few meters thick. Relatively pure and impure (argillaceous) halite layers are present. Anhydrite interbeds, generally less than a meter or two thick, represent relatively fresh water inflow at the beginning of evaporative cycles. All of these variations represent fluctuations in water chemistry and the influx of windblown and water-borne fine clastic sediments.

The layering and composition of the Salado impact the mechanical processes of room closure and the hydrologic processes (both gas and brine) that accompany room closure. A detailed stratigraphy, which defines the distribution of mechanical properties and processes, has been developed for use with the MD model (Munson et al. 1989). Christian-Frear and Webb (1996) asserts that a simplified model containing only impure halite and interbeds is sufficient for hydrologic considerations.

The presence of a significant fraction of clay (≈5%), primarily as interstitial inclusions, significantly impacts the mechanical behavior of halite rocks. The clay promotes fracture and reduces intergranular cohesion and friction, increasing the rate of creep. Impure halite is also more permeable than its purer analogue. This may be due to the interference of clay particles in intergranular spaces with the processes of pore closure related to creep under natural loads.

The pre-excavation hydrologic environment in the halite rocks of the Salado is one which may be characterized as having very low permeability and porosity due to void-filling by diagenetic processes and creep resulting from the superincumbent load. Although both display very low porosity and permeability, the pure halite rocks display lower (almost impossible to measure) permeability than the impure halite. No significant natural flow occurs in the pre-excavation Salado environment. The anhydrite interbeds are more permeable than the halite rocks and have natural fractures. This is presumed to result from the physical properties of anhydrite, which is stronger and more brittle than halite and resists creep at the repository lithostatic pressure. Beauheim (1987) documented that permeability is greater near the excavations (beyond the secondary DRZ) at distances of several meters and that pore pressures decrease near the excavations, implying that flow resulting from stress imbalance around the excavations is occurring. Brine seeps on excavation walls, collection of brine in boreholes in the repository floor, and the measured contribution of inflowing brine to humidity in the repository, are clear indications that brine inflow is occurring.

Three flow mechanisms have been proposed based on the varied, mostly qualitative data about flow into the repository (Howarth et al. 1995). These are: 1) far-field flow in response to potentiometric gradients resulting from excavation through naturally interconnected pore spaces; 2) redistribution of pore fluids (pores not necessarily originally interconnected) due to fracture and creep around the excavations; and 3) flow due to consolidation of water-bearing clay layers. None of these mechanisms can be eliminated on the basis of the existing evidence, so an inflow model combining the estimated volumes of brine from each mechanism is proposed. No consideration of the role of brine included in halite crystals is mentioned, although fracturing and some intracrystalline creep mechanisms may liberate brine from this source.

Estimates of quantities of brine inflow from each proposed flow mechanism over the repository history (to final closure) were made on the basis of best-estimate values. Although the volume of brine inflow from the far-field mechanism is theoretically unlimited, low permeability and the relatively short time available limit the probable actual volumes of brine that could reach the repository. The far-field mechanism may deliver between 25 to 110 m^3 of brine to a single disposal room over the life of the repository. Brine from the redistribution mechanism may range from 28 to 150 m^3. The clay compaction mechanism is assumed to have mostly ceased by the end of the disposal phase of work. These estimates depend on the repository gas pressures countervening the fluid potential gradient at a reasonably early time in the repository history. In any case, these mechanisms can supply enough brine to fully corrode the waste, between 100 and 150 m^3 per disposal room (Howarth et al. 1995). Flow out of the repository, due to elevated gas pressure by matrix flow or in fractures, is likely to be multiphase and will be less efficient than brine inflow. Specific data on Salado capillary pressures are not available.

Brine inflow and outflow have been simulated using the BRAGFLO model, and some specific enhancements to tie in specific conceptual model components have been proposed. These are: (1) Stratigraphy, (2) Salt Creep, (3) Fluid Flow, (4) Transport, (5) Thermally Driven Fluid Flow (insignificant), (6) Model Initial Conditions, (7) Disturbed Rock Zone, and (8) Interbed Fracturing. The model results were compared with the small scale brine inflow and Room Q experiments. McTigue (1993) evaluated the experimental results, using an exact analytical solution based on simple Darcy flow, for three flow histories for two flow mechanisms. This analysis provided an acceptable comparison between model and experimental results.

The INTERVAL program (Howarth et al. 1995) provided partial review of the model/experimental comparison and concluded that the Darcy-based version of BRAGFLO could replicate the Room Q results consistently with refinements of the inflow models to better simulate the pore pressure field around the excavations.

Electrogeophysical experiments were performed to evaluate the extent of the interconnected pore-space field around the repository and were found to support the far-field flow model (Borns et al. 1990). That is, the extent of saturated and interconnected pore spaces was seen to be infinite in the horizontal direction in the Salado.

3.4.2. Review of Criteria

The Salado is the primary barrier to radionuclide transport out of the repository. Its mechanical properties dictate the most important aspects of room closure and its hydrologic properties control brine inflow and gas and brine outflow. The objective of the Salado model is to provide a set of process and property descriptions unified to define the original state of Salado equilibrium with its natural environment and its responses to excavation of the WIPP facility. The mechanical aspects of the Salado model support the Creep Closure model. The hydrologic aspects of the Salado model define the framework for consideration of brine inflow and brine and gas outflow from the repository. Detailed consideration of the anhydrite interbed and impure halite behavior are presented in other conceptual model reviews. The Salado conceptual model is central to the performance assessment because of the general absence of important quantitative measurements of principal parameters describing flow in the very low permeability halite rocks.

3.4.2.1. Information Used to Develop the Conceptual Model

Surface-based hydrologic testing of the Salado was abandoned because of the extremely long times required for testing in the extremely low permeability environment. *In situ* testing in the facility excavations included testing in short boreholes in Room Q, laboratory testing on samples from the excavation, electrogeophysical surveys, and collection of water from wall seeps and openings such as unlined boreholes. Packer tests were performed to specifically examine questions about interbed permeability and critical pressures to activate interbed fractures. Mechanical property measurements include closure rate measurements and laboratory tests. Mechanical models are discussed in the Creep Closure and DRZ model reviews.

Inflow and outflow models are based on best estimates, since only indirect measurements of flow and pore pressures in the low permeability Salado in disturbed areas near the repository are available, and no actual data are available for the hydrologic properties of the undisturbed or far-field natural state of the halite rocks. Only one, yet to be qualified, hydrofract experiment far enough from the repository to imply undisturbed stress conditions, has been done. Models of flow are essentially limiting calculations based on estimated and projected process parameters. Hydrofracture of the repository is not considered in the model since such an event is considered a "conservative" result lowering gas pressure. It is also possible that interbed critical pressures are low enough that halite hydrofract pressures may never be reached. Interbed critical pressures are estimated at a maximum of 5 MPa and Salado critical pressures appear to be between 15 and 20 MPa.

3.4.2.2. Validity of Model Assumptions

The hydrologic model of the Salado assumes that the three proposed flow mechanisms (Section 3.4.1), exclusive of flow in the interbeds, are the only credible flow mechanisms and that the estimated volumes of brine inflow are credible. The estimated volumes of brine inflow are sufficient to corrode all of the corrodable materials in the projected waste. The key assumptions appear to be valid with respect to inflow processes. The inflow volumes depend on the interaction of inflow with repository gas pressures and on the estimates of the far-field flow response to repository excavation. The assumption of Darcy flow seems valid in the far field, but is difficult to demonstrate in the region near the repository. Inflow volume estimates are difficult to validate. Outflow hydrodynamics depend on two-phase flow models, which depend on capillary pressures in the Salado. No capillary pressure measurements are available. Larger outflow into the Salado beyond the DRZ by matrix flow is a conservative influence since the process would amount to interstitial storage of contaminants. Although likely to some extent, no credit is taken in final performance assessment calculations for this phenomenon. The assumption of cessation of flow from clay compaction before the end of the repository phase is acceptable because of the small brine volumes predicted.

3.4.2.3. Evaluation of Alternatives

No alternative models were evaluated by DOE (see Section 3.4.2.2).

3.4.2.4. Uncertainties

Although somewhat uncertain, the brine inflow model predicts sufficient volumes of brine to corrode all of the corrodable waste. There are, therefore, no consequences of reasonable additional uncertainty in terms of corrosion and gas generation. Brine volumes very much greater than those predicted would have to occur before brine mechanically interferes with room closure, and is unlikely. Brine availability for biogenic waste degradation is assumed. The Room Q and other observations appear to support the general validity of brine inflow estimates and the unlikelihood of very large uncertainties. Only very large underestimations of brine inflow would have significant impact, unless the sudden dissolution of dissolved gases during human intrusion might cause direct discharge of brine in the repository to the surface. The timing of the occurrence of gas pressures sufficient to retard brine inflow is the principle control of brine volume. This timing is addressed in the Gas Generation conceptual model and the porosity surface calculations.

3.4.2.5. Adequacy of the Conceptual Model

Given that the conceptual model predicts that there will be enough brine to corrode the waste and that other assumptions appear conservative, making other impacts unlikely, the model is adequate for its intended use.

3.4.2.6. Adequacy of Application

Assuming that the interaction of the inflow model with the gas generation model and the porosity surface calculation are adequate, the application of this model is adequate.

3.4.2.7. Accuracy of Results

It is unlikely that the results of the application of this model are highly accurate, but in view of the conservative assumptions and the large margin between the assumed impact on waste degradation and other significant impacts, the results appear to be accurate enough for the intended purposes of performance assessment.

3.4.2.8. Validity of Conclusions

The conclusions appear to be valid. Estimates of inflow volumes from the mechanisms proposed in the model appear to be reasonable.

3.4.2.9. Adequacy for Implementation

The model is adequate for implementation.

3.4.2.10. Dissenting Views

There were no dissenting views for this model.

3.5. Impure Halite

3.5.1. Model Description

The Impure Halite conceptual model explains the role of impurities in influencing the mechanical and hydraulic properties of the halite-rich rocks in the Salado. The model supports the treatment of the distribution and stratigraphy of impurities in the Creep Closure and Salado conceptual models.

There are two general classes of halite rocks in the Salado Formation. These are called pure and impure halite, based on the occurrence of significant proportions of mineral phases other than halite in the impure type. Impurities include evaporite minerals such as polyhalite and anhydrite, as well as iron oxide coatings and clay. The most abundant (as much as 5%) and important impurity is clay, with the exception of the anhydrite interbeds, which are discussed elsewhere. Clay occurs as clay seams, which are treated as mechanical discontinuities in the Creep Closure model and as sources of inflowing brine in the Salado hydrologic model. It is as dispersed, interstitial clay that impurities have the most impact on the behavior of halite-rich rock.

Pure halite is more impermeable (Howarth et al. 1995), more ductile, and stronger (lower creep rate by a factor of four) than impure halite (Munson et al. 1989). Mechanically, the elastic interstitial clay platelets probably act as flaws, concentrating stress and modifying plastic micro-mechanical strain mechanisms. Pure halite is thought to be almost perfectly impermeable because creep under natural lithostatic stress has caused adjacent crystals to conform to each other's shape along their interfaces so completely that there is almost no space for interstitial brine. Such close-fit crystal mosaics, even in the presence of thin brine films on their interfaces, have minimal interconnection between pore spaces and any movement through the interstices would be inhibited by adsorptive and film-strength forces.

Clay particles between halite crystals interfere with the closeness of fit of adjacent crystal faces, concentrate stress, and may promote solubility of pore walls. Clays are phylosillicates, which in many cases are capable of chemically driven adsorption and desorption of water, promoting flow and water storage in pore spaces. The mechanical influence of clay promotes microfracture, which may enhance flow in response to stress imbalance around the repository.

Christian-Frear and Webb (1996) has asserted that a hydrologic model of the Salado that ignores the stratigraphic variation within the halite rich rocks of the Salado leads to an acceptable and conservative flow model result if all the halite-rich rocks are modeled as impure halite. This model conservatively overestimates flow in the halite rocks to an acceptable degree and eliminates the need to consider variation in the degrees of impurity and stratigraphic complexities among pure and impure halite rocks. Conservatively chosen values for impure halite permeability make this an adequate approach to modeling of halite-rich parts of the Salado.

The geometry of flow in the impure halite is convergent/divergent as discussed under the Repository Fluid Flow conceptual model review. The probability of hydrofracture of impure halite is probably larger than for pure halite because of the loss of cohesive strength due to clay in the interstitial spaces. Hydrofracture is not considered because it would lower gas pressures (a conservative influence), and because critical pressures for fracture of impure halite are much higher than for interbed flow. Interbed threshold pressures vary from one to five MPa, while halite critical pressures approach 20 MPa. Also, outflow estimates are based on two-phase flow and are not based on measured capillary pressures.

3.5.2. *Review of Criteria*

The impure halite conceptual model provides a basis for the evaluation of brine inflow and outflow from the repository within the simplified stratigraphic framework based on work by Christian-Frear and Webb (1996). Although differences in the behavior of pure and impure halite, variable degrees of impurity, and complexities of stratigraphic distribution of zones of impurity exist, the modeling of all halite rocks in the Salado as impure halite is an acceptable model simplification (Christian-Frear and Webb 1996).

3.5.2.1. Information Used to Develop the Model

Measurements of impure halite hydrologic properties (see natural barriers panel review) and assumed flow geometry and mechanisms (see the Salado model review) provide the additional bases for brine inflow estimates. Christian-Frear and Webb (1996) evaluated the acceptability of the simplified stratigraphy using impure halite only for halite-rich rocks for the Salado model. The Impure Halite model lacks precise flow rates and capillary pressures from hydrologic measurements and the flow mechanism process models are based on assumptions which have only theoretical bases, but provide results that acceptably match experimental and observational data.

3.5.2.2. Validity of Model Assumptions

The model assumptions are the process models for flow mechanisms, the Darcy nature of far-field flow, and the conservatism of the simplification of stratigraphy proposed by Christian-Frear and Webb (1996). These assumptions are reasonable and are supported by arguments presented by Howarth et al. (1995), by the comparison of model elements and inflow observations by McTigue (1993), and by review of similar results by INTERVAL (Howarth et al. 1995).

3.5.2.3. Evaluation of Alternatives

Early WIPP models considered all halite-rich rocks to be unsaturated and impermeable. Observation of inflow after excavation forced the development of flow models for halite-rich rocks. All observational and most experimental data are from impure halite. No alternative flow mechanism models have been considered (Howarth et al. 1995).

3.5.2.4. Uncertainties

The impure halite model is almost entirely theoretical and no evaluation of uncertainties is considered. Results match *in situ* brine flow observations fairly well. The result of uncertainty in the case of the simplifying assumptions with regard to stratigraphy are conservative.

3.5.2.5. Adequacy of the Conceptual Model

The model appears to be adequate for the same reasons that the overall Salado model is adequate. Brine inflow sufficient to corrode the waste and to drive biogenic degradation is assumed. For error to be significant, brine inflow would have to be very large, which is unlikely.

3.5.2.6. Adequacy of Application

The impure halite submodel is applied adequately, with the assumption that its application in the Salado model and related other models is conservative.

3.5.2.7. Accuracy of Results

The results of the model are probably not highly accurate, but appear to be adequate in their application.

3.5.2.8. Validity of Conclusions

The conclusions drawn on the basis of the impure halite model are valid for performance assessment purposes.

3.5.2.9. Adequacy For Implementation

The model is adequate for implementation for performance assessment purposes.

3.5.2.10. Dissenting Views

There were no dissenting views for this model.

3.6. Salado Interbeds

3.6.1. Model Description

The three Salado interbeds are modeled in BRAGFLO and are represented by region 20 (Marker Bed [MB] 138), region 21 (anhydrite layers a and b), and region 28 (MB 139). All three interbeds have the same model parameters (see Tables 6-12 and 6-13 in Section 6.4) and initially, the parameters are spatially constant. The only initial model difference concerns bed location and thickness.

Three primary interbeds are identified in the region of the Salado Formation nearest the waste panel: MB 138, anhydrite layers a and b, and MB 139. All three interbeds are primarily composed of anhydrite, with clay seams bounding the lower contacts of MB 138 and MB 139. As discussed below, the interbeds have differing physical and chemical properties from the halite of the Salado Formation. Anhydrite is much less soluble than halite. The interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures (both healed and open) present in the anhydrites. Under differential stress, the interbeds may fracture while, under the same stress, halite would flow by plastic deformation. Fracturing of the relatively brittle interbeds would enhance the local permeability, allowing this otherwise low-permeability rock to carry groundwater. Furthermore, since the interbeds have a large contact area with the adjacent halites, even very small fluxes from the halite into the interbeds or to the halites from the interbeds can accumulate into a significant brine inventory. In this sense, the interbeds may cause the halite to act as a source or sink for brine in the repository. The three interbeds are explicitly represented in the conceptual model because of their physical properties and their existence in the disturbed rock zone around the repository, within which fluids are able to flow with relative ease compared to surrounding rock types.

Two major conceptual features of the interbed model are represented by, 1) transmission of brines from the impure halite to the repository via the interbeds and, 2) incorporation of fracturing and dilation of the anhydrite to allow porosity and permeability variations.

Feature one allows brine flow laterally along the higher permeability interbeds toward or away from the repository, and vertically between the interbeds and low-permeability halite. Horizontal fractures, dilation, and propping are due to gas pressures exceeding the threshold pressure. Induced vertical fractures in the interbeds are caused by interconnection of branching horizontal fractures over time, or high exceedence of the threshold gas pressure (i.e., greater than lithostatic). Pre-existing vertical fractures were caused by tectonic forces or the alteration from gypsum to anhydrite and subsequent volume reduction.

Feature two, alteration of porosity and permeability, is caused by the creation of new fractures or dilation of pre-existing, partially healed fractures due to high gas pressures. *In situ* hydrofracture tests have created sustained fracture apertures to 0.2 mm. Such pressure-dependent variables have created marked permeability changes. In the BRAGFLO model, a porous medium model simulating interbed fracturing and dilation causes porosity and permeability of a computational cell to increase as the pore pressure exceeds the threshold value. In addition, interbed transmissivity increases with increased anhydrite fracturing or dilation. Fluid is able to easily flow radially outward if adequate threshold pressure is available (1 to 5 MPa) to dilate the anhydrite. The model assigns a fracture initiation pressure at which local fracturing occurs and changes in permeability and porosity subsequently occur. Above the threshold pressure, the local compressibility of the interbed increases linearly with pressure. This greatly increases the porosity with respect to increasing pore pressure. Additionally, permeability increases as a power function of the ratio of altered porosity to initial porosity.

3.6.2. Review of Criteria

3.6.2.1. Information Used to Develop the Conceptual Model

Three primary sources of information were used to generate the conceptual model for the Salado interbeds. These included FEP documentation, position papers, and *in situ* hydraulic tests. Four FEPs were associated with the Salado Interbed conceptual model: DR-9 (anhydrite threshold displacement pressure); S-1 (verification of 2D radial flaring); S-4 (mechanical effects of gas generation); and S-5 (brine storage in anhydrite and halite). A second source of information was the Salado position paper. The third major source of information for developing the conceptual model was obtained from *in situ* field tests of the anhydrite interbeds. Location of these tests was in the vicinity of Rooms Q and L. These information sources are believed to be adequate for model development.

3.6.2.2. Validity of Model Assumptions

The main assumptions of this conceptual model are considered valid. The chemical assumption, that anhydrite is less soluble than halite in the WIPP environment, is proven by both experimental and crystal chemical factors. The Darcy flow model is also deemed reasonable. The type of fracture propagation and dilation used in the conceptual model has been substantiated by *in situ* tests. Assumptions of increased porosity and permeability due to fracturing (caused by gas generation exceeding threshold pressures) is reasonable. Therefore, the assumptions of this conceptual model that have the largest potential impact are believed to be appropriate.

Three other assumptions of the interbed model have not been well documented. The first of these is the description of the mechanism of vertical crack propagation. This potential effect of gas overpressurization needs to either be fully described or discounted from occurring in the interbeds. Second, there does not seem to be any incorporation of the fact that there are continuous clay seams at the base of MB 138 and MB 139. The physical properties of clay seams (water content, low cohesive structure, aniostropic characteristics) may have a substantial effect on the model of the interbeds. Third, the fluid storage capacity of the interbeds is not well documented.

3.6.2.3. Evaluation of Alternatives

Earlier models of the Salado Formation in the 1980 final environmental impact statement did not differentiate the anhydrite interbeds as a separate model. When the 1989 draft environmental impact statement was produced, anhydrite interbeds were included as a model. This was based on *in situ* tests that determined the interbeds had higher permeability than the remaining Salado Formation. The 1992 performance assessment concluded that the interbeds would then be the dominant fluid pathway. It was not until this factor was recognized and gas pressures were calculated to possibly reach 20 to 25 MPa (in the 1992 performance assessment) that an attempt was made to model fracturing in the anhydrite interbeds.

At the level of a conceptual model, the primary factors of the Salado Interbeds have been addressed properly. This has been accomplished by either using well-established models (Darcy flow) or *in situ* experiments, or by adopting reasonable, conservative assumptions.

The following items do not appear to have been addressed by DOE: (1) Is storage capacity of the anhydrite layers so small that brines would be forced to travel to the Land Withdrawal Act boundary? (2) What would the consequence be if the gas threshold pressure of the clay seams was very low (for example, 0.01 MPa)?

3.6.2.4. Uncertainties

The levels of uncertainty associated with the Salado Interbeds performance at the conceptual model stage appear to be quite small. The following uncertainties may affect the model but the consequences are unknown at present. The determination of consequences would hinge on a sensitivity analysis, which is presently unavailable.

The model assumes that fracture propagation would continue uniformly in a horizontal direction. In Domski et al. (1996), test results for interbeds indicate anisotropy. Assuming that the interbeds act in an isotropic manner would be conservative, especially since *in situ* values were determined for the weakest direction (laterally).

Another assumption is that enhanced porosity and permeability in the interbeds would mitigate each other in terms of gas migration responses. This does not seem plausible since permeability increases as a power function to an increase in porosity. It would seem that permeability factors would dominate and therefore allow longer gas migration distances.

The perturbation to the model that is completely unaccounted for (threshold pressure of bounding clay seams) is included as a secondary factor in Section 3.6.2.3 above.

3.6.2.5. Adequacy of the Conceptual Model

The Salado Interbed conceptual model describes fluid flow through three discrete anhydrite layers in the vicinity of the repository. CCA Section 6.4.5.2 reports flow model objectives in dealing with the anhydrite interbeds: (1) fluid flow through the interbeds, (2) fracture formation and/or dilation of the interbeds, (3) variations in porosity of the interbeds, and (4) variations in permeability of the interbeds within the constraints of the conceptual models. These requirements are thought to be adequate. The uncertainties associated with the model can not be constrained since a sensitivity analysis is not presently available.

3.6.2.6. Adequacy of Application

A much greater uncertainty is perceived when it comes to converting the field results into the mathematical model. In all but the simplest of field observations, one must make assumptions in applying a mathematical model. However, the ability to monitor the assumptions made in developing a numerical code to simulate the physical properties acting within the anhydrite interbeds is extremely difficult. SNL states at one point that parameters in the model are treated as fitting parameters and have little relation to physical behavior, except that they affect the porosity change. At no time was the logic clearly presented whereby one could track the implementation of this conceptual model into the numerical code developed for this portion of BRAGFLO. Therefore, one must state that the discussion of how the anhydrite interbed conceptual model is applied into an overall performance modeling element was not adequate.

3.6.2.7. Accuracy of Results

The results obtained for this conceptual model fall into two categories. The first set of results are those determined from physical tests. Hydraulic tests performed *in situ* near Rooms Q and L, and laboratory tests on core samples have provided results that are deemed adequate. These tests are based on standard procedures and have been qualified as to their accuracy. There is no further question as to the validity of these physical parameter results.

The second category is based on whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the physical and chemical processes modeled. It is not possible to make a judgment on this category of results since no values have been presented to indicate the outcome of this model. The 1992 performance assessment did not incorporate a fracture propagation submodel in the Salado Interbeds model, so results and sensitivity analyses from that performance assessment are not applicable to this review. Results for this section are not meant to be the final performance assessment results, but rather are the results of BRAGFLO during various permutations.

For example, hydrofracture experiments in the anhydrite beds have created sustained fracture apertures to 0.2 mm. If BRAGFLO produced fracture aperture dimensions of 5.0 mm during gas pressurization runs, one would conclude that the results are not accurate. This sort of comparison has not been possible because model runs have not been presented.

The implementation of the fracture modeling was not explained in sufficient detail in any document. The method of how the code represents the physical property is unknown and its accuracy cannot be judged. Results of the calculation could vary significantly, depending on whether the fractures propagate gradually or in a stepwise fashion.

3.6.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Salado Interbed model in the modeling framework are valid. Since the accuracy of results is inconclusive (see Section 3.6.2.7), it is difficult to assess the validity of the conclusions. The results of parameters listed in Table 6-12 of the CCA may be considered valid for the purpose of implementation in the overall performance assessment. The results listed in Table 6-13 of the CCA may not be valid at this point. Questions of validity are addressed below.

Fracture initiation pressure for MB 139 at 0.2 MPa above hydrostatic pressure is concluded to be valid. The percent increment to allow full fracture porosity for MB 138 and 139 (3.9%) is also considered valid. The same parameter for anhydrite beds a and b is 23.9%, and no discussion is presented for the large difference in the value. The increase needed to allow full fracture porosity in these two interbeds would not be expected to differ from MB 138 and 139. Such a difference should have been thoroughly explained. The conclusion of maximum permeability (10^{-9} square meters) is extremely suspect since the storativity of the beds was not calculated. These two factors are closely linked and it is hard to envision that the permeability can increase ten orders of magnitude without a dramatically substantial change in storativity of the interbeds. Finally, the parameter "increment above fracture initiation pressure to obtain maximum fracture pressure," does not account for the effect of bounding clay seams associated with the interbeds. To assume that an increase of approximately 1.5 MPa above lithostatic pressure is needed for maximum fracturing is probably not valid when clay seams are in close proximity

3.6.2.9. Adequacy of Implementation

The conceptual model for the Salado Interbeds is well thought out and substantiated by *in situ* experiments. However, certain items were not clearly explained or documented in Chapter 6 of the CCA. It would be helpful if the following questions were clarified:

- What is the mechanism for vertical crack propagation?
- What is fluid storage capacity of the interbeds after dilation?
- Enhanced porosity and permeability are presumed to mitigate each other in terms of gas migration responses. How can this happen when permeability is a power function (not linear) of porosity?
- What assumptions and limitations are made to represent the conceptual model by the mathematical code?
- Why is the full fracture porosity increment of 23.9% for anhydrite beds a and b so different from the 3.9% for MB 138 and 139?
- What are the calculations that show that permeability increases by 10 orders of magnitude?

It is believed that this model would be adequate for implementation in the compliance application after the question raised below is fully addressed.

- How do the physical properties of clay seams at the contact of the interbeds affect the fracture propagation and permeability of the model?

3.6.2.10. Dissenting Views

There were no dissenting views for this model.

3.7. Disturbed Rock Zone

3.7.1. Model Description

The Disturbed Rock Zone model consists of a description of a fracture zone surrounding excavations that is created by induced stresses. At the WIPP, the primary DRZ exists in all rocks; the secondary DRZ is applicable only in viscoelastic rocks such as halite. The DRZ varies in depth away from the excavation and has been reported to be up to 50 m deep for large excavations. It exists in the repository roof, floor, and walls, and around shaft and borehole walls. Because of the distinctly different stress fields in each of these locations, the DRZ can have different properties at each location. For example, it is considered to disappear under appropriate conditions and with time in the borehole seals program, and is variously applied as it relates to the repository rooms and panels. Related models include Creep Closure, Shafts and Shaft Seals, Disposal Room Geometry, Repository Fluid Flow, Salado, and Salado Interbeds.

Induced changes to the stress field occur immediately on the passage of mining equipment during excavation. In halite, as the salt adjusts to these changes through the creep process, further micro- and macro-fracturing progressively occur in the intact rock, adding to a fracture region known as the DRZ. This DRZ was first technically addressed and demonstrated by Borns et al. (1987, 1988, 1989, 1990). Van Sambeek et al. (1993) have referred to the mining-induced fractures as the initial DRZ and the progressive fracturing as the secondary DRZ. In this analysis, the Panel will not distinguish between these except for their applications. The characteristics of the DRZ include increased rock volume and permeability and decreased brine saturation due to drainage and drying, load bearing capacity, and lithostatic pressure. Clearly these properties could lead to the DRZ providing flow paths for fluids and gases from the repository to those zones that might carry them to the accessible environment. Studies by Munson et al. (1994) have characterized the DRZ and found it to be irregular in thickness and fracturing and able to heal with time under an applied confinement. Two versions of a creep model, applicable to room closure and DRZ development, have been formulated during this period. These are a model that includes both transient primary creep and steady state creep (MD model), which has been used in the porosity surface lookup table calculation of repository void space, and the MD model, with added tertiary creep fracture (MDCF), used to confirm DRZ thickness, fracture porosity, and healing characteristics. The MD model is central to the porosity surface calculation (SANTOS), which relates creep, waste compaction, and gas pressure to overall room closure rate. The DRZ is not considered in room closure calculations since all DRZ fracture porosity is assumed to be recovered by healing at final closure. For the waste room, the DRZ model is incorporated by assuming a high permeability and low porosity, with the result that the DRZ is unable to act as a constraint to brine or gas flow from the repository rooms and is unable to store brine. A primary reason for this approach is the uncertain behavior of the rock zone, which is dependent on many uncontrollable factors.

3.7.2. *Review of Criteria*

3.7.2.1. Information Used to Develop the Conceptual Model

The treatment of the DRZ in both the shafts and the repository rooms is the result of development of an equivalent permeability and porosity for addition to the main room and shaft seal model elements rather than by a specific DRZ input. Analyses were conducted evaluating the reasonableness of this approach, but parameters representing the DRZ over the history of WIPP were not developed. Therefore, the information supporting evaluation criteria for review of this conceptual model is essentially the completeness of the considerations and the reasonableness of the DRZ concepts.

The DRZ has several significant impacts on the performance assessment calculations. These include a) room performance, b) gas pressure calculations, especially near term, and c) permeability of the shaft regions. The DRZ in the salt around the rooms appears to be the toughest to model because of the sizes and shapes of the openings. The shaft DRZs appear to be less difficult to model because of their simpler shape. First, the shafts are smaller than the rooms, second they are stable cylindrical forms, and third, studies show that, given a stiff support against creep, the DRZ fractures will heal in a relatively short time. For example, from analysis of WIPP data, Chan et al. (1995) projects full healing within 25 years after the shaft seals have been placed. Within the healed zone, the induced high permeability drops to a level below that of the placed seals, reducing the concern of a large flow path surrounding the sealed shaft. Contrary to this favorable healing in the shafts, DRZ healing in the waste room will not be as responsive in time or extent. Because of the relatively large room, the necessary rigid backing to support the healing process is delayed, and the DRZ functions as a more open fractured rock mass. Furthermore, only the DRZ in the roof and floor of the repository are modeled; the walls of the room are not included in the Repository Fluid Flow model. Neither the roof nor the floor will receive the support needed to close the open cracks and open boreholes that are assumed to be a part of the roof DRZ. Early healing of the floor would be optimal in order to restrain fluid flow downward, and the roof will continue to develop an open fracture DRZ upward, due to roof spalling, as the room seeks its most stable shape within the stress field. The most notable impact of the open fractures to performance assessment in the near term will be in deterring brine flow to the repository because of brine storage in the fracture zone. This could have significant uncertainty effects on the gas pressure calculations.

It should be noted that no information was found concerning studies of how soon after excavation the DRZ is fully formed. It is reasonable to consider that its formation begins concomitant with excavation and progresses until the salt creep and the stress field have stabilized. The MDCF model appears to be an excellent tool for conceptualizing the phenomenology of salt creep and its mechanisms resulting in fracture closure and healing. Excellent progress in understanding salt's viscoelastic behavior and adding this capability to the creep flow behavior has made the modeling capability a highly supportive tool critical to understanding the DRZ. Testing of these concepts has produced favorable responses that have specifically aided the shaft seals program in mitigating concerns over seals integrity. Significant among these tests are the Room Q experiments, where identification of the reduced brine flow and increased permeability in the DRZ were measured. Data from the air-intake shaft tests showed the change of permeability as a function of distance from the shaft wall and the changes in permeability with time. Knowles et al. (1996) conducted rigid inclusion tests that confirm the ability to heal the DRZ, restoring it to ambient conditions. The many parameters associated with the DRZ have been well defined to support the BRAGFLO models. The permeability and porosities appear to be the most critical parameters for use in performance assessment. Information examined for the DRZ characterization, including its extent, ability to be restored by salt creep and restraint, and ability to be represented by modeling, was found to be acceptable.

3.7.2.2. Validity of Model Assumptions

The following assumptions are basic to the DRZ model:

- A DRZ surrounds the surfaces of any mined opening.
- A permeability value is selected that assures the DRZ is not the limiting zone for fluid transport between the waste rooms and the marker beds.
- A fixed high-level permeability value should be assigned to the DRZ everywhere.
- Roof bolts or other roof support system penetrations of the halite and boreholes through the halite into the marker beds are included as part of the DRZ, and these penetrating boreholes may not close completely.
- Various other processes may contribute to fracturing in the future.
- The DRZ surrounding the shafts will progressively heal toward near complete restoration following placement of the seals.
- The porosity and permeability are increased by the DRZ, except where a rigid backing is present to support the DRZ against creep; however, a low porosity is assumed in the room DRZ to reduce the storage capacity of that zone for performance assessment.

The basic assumption that a DRZ exists at the surface of any mined opening in the Salado is fundamental to the definition of a DRZ. That the leading boundary of the DRZ will heal, provided support exists to resist the creep, has been substantiated through the WIPP research program. Basically, the outer reaches of the DRZ (microfractures) will heal in the near term, and the DRZ primary fractures will close and heal once seal material is placed in the openings to support the process. This might reliably be achieved via the vertical cylindrical openings, but the healing problem is more complex around the waste room. There it is recognized that a variety of effects may work against the reconsolidation of the DRZ. These effects range from uneven placement and non-characterized waste support against room closure to other processes, such as roof falls, that might contribute to further development of the DRZ. These assumptions concerning the DRZ existence and its behavior appear to be adequate.

Given the shaft seals design, it is assumed that the shaft DRZ heals to the point that its permeability is below the level of seal permeability, thereby reducing its importance. Therefore, flow through the sealed shafts is attributed to the permeability of the shaft seal materials, with an adjustment to account for any DRZ component to the permeability (see Section 3.20). At the waste room, the situation is far more complex and the technology less well defined. Therefore, at the room boundary, it appears that the above assumptions support the assignment of a high permeability that essentially removes the DRZ from a limiting position of flow to and from the room, and a low porosity that will not perturb storage of the brine.

3.7.2.3. Evaluation of Alternatives

Fracture zones in the walls of excavations have always been of concern to the mining and construction industries. In most cases, however, fracturing occurs in brittle materials with elastic behavior, which is largely not the case in the viscoelastic host rock of the WIPP repository. Restoration of the DRZ to the original halite properties, as described in this report, would be applicable within most salt formations. However, at locations other than in the Salado Formation at the WIPP site (such as in the Culebra, Magenta and other members of the Rustler Formation), the DRZ will not obey the concepts forwarded. Because the DRZ in MB 138 and 139, and perhaps the anhydrite interbeds a and b, are different from the DRZ discussed here, they pose a concern for the open fractured DRZ concept and its ability to heal. This concern is discussed and analyzed within the seals design (WIPP 1996). It appears from the information available that numerous alternatives have been processed in the analysis and testing programs leading to present concepts and understandings of the DRZ. The assumptions adopted for the DRZ model are alternatives that appear to appropriately represent the existence and effects of the DRZ.

3.7.2.4. Uncertainties

A DRZ thickness of 0.8 shaft radius appears to be conservative. Munson et al. (1994) state that from the air intake shaft data (Dale and Hurtado 1996), the extent of the DRZ at 6 years is certainly less than 1.0 shaft radius, and probably only 0.7 radius. Using these same data, Chan et al. (1994) show a reasonable correlation between the test data and calculations from the multimechanism deformation coupled fracture (MDCF) model. No data were found to evaluate the effects of time on the relationship between excavation and closure. Relative to the room DRZ, the behavior of the roof DRZ might be the source of additional uncertainties in other models. Except for the shaft seals, no data were found to characterize applications of the DRZ in unique locations, such as the unsupported roof and the floor buckling from unrestrained creep.

3.7.2.5. Adequacy of the Conceptual Model

Recognition of the deleterious conditions produced by the DRZ appears to be positively addressed in studies showing the effects on brine flow in the repository and on the ability to heal under conditions of support in the shaft that makes the shaft seals issue more tangible to resolve. Because the uncertainties of possible unknown future effects of the room DRZ might go beyond the recognized problems caused by the DRZ, the room DRZ is dealt with from a conservative viewpoint. It appears that the model adequately addresses the genesis and existence of the damage zone. The MDCF model provides a realistic tool by which to examine the effects and project possible DRZ performance. Research, including that in the Room Q, the air intake shaft tests, and the rigid inclusion in salt tests (Knowles et al. 1996), has been supportive in calibrating and confirming model results (see Section 3.19). Because the roof DRZ is uniquely different from the other DRZs, the model does not adequately represent flow to the overhead marker beds. This issue is discussed in Section 3.3, Repository Fluid Flow, and in the following section. Except for this caveat, this model has the appropriate elements to support its use in the WIPP performance assessment.

3.7.2.6. Adequacy of Application

Recognition of the DRZ phenomenon around the shafts and measurements of its effects are important contributions to waste containment; in some cases these effects are among the few WIPP conditions that can be dealt with in engineering terms. It was important to find that the DRZ nearly completely heals once there is adequate backing within the shaft or borehole against which the creeping salt will reestablish its original state of stress. Because of the healed state and because tests show conservatively that the DRZ areas of influence are within 1.0 shaft radius, it is possible to demonstrate that the DRZ permeability will become lower than that of the seals. This appropriately allows the performance assessment calculations to treat the DRZ permeability as an integral part of the seal. It is important to recognize that this healing factor is a function of the shaft seals' mechanical properties and time of placement. It is also important to recognize that because of the overwhelming uncertainties of DRZ performance in the waste rooms, it be dealt with conservatively by assumption, as stated in the model description. The waste room DRZ uncertainties basically apply to specific locations such as the roof, floor, or walls, and its extent in each.

Because of the variability of the geometry and the timing of the healing of the DRZ in the different environments in which it occurs, the DOE has substituted conservative permeabilities to represent the effect of the DRZ on repository rooms and shaft seal flows. These permeabilities are carried through the processes of repository closure and the evolution of shaft seal design, taking into consideration the marked differences in characteristics of these zones. While the shaft DRZ has been carefully studied, the repository room roof and floor DRZs have not had equal attention because of their complexity. To compensate for this, the DOE chose to use a constant, conservative value for the permeability of the repository DRZ that would not be the limiting condition for flow to and from the interbeds. This approach has not been adequately supported, particularly for the roof DRZ, where the fractures may be open, large, and progress to roof collapse. Furthermore, this zone is host to drill holes that may not be plugged and can penetrate beyond the overlying marker beds. This issue has been identified as a concern for the Repository Fluid Flow model in Section 3.3. The DRZ in the room walls is not modeled, and is thought to be of little structural impact because by conservation of pore space, the initial fracture volume of this DRZ is recovered during room closure and healing.

This evaluation recognizes that the disrupted zones near the shafts have been characterized. Also, this evaluation has shown that DOE used this information in several ways, leading the Panel to conclude that the DRZ needs to be separately considered for each of its applicable areas. These areas include the roof, floor, and walls of the waste room, and the walls of the long annular openings such as shafts and boreholes. Except for modeling the roof DRZs, the Panel believes that the work to date adequately addresses the DRZ characterization for application to the performance assessment process.

3.7.2.7. Accuracy of Results

While the Room Q tests produce data that contribute to the understanding of the waste room DRZ, it appears that the value of these results is to provide background concepts and guidance for addressing the DRZ issues. After looking at the numerous unknowns or uncontrolled processes in the waste room, it seems prudent to defer analysis of the DRZ issue in the waste room until further understanding of the waste characterization becomes available, in order to more fully consider the effective resistance the waste provides to room closure by creep.

For the shafts and boreholes, the air intake shaft permeability data (Dale and Hurtado 1996), which show the extent of damage resulting from the shaft excavation to be approximately one shaft radius, has provided good basic information on this issue. Other analyses of related data and observations from the air intake shaft tests (Munson et al. 1995; Chan et al. 1995) show that the extent of the DRZ is related to shaft size, and make phenomenon amenable to incorporation in a mechanistic model. The collaboration of Munson et al. (1989) and Chan et al. (1995) has proposed one such model through coupling the DRZ fracture to the creep model (the MDCF Model). Other calculations include the determination of fracture healing time and projections of the effects of shaft seal mechanical properties on fracture healing. It should be recognized that the MDCF modeling results largely represent an early stage in this technological development and are subject to projected corrections as more time-dependent follow-up data become available. Because of the predicted low impact of the DRZ on sealed shaft permeability a few years after seal placement, it appears totally appropriate to adjust the permeability of the shaft seal components for the small contribution that the DRZ will make to the performance assessment calculations.

The same closing comments for Section 3.7.2.6 apply to this section; therefore, the results obtained are sufficiently accurate for application of the DRZ in the performance assessment process.

3.7.2.8. Validity of Conclusions

All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understanding developed of DRZ phenomena and data reveal that it is critical to engineering waste containment overall because of its potential for negative impact on shaft seal permeability and integrity, and fluid flow in the rooms and room seals. It appears that all considerations of this impact and the conclusions discussed here are sound and valid.

Relative to DRZs in the waste room roof and floor, the fractured zones have a high probability to exist and not much can be done to mitigate their effects, such as providing the stiff support needed to foster healing of the DRZ as shown by the Knowles (1996b) report test results. Credits taken for room closure due to creep will be beneficial, but this may not be significant help in later years, when the potential higher gas pressures may reverse the creep. At high gas pressure this problem is exacerbated by an expanding room scenario which could extend the DRZ even further. It appears the concepts of characterization of the DRZ, particularly in the floor, have not been well researched; perhaps an elicitation panel would be constructive on this. The roof DRZ should have less significance than the floor DRZ because brine is more likely to flow through the floor than the roof; however, the roof DRZ does facilitate the access of gas to the release pathways. The Panel concludes that while the conservativeness of the assigned DRZ permeability might overcome the lack of detailed information for the roof DRZ, further analysis of the roof behavior would enhance defendability of the otherwise valid model.

3.7.2.9. Adequacy for Implementation

Given the lack of tangible controls over remedying the room DRZ, but the encouraging test results for mitigating the shaft DRZs, it appears that appropriate considerations are being made for the DRZ conditions in all applications. It is clear that continued studies of the room DRZ would provide a better background to more explicitly model the waste room and to ascertain the variation of DRZ characterization for each of its location sites, such as in the roof, floor, or walls of a room. The Panel concludes that the present DRZ model is adequate to be implemented in performance calculations. However, since the roof is different, some other approach may be appropriate for this area.

3.7.2.10. Dissenting Views.

There were no dissenting views for this model.

3.8. Actinide Transport in the Salado

3.8.1. Model Description

The only transport mechanism that will be used in this conceptual model is advection. The Actinide Transport in the Salado conceptual model previously addressed three mechanisms: 1) advection (transport with bulk flow of liquid); 2 dispersion (liquid velocity differences while moving through pores or surface irregularities); and 3 diffusion (molecular motion in presence of concentration gradients). These mechanisms are all standard contaminant transport phenomena. DOE assumed that these three transport mechanisms of actinides in brine represented the most important processes of actinide movement in the Salado Formation. All three mechanisms look at the transport of dissolved or colloidal actinides through the anhydrite interbeds (MB 138, MB 139, and anhydrite interbeds a and b).

The advection transport mechanism is implemented by the NUTS computer code in conjunction with the Salado fluid flow portion of BRAGFLO. The NUTS code is described in Section 6.4.11 of the CCA and Appendix NUTS (which were not available for Panel review). The actual inventories of actinides come from the Dissolved and Colloidal Actinide Source Term conceptual models. The actinide source terms incorporate the assumed oxidation states and solubility factors for various actinides and a proportion of all colloids permissible.

Three physical influences that may affect actinide transport in the interbeds have been left out of the conceptual model by DOE to promote a conservative philosophy. These influences are sorption of dissolved actinides on clays, retardation of colloidal actinides by surface features, and mineral precipitation containing trace actinides from brine. Sorption of actinides onto clay surfaces is a known reaction, and DOE is highly confident that it will occur; however, the model conservatively neglects the effect. With regard to retardation of colloidal actinides by surface features, it is assumed that offsetting interactions will occur. The philosophy is that colloids can be retarded by surficial features, but will travel faster than the average velocity of the bulk liquid. Precipitation of minerals as brines move into the interbeds due to chemical gradients is a possibility. Given the concept that the amount of precipitation will be minor, and that actinides will only occur in trace amounts in the crystal structures, DOE has decided to neglect this effect in the performance assessment.

Three other mechanical processes may have a lesser impact on actinide transport in the Salado. These are fracture flow, channeling, and viscous fingering. Fracture flow is accounted for in the Salado Interbed model and takes into account increased porosity and permeability through fracture propagation and dilation. DOE expects that other fracture processes and effects not taken into account in the fracture model will be negligible. One process not incorporated, channeling, has offsetting effects. Channeling is the fluid movement through large apertures of a fracture network (i.e., locally high permeability). DOE believes this mechanism will be negated for two reasons. First, if gas is present in the undisturbed state, it will preferentially occupy areas of high permeability over brine. This will preclude these regions of fast transport from brines. Second, the incoming brine will be miscible with the interbed brine. Such miscibility will allow diffusion and mixing phenomena to broaden finger fronts (i.e., reduce concentration gradients) until they are indistinguishable from the advancing brine front.

Gases may also penetrate interbed brines as a fingered front. However, such a mechanism will not affect actinide transport because the actinides of interest are only incorporated in the liquid phase. DOE also assumes that a liquid will not displace gases in the high-permeability regions (channels) due to capillary effects.

3.8.2. Review of Criteria

3.8.2.1. Information Used to Develop the Conceptual Model

The Actinide Transport in the Salado Formation model is based primarily on the computer code NUTS, with input from BRAGFLO. Since NUTS relies on BRAGFLO input parameters, all BRAGFLO FEPs became information used in the model development. In a sort of circular logic, NUTS was used to evaluate BRAGFLO FEPs by converting flow measurements to normalized release values. The original NUTS program was extremely intricate and robust, with its basis in classical fluid transport. However, FEP studies and system prioritization events have simplified the code. NUTS now only uses advection as a transport mechanism, tracks only the wastes encountered along the flow paths, and treats downstream fluid and the fraction that came into contact with waste. The transport mechanisms of diffusion and dispersion have been excluded from the code, based on policy decisions associated with the system prioritization analysis. The exclusion of these two transport mechanisms is believed to make this conceptual model more conservative. As stated in the model description (Section 3.8.1) the exclusion of six other processes (clay sorption, surface feature retardation, mineral precipitation, fracture flow, channeling, and viscous fingering) is deemed to allow the conceptual model to be more conservative.

A second source of information critical to the NUTS code is the field of radiochemistry. Concepts dealing with radioactive decay, half-lives, and solubilities allow major assumptions to be implemented in the NUTS program.

The third major source of information folded into the actinide transport of the Salado Formation is physical properties of the anhydrite interbeds. These interbeds are the major pathways for fluid transport in the Salado. Data concerning the physical properties of anhydrite were obtained by *in situ* hydrologic tests. The fracturing properties of the beds were deduced from both field and laboratory experiments. It is deemed that the information used is adequate to develop the model.

3.8.2.2. Validity of Model Assumptions

The following assumptions are critical to the conceptual model being evaluated here. Diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in the model. DOE has taken the stance that by not including these factors, the actinides are not further dispersed and therefore the model is made more conservative. These assumptions are considered valid.

The assumption of lumping radionuclides by similar half lives and solubilities is based on the basic tenets of radiochemistry. If any computer run later indicates a potential to exceed EPA's criteria, such lumping factors can be recalculated using specific data for each radioisotope. Evaluations have not been performed to see if the lumping assumption could, in effect, mask runs from approaching the EPA limits. With this caveat in mind, the assumptions made about lumping can be considered valid.

Actinide source terms (dissolved and colloidal) in the repository are used as the input for NUTS. The assumption that these source terms are the limiting cases may not be valid, however that determination is not within the scope of this model (see Sections 3.23 and 3.24).

Once the total concentrations are calculated for the dissolved and colloidal sources for each run, the final value is then transported as one package at the average flow value. The assumption made is that colloids can be transported at this slower rate and still be adequate since sorption and filtration of colloids are not accounted for. This assumption has not been proven to the Panel's satisfaction.

The final major assumptions of this model are that the grid blocks and time steps from BRAGFLO are proper to use in NUTS. Although this final set of assumptions may be reasonable, numerical results must be examined to determine if this concept (and inherent coarseness) is valid. At present, such results are not available.

3.8.2.3. Evaluation of Alternatives

Earlier versions of the NUTS code were much more comprehensive than the present version. Previous compilations had the capacity to treat virtually all special effects of radionuclide migration. However, system prioritization exercises and FEPs studies indicated that a much more simplified version of NUTS was desirable, in that results were still representative and computer run time was compressed. Hence, the present version of NUTS is streamlined. Factors that have been removed (or zeroed) include diffusion, dispersion, channeling, chemical sorption for dissolved actinides, physical retardation for colloidal actinides, fracture flow, and viscous fingering. The present version of NUTS is reasonable for its intended use.

3.8.2.4. Uncertainties

There are a multitude of uncertainties associated with this conceptual model and the NUTS code. First, there are all the uncertainties associated with the BRAGFLO conceptual model and its parameterizations (see Section 3.3). Values plugged into NUTS from BRAGFLO contain the inherent uncertainties from BRAGFLO since the input parameters are not screened for rationale values. These uncertainties will then be propagated through the NUTS code to the next step (SECOTP2D). The second group of uncertainties centers around the coarseness of the grid blocks and time steps used in NUTS. Although these parameters may be reasonable for BRAGFLO, it has not been justified that the same applies for the NUTS code.

Since Section 6.4.11 of the CCA and the Appendix NUTS are not presently available for review, many questions are unresolved and remain as potential uncertainties. These issues involve long-term transport of radionuclides in the repository rooms, repository panel seals, DRZ, and undisturbed and fractured interbeds, and input to sealed boreholes and shafts to the Culebra Formation. Advection should allow actinides to be transported directly to the Culebra Formation; however, it is not possible at the present time to evaluate how DOE handles these unknown factors.

There are also uncertainties associated with all the assumptions listed in Section 3.8.2.2. In the cases of all valid assumptions, the associated uncertainties are negligible. Since the soluble actinide source term input parameters are directly fed to NUTS, if the values are incorrect, the consequences could be significant in that the code would transmit such errors directly to the Culebra Member.

3.8.2.5. Adequacy of the Conceptual Model

The Actinide Transport in the Salado conceptual model describes the movement of the actinide source terms by advection, using hydrologic phenomena from the BRAGFLO computer code. The concepts of advection and Darcy flow are well characterized in the geosciences and are the mainstays of this conceptual model. However, the specifics of long-term transport through the components of the repository are poorly defined. Documentation that is not present includes Table 6-15, Section 6.4.11, and Appendix NUTS of the CCA. The section describing this conceptual model (Section 6.4.5.4) does not document in any way how the "lumped" actinide source terms are transported from the rooms through the panel seals and the DRZ, how transport is performed through undisturbed and/or fractured anhydrite interbeds, and up sealed boreholes and shafts to the Culebra. Since this conceptual model is not yet fully described, the Panel can not determine if the model is adequate.

3.8.2.6. Adequacy of Implementation

The description of how this conceptual model is integrated from one computer code to the next (BRAGFLO to NUTS) is supposedly seamless. It is stated in the ten questions document that "NUTS interface with BRAGFLO is essentially perfect in completeness and validity in that NUTS takes virtually all its flow and flow-related attribute and property data from BRAGFLO and treats them as incontestable. Thus the .. interface is perfectly smooth." Hence, in the sense of transferring flow data into the NUTS code, one would conclude that the implementation is adequate.

Two other aspects of implementation are considered. One aspect involves how dissolved actinide solubility is handled in the "lumping" sense. The second aspect of implementation deals with how colloidal actinides are dealt with in the NUTS code. It seems DOE has provided a very rational way to "lump" all the various solubilities of dissolved actinides and to describe how the four main types of colloids will be "lumped" for transport. Both of these source terms have complex properties that could have been negated by the "lumping" factor. As an example, each actinide in its various oxidation states would have specific solubilities. Therefore the dissolved actinide source term is calculated for Salado and Castile brine compositions in both the low and high oxidation states. These four main permutations would then cover the possibilities for total inventories for dissolved actinides. Colloidal actinide sources are handled in a slightly different manner. Mineral fragment and intrinsic colloid values are held constant through all the runs. Humic and microbe actinide inventories are based on mass balance calculations using inventories from waste materials. These two philosophies of solubility "lumping" have been clearly explained for dissolved and colloidal actinide transport in the NUTS computer code by the Principal Investigator and, by this means, the implementation was determined to be adequate.

3.8.2.7. Accuracy of Results

Conclusions for this section are based on preliminary results provided by the Principal Investigator. The results proved to be accurate. However, without the final parameter listings of Table 6.15 of the CCA, one cannot make a final judgment of actinide transport in the Salado Formation. It would be useful to have the following information for comparison: first, actinide values after transport through the Salado

Formation to a borehole or shaft; second, what are the final values that NUTS would produce at the interface with the Culebra; third, an example of a NUTS transport run ("lumped") that approaches the EPA standard, and then a recalculated run using the individual radionuclides. This information would be very useful in determining whether the finalized results of this conceptual model are accurate. Finally, a complete model run has not been performed that transports dissolved actinides at the median velocity and colloidal actinides at maximum velocity. These results could be critical in deciding the accuracy of the model.

3.8.2.8. Validity of Conclusions

This section presents a judgment on whether the key conclusions that have been drawn based on the results of actinide transport in the Salado Formation in the modeling framework are valid. Although the concept of lumping is shown to be rational, the explanation of transporting colloids at a median velocity may be deficient. The parameter values (Table 6-15) were not available for the Panel to review and may bear on the judgment of validity for this model. Until these two final issues are resolved, it is premature to evaluate the validity of the model conclusions.

3.8.2.9. Adequacy for Implementation

This section is an overall assessment of whether this conceptual model represents a reasonable approximation of the actual phenomena and is adequate for implementation in the compliance application. Due to the lack of information provided (Table 6-15, Section 6.4.11, and the Appendix NUTS of the CCA), and the insufficient documentation of how colloid transport at a median velocity is rationalized, it is premature to say that the full conceptual model is completely adequate for implementation. However, if one assumes that BRAGFLO is a competent model for fluid flow in the repository setting, the next step of inputting hydrologic data into NUTS for actinide transport should be straightforward. Because of this, the model is wholly adequate and reasonable for implementation.

3.8.2.10. Dissenting Views

There were no dissenting views for this method.

3.9. Units Above the Salado

3.9.1. Model Description

The conceptual model of the Units Above the Salado has much in common with the conceptual model of the Culebra. The Culebra Dolomite is a member of the Rustler Formation, which is a prominent part of the supra-Salado stratigraphy. The Culebra is modeled separately (Section 3.2) because of its importance as a potential contaminant flowpath. The model of the Units Above the Salado results from a complex of several approaches to the hydrology and hydrogeology of the region and the WIPP site area. The conceptual model would ideally serve as an integrating set of hydrogeologic processes, properties, and principals that could be used to support assumptions about the potential performance of the site, to interpret regions of low data; and to place in context the results of hydrologic testing. The Units Above the Salado conceptual model provides a geometric characterization of the hydrologic system and a general description of the geometry and processes of flow. As with the Culebra, however, no correlation is provided of variation of hydrologic properties at the site scale with hydrogeologic character. The most important assumption in the model is that the Culebra Member of the Rustler Formation is the only potential pathway for radionuclide release to the environment.

The performance assessment of the Culebra is based on a considerable hydrologic testing data base, which addresses many of the potentially significant questions and issues concerning flow along the Culebra flowpath at and around the site. The significance of the hydrology and hydrogeology of the other members of the Rustler Formation and overlying formations lies partly in their interaction with Culebra hydrology and their influence on the interpretation of flow through that unit. The Culebra is treated as a confined aquifer with a much higher transmissivity than the overlying and underlying stratigraphic units and a horizontal flow gradient generally to the south. Flow in both the enclosing units (Unnamed Lower Member and Tamarisk) is believed to be predominantly vertical and into the Culebra. Water pressure in the Culebra is characterized as low because its transmissivity and gradient are capable of discharging more water than is presently being recharged.

The interpretation of the hydrologic processes for performance assessment purposes in the units above the Salado is based mostly on the results of hydrologic testing. A regional hybrid hydrogeologic/hydrologic process model (Corbet and Wallace 1993) sets model boundaries and speculates about regional processes contributing to the transmissivity contrasts, but offers no site-scale correlation with the testing data. This model does not address mesoscale hydrogeologic variables such as fracture orientation and distribution and the distribution of matrix permeability.

The performance assessment activity associated with the units above the Salado is the two-dimensional Culebra flow model, based solely on the hydrologic testing results. The variability of transmissivity represented in that model within and around the site area is attributed to the relative proportions of flow through fractures and variably permeable matrix, and to fracture distribution and hydraulic activity. The model does not address those variations of hydrogeologic process and properties relative to petrologic, sedimentologic, or structural features, which are the primary sources of variability. The conceptual model is disconnected from the numerical hydrologic model at the scale at which hydrogeologic information could most usefully condition the numerical model.

The assumption that the Culebra is the only potential pathway for release to the environment is related to the movement of radionuclides up a borehole or up the sealed shaft region. The assumption that radionuclides reaching the Magenta Dolomite member of the Rustler Formation or the Dewey Lakes Redbeds, which overlie the Rustler Formation, are not transported to the accessible environment is based partly on the results of very limited hydrologic testing and assumed retardation in the Dewey Lakes.

Hydrogeologically, the Culebra and Magenta Dolomites bear many similarities. Both are dolomites deposited in the same sedimentary environment. They are comparable in thickness and differ in stratigraphic position by a few tens of meters. Their post-depositional histories are identical from location to location. Their porosities are nearly identical and their ranges of permeabilities overlap. The definition of the hydrologic character of the Magenta is based on modeling of approximately 15 data points constrained to a very small geographic area.

The principle hydrogeologic difference between the Culebra and Magenta is purported to be the absence of hydrologically active fractures in the Magenta. This assertion is based on two slug tests and very limited field observation in shaft excavations. The transmissivity of the Magenta is very low in all of the limited number of tests and its low transmissivity is supported by drawdown during the sinking of the air shaft. The characterization of Magenta hydrology as unfractured is based on a very limited observational and testing data base, and the conclusions that there are no regions of high transmissivity due to fractures and that all flow in the Magenta is matrix flow are weak.

The position of the groundwater table at the level of the Dewey Lakes Redbeds is very unclear. Hydrologic testing has not been done to differentiate between purported perched water zones, to characterize saturated zones with continuity to underlying units, and to identify the general hydrologic character of the Dewey Lakes Redbeds. It is presumed that most of the materials above the Dewey Lakes are unsaturated (Gatuna and Pleistocene alluvium) and that recharge through those materials is minimal.

3.9.2. Review of Criteria

The units above the Salado contain the Culebra Dolomite, which is identified as the principal potential pathway for release of radionuclides to the environment. The conceptual model for these units provides the framework for consideration of the hydrology of the Culebra and contains other hydrostratigraphic units (Magenta and Dewey Lakes) whose potential as pathways must also be evaluated.

3.9.2.1. Information Used to Develop the Conceptual Model

The conceptual model is based on stratigraphic information from site borings and shaft excavations and on the position and nature of regional hydrogeologic features. Corbet (1993) has synthesized those features well and uses them as the basis for suggesting model boundaries and to support general flow gradient direction predictions. The model used for performance assessment purposes is a two-dimensional computational flow model based entirely on hydrologic testing in the Culebra. The conceptual model generally supports the descriptions of the hydrologic roles of the units above the Salado, with reservations about the characterization of flow in the Magenta Dolomite and the universal presence of retardation in the Dewey Lakes Redbeds. Hydrologic test data are sparse or nonexistent in all units above the Salado, except the Culebra.

3.9.2.2. Validity of Model Assumptions

The assumption that the Culebra Dolomite is the only hydrostratigraphic unit within the stratigraphic sequence above the Salado, which has the potential to act as a flowpath to the accessible environment, is the principal assumption affecting this conceptual model. That assumption implies that the Magenta Dolomite and the Dewey Lakes Redbeds are not potential pathways and that flow and transport assessments of those units are unnecessary. Estimates of contaminated brine flow up an intruding borehole in the long term imply very small (0.5 m^3) volumes of brine reaching the interval above the Culebra (personal communication, P. Vaughn). This is the consequence of underpressure hydrologic conditions purported to exist in the Culebra throughout the repository area, which lead to injection of most of the brine rising up the borehole into the Culebra. The magnitude and distribution of underpressure in the Culebra are based on averages of several measurements and an assumed process model, which explains the underpressure condition. The assumption that the Dewey Lakes and Magenta are not flowpaths is not well supported. The assumption of availability of only small amounts of brine to those units appears to be well supported.

3.9.2.3. Evaluation of Alternatives

The conceptual model has evolved over the entire period of site characterization and performance assessment. Some alternative submodels were considered and rejected (e.g., local halite dissolution and anhydrite hydration, gravitational loading). All of these submodels failed to conclusively account for the variations in transmissivity at a useful scale. The final performance assessment model is almost entirely based on numerical assessment of hydrologic test data, which are very sparse except in the Culebra Dolomite, the most thoroughly tested stratigraphic unit at the site.

3.9.2.4. Uncertainties

The principal uncertainty in the conceptual model of the units above the Salado (excluding the details of Culebra flow, treated elsewhere) is the assumption that the Magenta and Dewey Lakes units do not constitute potential release pathways. The effect of underpressure in the Culebra appears to limit flow up an intruding borehole to the upper units in such a way that there is little consequence associated with the Dewey Lakes and Magenta flowpaths.

3.9.2.5. Adequacy of the Conceptual Model

The conceptual model adequately defines the regional and general stratigraphic geometry of the units above the Salado. It does not provide supporting explanations for the variability of hydrologic parameters and processes at the site scale. If the need to assess transport in the Magenta and Dewey Lakes were shown to exist, the small hydrologic testing data base and the existing conceptual model would not be adequate to such an assessment.

3.9.2.6. Adequacy of Application

There is no application of the conceptual model to the computational flow modeling at the site scale except for the definition of stratigraphic geometry. A thorough demonstration of the potential of the Magenta and Dewey Lakes as flowpaths is absent, and the conceptual model is inadequate to support such a demonstration. The conceptual model adequately provides geometric and process elements to support the Culebra model.

3.9.2.7. Accuracy of Results

The accuracy of results depends on the adequacy of the testing data base and the computational flow models and are beyond the scope of this review.

3.9.2.8. Validity of Conclusions

See Sections 3.9.2.6 and 3.9.2.7. Conclusions are based on the Culebra numerical flow model and are beyond the scope of this review.

3.9.2.9. Adequacy for Implementation

The conceptual model is not significantly implemented in the computational flow model used for performance assessment (the Culebra two-dimensional flow model). The conceptual model provides adequate peripheral support to the implementation of the Culebra flow model by defining geometry and a general description of flow conditions in adjoining beds. The conceptual model is not adequate to support an assessment of the Magenta and Dewey Lakes hydrostratigraphic units as flowpaths. Assumptions supported by analysis imply that the consequences of transport in the Magenta and Dewey Lakes are low because of insignificant input of contaminants as a result of human intrusion.

3.9.2.10. Dissenting Views

There were no dissenting views for this model.

3.10. Transport of Dissolved Actinides in the Culebra

3.10.1. Model Description

The transport of actinides in the Culebra Dolomite Member of the five-member Rustler Formation was determined by DOE to be a significant pathway for potential releases to the accessible environment. This model describes the transport of soluble actinides once the material has moved into the Culebra, which could occur either under undisturbed conditions by movement up the shafts, or under disturbed conditions through intrusion boreholes, which provide a path by which gas or brine can be released up to and above the Culebra. These processes are described in other models. The quantities of actinides transported into the Culebra, as well as their chemical form, are described in the source term models.

The characteristics of the Culebra that relate to flow and transport are described in Section 3.9, and the model for spatial distribution of flow rates in the region and site area is described in Section 3.2. Therefore, this model is related to output from Shaft Seals, Chemical Conditions, and Dissolved Actinide Source Term, as well as Culebra Geometry and Flow, Gas Generation, Fluid Flow in the Salado, Disturbed Rock Zone, and the models related to intrusion, Exploration Borehole, Castile Formation and Brine Reservoir, and Multiple Intrusions.

The model, Transport of Dissolved Actinides in the Culebra, is also related to a parallel model, Transport of Colloidal Actinides in the Culebra, which depends on many of the same processes. Fundamentally, the model describes the horizontal transport of dissolved actinides by water flowing through the porosity of the dolomite, and retardation that may occur along the way. The flows are confined to the lower 4 meters of relatively permeable dolomite of the 7-meter thick Culebra. The model describes advective transport, as well as holdup due to matrix diffusion and chemical retardation. The model assumes that the overall rock porosity is composed of interconnected porosity, which forms the principle paths for advective water flow, and relatively unconnected diffusive porosity, into which species may diffuse under concentration gradients. This model is therefore referred to as a double porosity model.

The advective porosity is envisioned as a web of interconnected horizontal and vertical fractures in the dolomite, with some contribution from flow through interconnected vugs, and comprising less than 1% of the overall rock volume. The diffusive porosity is described as being accessible from advective porosity through small intercrystalline pores of the Culebra rock matrix, and comprising about 15% of the overall rock volume. Physical holdup and chemical retardation are therefore described as predominantly related to the diffusive porosity, with the surface area for chemical adsorption located within the diffusive porosity. This surface area has been measured at about 1 m^2/gm of dolomite.

Diffusion into the rock is described as related to the chemical diffusive properties of dissolved species, the tortuosity of the diffusion paths within the rock, and the surface area for diffusion between advective and diffusive porosity per unit volume of diffusive rock. Chemical retardation is described as chemical adsorption onto the dolomite grains exposed in the diffusive porosity. Although clay is believed to be present in the Culebra dolomite, particularly between horizontal bedding planes, adsorption onto this clay is not specifically assumed because its distribution and quantitative effect have not been demonstrated. Chemical adsorption is further described as a linear isotherm model, with single constants, K_ds, to describe the equilibrium relationship of the ratio of adsorbed concentrations and dissolved actinide species.

Fifteen years of development of information and models to describe actinide transport in the Culebra has considered two controversial issues. The first is whether a single matrix porosity or a double porosity model is appropriate to describe flow and retardation. The second is whether and how chemical retardation, particularly on corrensite clay, is to be modeled. The project has used a single porosity model and adsorption on clay in the past, but currently uses a dual porosity model with adsorption onto dolomite but not onto clays. This is discussed in more detail later.

3.10.2. Review of Criteria

3.10.2.1. Information Used to Develop the Conceptual Model

The site-related information used to develop the Culebra actinide transport model has included direct observation of the formation in outcrop, borehole cores and wells, and laboratory testing. These site observations have included chemistry measurements, studies of mineralogy, and field hydraulic and tracer testing. The laboratory testing has developed the quantities of actinides in solution in brine, their oxidation states and solubilities in brine, and measured adsorption properties.

Laboratory studies conducted to understand the adsorption process included column tests and the use of intact Culebra cores. Studies of adsorption on dolomite and corrensite clay were conducted, but information on the amount and distribution of clay in advective porosity pathways was judged insufficient to justify assuming adsorption onto clay. Laboratory studies have used four synthetic brine compositions representing the range of actual brines in the Salado, Castile, and Culebra. Information was developed on effects of carbon dioxide on adsorption at partial pressures expected in the Culebra. Adsorption information for plutonium, americium, uranium, thorium, and neptunium at expected oxidation states was developed using laboratory measurements and the oxidation state analogy.

Recently, the H-11 and H-19 tracer testing was completed and the results analyzed and summarized, although no reports of this key work were available to the Panel for review. This additional tracer testing was conducted because the results of earlier tracer testing with soluble dyes did not provide adequate information to convincingly show that the dual porosity model was appropriate for actinide transport purposes. The evaluation of the current work and reevaluation of earlier work has improved the information base. However, much of the work in support of this model is recent and has not yet been published. Improved correlation with modeling analyses has been achieved for increased ranges of flow rates and other improvements in test conditions. The information base appears generally adequate, although the parameters that relate to this model will need to be carefully chosen. These parameters are the advective and diffusive porosity, the range of block sizes, the soluble species diffusion coefficients, tortuosity, and retardation coefficients.

3.10.2.2. Validity of Model Assumptions

Some of the principal assumptions are that the transport can be described in the dual porosity model, that the oxidation states of actinides in brine transferred into the Culebra do not change during subsequent flow and transport in the Culebra, that dissolved actinides will diffuse into the matrix and be physically retarded, and that dissolved actinides can adsorb on diffusive porosity surfaces.

The basis for the assumption that the transport model should assume both advective transport in principal flow paths and diffusive transport into the rock, is that results of tracer tests along principal flow paths at the WIPP site are only explained using the dual porosity model. This is believed valid in the areas of the site where transmissivity is greater than 1×10^{-6} m^2/sec. In areas of low transmissivity, which have little advective porosity and flow, a matrix diffusion model best explains results, but is not used for the performance assessment because these low transmissivity areas do not contribute significantly to the flows away from the repository. In high transmissivity areas, a single porosity assumption is not consistent with the tracer test results. Therefore, for purposes of transport, the dual porosity assumption appears appropriate.

For purposes of determining appropriate values of adsorption coefficients and solubilities, the project assumes that the oxidation states of actinides generated in the repository do not change when the deep brines are injected into the Culebra brine. Adsorption behavior would be different if oxidation states were different, while concentrations would not be different since precipitation is assumed not to occur in Culebra brine. The assumption of constant oxidation states is based on the repository brines being strongly reducing, the Culebra brine being reducing (though perhaps less so), and the rate of any changes in oxidation state that might occur at low ambient temperatures being slow. This assumption is supported by retardation research program studies involving four different brines, including Castile and Salado brine and two brines representing the Culebra, four different chemical constituents affecting conditions, including sulfides, cellulosics, iron and nitrates, and two different chemical equilibrium data bases. It was stated that 30 of the 32 possible combinations of information indicated reducing conditions, with only some combinations of nitrates producing slightly oxidizing conditions. Measurements of the redox states of groundwater sampled from over 20 wells around the WIPP site indicated reducing conditions everywhere on and around the site, except for areas a few miles south where recharge was thought to affect redox conditions. Thus, this assumption appears fairly well supported.

The model assumes that the properties of actinides of the same oxidation state generally are similar. This issue is discussed in Section 3.23 and will not be covered here. The most recently conducted tests of adsorption parameters included column tests with crushed dolomite at Lawrence Livermore National Laboratory, and flow-through tests using dolomite cores from the WIPP air intake shaft.

The assumption that batch tests using small particles and flow-through retardation experiments can give valid results for the adsorption parameter needs consideration. In the column tests, not yet published, K_ds were measured using dolomite, with no detectable (<1%) clay, that was crushed and sieved to give particles of about 100 mm diameter. The issue was raised that this might make the internal surface area and the clay that might be present more accessible in the experiment than it is in the intact Culebra. It was noted that measured grains in dolomite are on the order of 2 mm and pore openings are approximately 0.6 mm, and therefore a dolomite particle of 100 mm would have roughly the same surface-to-volume relationships as the rock. Also, the contact times were long enough in the experiment for diffusion transport to reach equilibrium. The issue of diffusion rates into the matrix is determined by other parameters, including porosity and tortuosity, which have been measured in other testing programs.

The flow-through tests used intact horizontal Culebra cores with pressure-induced flow of non-absorbing tracers, as well as five actinides, Pu, Am, Th, Np, and U, in solution. In this case, K_ds were inferred from the overall retardation of the core. The results of these tests are being evaluated and K_ds were determined using the values for the likely oxidation state and the brine type with the lowest values. Without commenting on the specific numerical values, which have not been finalized, this appears to be a reasonable approach. Interpretation of the results of such experiments needs to be made carefully, so that values of K_ds, tortuosity, and porosity can be reliably applied into numerical models. It would also be useful to compare the values thus obtained with other data from past determinations.

One uncertainty in the column tests is that associated with the amount of clay in the tested dolomite. X-ray diffraction studies did not detect clay, with an apparent minimum detectable value of about 1%. There is also clay in the Culebra dolomite, reportedly in the range of 1 to 5%. The intent was to use clay-free dolomite in the column tests, but it appears this experiment may inherently include the adsorption effects from whatever amount (<1%) of clay was in the dolomite matrix. While it was not shown that this was representative of truly pure dolomite, this appears to be conservative, because the clay was likely at the low end of the range. This is a tentative conclusion however, because the results of this work were not available in published form for review.

3.10.2.3. Evaluation of Alternatives

The principal alternatives considered relate to whether transport is best described by a single porosity fracture only, a single porosity matrix only, or a dual porosity model. Neither of the single porosity models explain the data from tracer tests everywhere on the site, whereas the dual porosity model best explains the data, particularly in the regions on the site where transmissivities are high.

3.10.2.4. Uncertainties

Uncertainties related to oxidation state in the repository source term translate directly into transport-related uncertainties (see Sections 3.23 and 3.24). These uncertainties could have a large effect on the result of performance assessment. However, as discussed in Section 3.10.2.3, there appears to be a reasonable basis to conclude that the oxidation states would not change significantly on entry into the Culebra from the repository. Uncertainties on the extent of adsorption could have a significant effect as well. However, at the conceptual level, the model attempts to proceed in a reasonably conservative manner in light of these uncertainties. This does not mean that particular values of K_ds to be chosen from the conceptual model are all conservative, since numerical values for these parameters have not been evaluated.

3.10.2.5. Adequacy of the Conceptual Model

It is concluded that a dual porosity model is adequate for dissolved actinide transport analyses if ranges of model parameters are chosen properly in light of uncertainties. In that the model is supported largely by evaluation of recently completed but undocumented field and laboratory experiments, this conclusion is necessarily tentative.

3.10.2.6. Adequacy of Application

This model utilizes direct input from only a few other conceptual models: the Actinide Source Term models, and the Culebra Hydrogeology model, as well as output from the flow models under undisturbed and disturbed conditions. At the conceptual level, these model outputs appear compatible as input to the Culebra Transport model. This does not mean there could not be problems in application through the equations and mathematical formulations in the NUTS code. A more informed judgment could be made from a review of sensitivity among key parameters, such as the relationship of the sensitivity of repository releases on source term concentrations of dissolved actinides, on K_ds, on volumes of brine injected, on effects of climate change, and mine subsidence effects on Culebra transmissivities.

3.10.2.7. Accuracy of Results

A judgment on whether the conceptual model affords sufficiently accurate results for performance assessment depends on the overall importance of various model assumptions. It is judged that the dual porosity model itself is a sufficiently accurate conceptual representation for performance assessment, based primarily on verbal briefings of the results of the latest tracer testing in the Culebra and on visual observations. However, since the results of the latest tracer tests have not been documented, this judgment is tentative. Furthermore, the method of developing parameters of importance to numerical results also have not been supported by written reports of the related recent work. Therefore, these parameters have not been reviewed, although some important uncertainties were identified above. Accuracy of results imply review of results, and none using the current model and parameters were available for review. It would be useful to review results of sensitivity analyses to understand which are the key variables, and then focus on the accuracy of those key variables. Until such information is reviewed, a firm conclusion on their accuracy cannot be properly drawn.

3.10.2.8. Validity of Conclusions

The conclusion that the actinide transport in the Culebra can be adequately modeled in a dual porosity model, with advective transport in the main flow porosity, diffusion into and physical and chemical retardation in the rock matrix porosity, is valid. Other conclusions have not been presented since the model, using the chosen parameters, has not yet been used in the performance assessment.

3.10.2.9. Adequacy for Implementation

The conceptual model appears compatible with other models it intersects with directly. The implementation of the conceptual model is through mathematical formula and computer codes which have not been evaluated. It is concluded that the conceptual model is adequate for implementation. However, the selection of model parameters needs to be critically reviewed when the reports of the laboratory and field tracer tests are available.

3.10.2.10. Dissenting Views

There were no dissenting views for this model.

3.11. Transport of Colloidal Actinides in the Culebra

3.11.1. Model Description

This model is closely related to Transport of Dissolved Actinides in the Culebra (Section 3.10), and shares many aspects and assumptions of that model. This model differs from the Dissolved Actinides model in its application of colloidal properties as opposed to dissolved properties to the transport process. The issue of whether, for transport purposes, a dual porosity approach is appropriate, is not repeated since that issue was covered in Section 3.10. However, differences in how the colloids are transported in this model are covered.

Model adjustments for colloidal transport include the different properties and processes that occur for colloids. For example, colloidal particles travel slightly faster in advective transport than dissolved species due to velocity gradients in flow apertures. Colloids can be trapped along the way, and they can diffuse into the diffusive porosity in the dolomite if they are smaller than the pore throat diameter of the dolomite. Four types of colloids are considered: mineral fragments, microbes, humic and fulvic acids, and actinide intrinsic colloids. These four types are different in size and properties; for example, some are hydrophilic, some are kinetically stable, and others are less so. Colloidal particles that are small enough to enter the dolomite matrix may chemically adsorb on surfaces once inside the diffusive porosity.

The model assumes that the colloidal particles containing actinides originate in the repository and are transferred into the Culebra in the same way as dissolved actinides, as represented in the NUTS code. In this model, it is assumed that soluble actinides do not attach to colloids that may already exist in the Culebra brine when brine containing dissolved actinides is injected into the Culebra and mixes with Culebra brine.

Colloidal transport has not been considered in the earlier assessments of repository performance; therefore the only other model implicitly considered was the null hypothesis. However, experience in other environmental situations at other DOE sites has lead to consideration of colloidal transport to explain greater transport of actinides than had been expected in these other situations, based on models that considered only soluble transport.

3.11.2. Review of Criteria

3.11.2.1. Information Used To Develop the Conceptual Model

Information used to develop the colloidal actinide transport model included the amounts and types of colloids thought possible in the source term model, the chemical properties and physical sizes of the particles, and how these would be transported in advective flow. In addition, information was developed on diffusion coefficients, measured pore throat diameter distribution in WIPP dolomite samples, and results of experiments to quantify whether and the extent to which colloids can adsorb onto dolomite matrix surfaces. A growing body of scientific literature and various computerized numerical models have been consulted to develop the conceptual model, and to help guide implementation.

The available information and experience with colloidal actinides is not as robust as for transport of dissolved actinides and, therefore, is likely to be less able to support a completely robust model. This model was conceived to fill a weakness in models considering soluble transport only. The available information appears adequate to formulate a useful conceptual model, but this does not mean that adequate information is yet available to fully implement a conceptional colloid transport model.

3.11.2.2. Validity of Model Assumptions

Some of the key assumptions are that 1) actinide oxidation states do not change when deep brines containing these colloids are mixed in Culebra brines; 2) soluble actinides in brine from the repository do not interact with and become attached to colloidal particles that exist in the Culebra; 3) colloids can be filtered in the advective porosity but not chemically adsorbed there; and 4) colloids which are smaller than a 0.63μm can diffuse into pore throat openings in dolomite and be chemically adsorbed onto surfaces there.

The assumption of oxidation state stability is discussed in Section 3.10.2.2, and no basis has been provided to assume colloid actinides would behave differently from soluble actinides.

The assumption that dissolved actinides do not attach to preexisting Culebra colloids is difficult to justify in principle. This assumption has been made to avoid the complication of the computer code having to simultaneously solve the dissolved species problem and the colloid transport problem. If there were significant transfer of soluble actinides to large colloidal particles in the Culebra flow, the transport of this actinide material could be significantly faster than the current model, due to reduced physical and chemical retardation. If the transfer of soluble actinides to small colloids occurred, it would not increase the transport as much, since advective transport would be slower and, more importantly, small colloids could diffuse into diffusive porosity in the dolomite matrix and be significantly retarded and perhaps chemically adsorbed. The arguments made to simplify the test plan and model do not consider this effect. Models to predict transport by adsorption onto colloidal particles along the transport path have been developed precisely because models of soluble only transport were inadequate. It is therefore judged that this assumption is unjustified based on the literature and information developed specifically for the WIPP project.

The assumption that colloidal particles can be filtered by entrapment in narrow passages in advective porosity appears viable at the conceptual level, but no information has been presented to demonstrate this occurs significantly in the Culebra, and no information has been presented to confidently quantify the effect. The assumption is implemented as a simple "decay" term for those colloids that are too large to enter diffusive porosity. On the other hand, particles in flowing systems do indeed tend to collect in areas of low flow velocity, so such a filtering process is likely to be useful if parameters are selected carefully to avoid trivializing the overall colloidal transport.

The assumption that colloidal particles smaller than the mean pore throat diameter of 0.63μm can diffuse into the dolomite matrix and be adsorbed onto the interior surface area in the dolomite matrix needs some discussion. Of the four types of colloids being considered, the humic/fulvic acid colloids and the plutonium intrinsic polymer are believed to be smaller than 0.63 μm. Measurements of many different properties of WIPP dolomite were made to develop their ranges and statistically average values, including porosity matrix interior surface area, permeability, grain density, tortuosity and pore throat sizes. Pore size distribution measurements were made on 24 samples using the mercury injection porosimetry technique. These data were interpreted to provide a mean pore throat diameter of 0.63μm. Analysis of the data showed that the accessible internal surface area was a function of pore throat size. For a typical sample with a porosity of 14.8% overall, the data indicated that no internal surface area was accessed for pore throat diameter greater than about 1μm; that about 35% of internal area was accessible at a pore throat diameter of about 0.37μm; and 50% of the internal surface area was accessible at a pore throat diameter of about 0.2μm. Total internal surface area is about 1 m^2/gm of dolomite. Humic acid colloids and the plutonium polymer are thought to be small enough to enter the dolomite. Humic acid colloids are reported to be about 0.1μm or less and single unagglomerated plutonium polymer colloids are on the order of 0.003μm. Intrinsic colloid agglomerates could be as large as 0.04μm. Microbial colloids are 1 or 2 μm and mineral fragments are on the order of 1μm as well. Based on this information, it appears feasible that the humic/fulvic acid colloids and plutonium intrinsic polymer colloids could diffuse into the matrix, unless surface charge forces prevented this from occurring.

The assumption that colloidal particles could be adsorbed onto the surfaces in matrix porosity is a more complex process to understand because colloidal interactions are less well understood. For example, if the colloids have the same surface charge as the rock, adsorption would be prevented, and if the charges were opposite, adsorption would be relatively strong. To explore this assumption, the project attempted to measure K_ds for actinide colloidal particles of the various types in the same laboratory column tests, and core flow through tests as for soluble actinide measurements. The results showed apparent adsorption in both situations. However, for some of the flow-through experiments, soluble actinides and colloids were mixed and the resulting K_ds were found to be the same as for soluble actinides. Therefore, this experiment did not demonstrate colloidal adsorption so much as perhaps soluble adsorption or filtration, since the experiment did not obviously assure that the actinides were on colloidal particles before being contacted through the dolomite. For microbe colloid experiments, no nitrates were added to keep the microbes growing, so as to prevent changing the oxidation state of the actinides. This may have prevented bioassimilation of actinides in microbe colloids, and again lead to the measurement of K_ds with the same values as for soluble species. Resolution of these and perhaps other uncertainties would add confidence to the assumption that actinide colloids adsorb onto surfaces and the extent to which they adsorb. In the absence of a satisfying resolution, colloidal adsorption onto dolomite matrix porosity may not be a justifiable assumption in the model.

3.11.2.3. Evaluation of Alternatives

Since consideration of transport of colloidal actinide transport has only recently been included in performance assessment, no alternatives were considered.

3.11.2.4. Uncertainties

Uncertainties in the model are associated with the key assumptions discussed in Section 3.11.2.2. The Panel concludes that very large uncertainties exist with the lack of interaction of soluble actinides and Culebra colloids in the model, and with the diffusion into dolomite porosity followed by chemical adsorption. Because of the lack of availability of published reports on the recent testing, a more definite conclusion cannot be drawn.

3.11.2.5. Adequacy of the Conceptual Model

The uncertainties in the validity in some of the key assumptions cast some doubt on the adequacy of this model. Even though the overall performance assessment model is greatly improved by the addition of colloidal actinide consideration, it appears that model predictions will result in negligible transport based on the model and parameters presented to date. If this were the outcome of the fully developed and qualified model, one could have more confidence. However, since significant uncertainties exist in major features of this model, its results could not be trusted, based on the available information. It may be that the issues raised here are readily resolved, but application of colloid science in environmental transport is a new and difficult application, and a cautious approach is believed most appropriate.

3.11.2.6. Adequacy of Application

Soluble actinide interaction with colloidal particles in the Culebra has been assumed not to occur without justification. This represents an issue of integration of this model with the Dissolved Actinide Transport in the Culebra model. Other than this, other system-wide integration issues have not been identified.

3.11.2.7. Accuracy of Results

No actual results have been provided. However, on the basis of the information reviewed, it appears this model, as currently envisioned, would not provide sufficiently accurate results.

3.11.2.8. Validity of Conclusions

Since there is doubt about other criteria, this criterion is also in doubt.

3.11.2.9. Adequacy for Implementation

It does not appear that the information available demonstrates that this model provides a sufficient basis to give confidence in the adequacy of treating colloid transport in performance assessment. It should be noted that, because of the recent undertaking of this work, none of the laboratory test reports or flow-through test reports, on which significant aspects of this model are based, are completed. Further review of the information, when published, could provide a basis to resolve some of the issues raised, after adjustment of some of the assumptions and judicious choice of parameters for a numerical solution. This could lead to an adequate model for implementation.

3.11.2.10. Dissenting Views

There were no dissenting views for this model.

3.12. Exploration Boreholes

3.12.1. Model Description

The Exploration Borehole conceptual model addresses drilling locations, methods, and frequencies within the WIPP controlled area, borehole sealing, and long-term fluid flow through the sealed borehole. Short-term flow through the unsealed borehole is addressed in the Direct Brine Release conceptual model. Associated conceptual models that describe movement of contaminated materials to, within, and from the borehole include Repository Fluid Flow, Castile and Brine Reservoir, Cutting/Cavings, Spallings, Culebra Hydrogeology, and Dissolved and Colloidal Actinide Source Terms. Actinide transport accompanying long-term brine migration is addressed by the Actinide Transport in the Salado conceptual model. The Exploration Borehole conceptual model is limited to a single borehole penetrating the repository. The Multiple Intrusion conceptual model describes conditions when more than one borehole is assumed to penetrate a waste panel. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Section 6.4.7, The Intrusion Borehole (DOE 1996, pp. 6-64 to 6-75), from verbal descriptions, and from the cited references.

An exploration borehole may be drilled on the WIPP site for natural resources investigation and may by chance penetrate a waste panel in the repository. Such boreholes are assumed to be drilled by individuals who have no knowledge of the buried waste, after active institutional control of the site has ceased. The conceptual model for exploration boreholes is based in large part on proscriptive requirements of EPA 40 CFR 194. The EPA requirements are paraphrased as follows:

- The regulatory time frame is the time period beginning at disposal and ending 10,000 years after disposal [40 CFR 194.2].
- Both deep drilling (to or below a depth of 2,150 feet) and shallow drilling (less than a depth of 2,150 feet) that may potentially affect the disposal system during the regulatory time frame are assessed [40 CFR 194.33(a)]. The approximate depth of the repository is 2,150 feet.
- Exploratory drilling is assumed to be inadvertent and intermittent [40 CFR 194.33(b)(1)].

- Exploratory drilling for those resources provided by the waste in the disposal system or the engineered barriers designed to isolate such waste need not be considered [40 CFR 194.33(b)(1)].

- Drilling events in the Delaware Basin are assumed to occur at random intervals in time and space during the regulatory time frame [40 CFR 194.33(b)(2)].

- The frequency of deep drilling within the WIPP controlled area is assumed to be the sum of the rates of deep drilling for each resource in the Delaware Basin over the past 100 years [40 CFR 194.33(b)(3)].

- The total rate of shallow drilling at WIPP is assumed to be the sum of the rates of shallow drilling for each resource in the Delaware Basin over the past 100 years; however, in considering the historical rate of all shallow drilling, the DOE may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area [40 CFR 194.33(b)(4)].

- Future drilling practices and technology are assumed to remain consistent with practices in the Delaware Basin at the time the CCA is prepared, including the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of boreholes that are sealed [40 CFR 194.33(c)(1)].

- Natural processes are assumed to degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame [40 CFR 194.33(c)(2)].

- The effects of techniques used for resource recovery following drilling need not be considered [40 CFR 194.33(d)].

In developing a conceptual model that incorporates these assumptions, DOE has considered the following:

- Shallow boreholes will not intercept or affect the integrity of the repository and therefore need not be considered.

- Present drilling practices include the relative economic value of the target resource; on this basis, the objectives of exploration drilling at the WIPP site are assumed to be oil and gas because these are the only commercially viable resources for which exploration drilling would occur to or below the depth of the repository horizon.

- Although commercially viable reserves of potash are known to be within the WIPP controlled area, inadvertent penetration of the repository during exploratory drilling for this resource was not considered because such reserves lie above the repository depth.

- The frequency of deep borehole drilling is estimated based only on historical frequencies of drilling for resources of similar type and quality to those found at the WIPP site.

Exploratory drilling for hydrocarbon resources within the Delaware Basin is assumed by DOE to occur at a rate of 47 holes per square kilometer over the 10,000-year regulatory time frame. Although the timing of intrusions into the waste panels is randomly sampled, based on the 0.125 square kilometer area of the waste panels, the expected average rate of penetration is about 6 boreholes per 10,000 years. Boreholes penetrating the waste panel area but passing through a pillar or wall rather than through the waste are assumed to have no effect on waste releases, but may penetrate and partially deplete brine reservoirs in the Castile. The concept of partial reservoir depletion is discussed further in Section 3.16. Penetration of the operations or experimental areas of the repository by a borehole is assumed to have no significant consequence. All exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations. Approximately 10% of these are tentatively assumed to encounter pressurized brine in the Castile (E1 scenarios), and the other 90% are assumed to not encounter pressurized brine (E2 scenarios) (see 23 May 1996 Draft CCA, Section 6.4.13.6 (DOE 1996, p. 6-119)).

Drilling is assumed to be conducted by standard rotary methods. At the time of repository penetration, the borehole is assumed to have been cased to the bottom of the Rustler Formation, following current standard practices. After drilling has progressed through the salt section, an intermediate casing is installed to the bottom of the Castile. Below that depth a third, final production casing is installed, which typically extends to the ground surface during production, but is only cemented near the production zones. On abandonment, the production casing is commonly cut above the cemented zone and reclaimed (Thompson et al. 1996, p. 6). Fluid and solids that flow through the open borehole immediately on repository penetration are described in the aforementioned Direct Brine Release, Cuttings/Cavings, and Spallings conceptual models. Long-term fluid flow through the sealed borehole is described in the following paragraphs.

On abandonment, three different scenarios have been adopted by DOE to describe the range of current borehole plugging practices. These are (1) a single, continuous cement plug extending from the top of the Salado to the bottom of the Castile; (2) two 40-m cement plugs, one at the bottom of the Castile (top of the Bell Canyon) and one at the bottom of the Rustler; and (3) three 40-m cement plugs, consisting of the two plugs described above plus an additional plug near the Salado/Castile contact below the repository. In addition, all boreholes have approximately 15-m long concrete surface plugs (Thompson et al. 1996, p. 3).

Degradation of the plugs generally follows the scenarios and rationale presented by Thompson et al. (1996). The continuous plug is not considered to degrade over time because of its structural integrity and the very low brine flow through it. The surface plug is also not considered to degrade over time because of the lack of physical or chemical stresses in the near-surface environment. In the two- and three-plug scenarios the steel casing in the Salado and Castile is expected to be locally pitted and leak within a few decades after abandonment. In these scenarios, within 200 years after abandonment the 40-m concrete plug and remaining casing above the repository and the open casing below the repository are assumed to fail completely from both mechanical and chemical stresses. Simultaneously, with the exception of the concrete plugs below the repository, the entire borehole is assumed to be filled with degraded concrete, corrosion products, and sloughed native materials that are assigned the hydraulic properties of silty sand in accordance with regulatory guidance. Because of increased stresses and halite creep rates below the repository, the borehole filling below the repository is subsequently assumed to be compacted, with a concurrent decrease in permeability. The cement plugs below the repository, however, are assumed to maintain their integrity for the duration of the 10,000-year regulatory time frame because degradation rates will be significantly reduced due to a less aggressive chemical environment (see 23 May 1996 Draft CCA, Section 6.4.7.2.2 (DOE 1996, p. 6-74). Long-term brine flow is expected to occur to or from the repository through the degrading upper borehole plugs as a function of brine availability and repository pressure.

The same version of the BRAGFLO code used to model repository fluid flow is used to implement the Exploration Borehole conceptual model. This model, which portrays a two-dimensional vertical section, is discussed in Section 3.3 of this report and in Section 6.4.2 of the 1 April 1996 Draft CCA (DOE 1996, p. 6-2). The exploration borehole is assumed to penetrate the center of one of the waste disposal panels in the repository. Boreholes penetrating into a waste panel were found in modeling results to not significantly affect brine saturations in neighboring panels, even over the regulatory time frame, because of low hydraulic gradients across the panel closure seals. The borehole is modeled by modifying the material properties of the cells representing the borehole as a function of the type of intrusion (E1 or E2) and the time after intrusion. Short-term brine flow in the open borehole is separately modeled (see Section 3.15).

For long-term flow, the borehole is assumed to be plugged immediately after repository penetration by randomly selecting one of the three plugging scenarios in accordance with its probability of occurrence. The basis for the random selection is discussed in CCA Section 6.4.12, which was not available to the

Panel for review. In an E2 scenario, where the borehole through the Castile is assumed to not encounter pressurized brine, the lower part of the borehole below the repository is given the properties of the surrounding media. In an E1 scenario, where pressurized brine is encountered below the repository, the lower borehole cells are specifically addressed in the model as described in the following paragraph.

The borehole plugs are degraded according to the following assumptions. The continuous plug, the surface plug, and the 40-m plugs below the repository will maintain their initial permeability of 5×10^{-17} m^2 throughout the 10,000-year regulatory time frame. The 40-m plug above the repository maintains its initial permeability of 5×10^{-17} m^2 for 200 years. The borehole between the plugs is assumed to remain open during this period and is assigned a permeability of 1×10^{-9} m^2. The casing is not specifically addressed in the long-term flow model and is assumed to not be present. After 200 years, the upper 40-m plug is assumed to fail and the entire borehole between plugs is assumed to have filled with a material with the properties of silty sand, whose permeability is sampled within the range of 1×10^{-11} m^2 to 1×10^{-14} m^2. Beginning 1,200 years after waste panel penetration, the permeability range of the filling material in the lower borehole below the repository is reduced by one order of magnitude to 1×10^{-12} m^2 to 1×10^{-15} m^2. The porosity of all borehole materials is held at a constant, conservatively high value of 0.32. Pore compressibility is assumed to be zero, giving the medium the approximate compressibility of brine. Two-phase brine and gas flow is modeled using a zero threshold pressure and zero residual brine and gas saturations.

The BRAGFLO model does not explicitly address the continuous plug configuration because the plug permeability is so low that flow is negligible. Under this configuration the borehole cells are given the material properties of the surrounding native materials. BRAGFLO also does not explicitly model the plugs beneath the repository. The plug at the base of the Castile is not modeled because it is considered as part of the impermeable lower boundary. The plug in the upper Castile/lower Salado, which is part of the three plug scenario, is not modeled because it results in conditions essentially equivalent to an E2 scenario in which pressurized brine is assumed to not be encountered in the Castile. If pressurized brine is not encountered in the Castile, the middle plug has negligible function regarding fluid flow in the repository. If pressurized brine is encountered, DOE assumes that the middle plug remains intact and provides an effective seal to brine flow from the Castile reservoir to the repository for the duration of the regulatory time frame. Thus, under either circumstance, the long-term repository fluid flow for the three-plug configuration would be essentially the same as the E2 scenario. Only the two-plug configuration is assumed by DOE to allow long-term releases from a Castile brine reservoir.

BRAGFLO input to performance assessment is accomplished through the use of reference conditions, eliminating the need to run BRAGFLO for each separate set of randomly occurring future intrusion events. Different sets of reference conditions are prepared from BRAGFLO results for each interface with other performance assessment models. For analysis of single exploration borehole penetrations, BRAGFLO is used to calculate cumulative releases over the 10,000-year regulatory time frame for four scenarios: an E1 intrusion at 350 years, an E1 intrusion at 1,000 years, an E2 intrusion at 350 years, and an E2 intrusion at 1,000 years. These calculations are accomplished by running the undisturbed case until the year of the intrusion, and subsequently modifying the properties of the borehole cells in the model over time, according to the degradation rate assumptions described above. The cumulative releases calculated in these runs are used as the reference conditions for analysis of long-term releases.

The reference conditions for long-term releases through exploration boreholes, thus, essentially consist of flow rates over time to the Culebra resulting from borehole intrusions at two specific times (350 and 1,000 years) for each type of intrusion (E1 or E2), and for each set of BRAGFLO parameter input values (that is, for each CCDF). These flow rates are used as input to the NUTS code to calculate cumulative releases to the Culebra. Flow rates (or cumulative releases) resulting from intrusions occurring at other times are determined from the releases computed for these two times by either correlation or interpolation. For intrusions occurring prior to 350 years, the release is assumed to be the same as at 350 years. For intrusions occurring between 350 and 1,000 years, the release is interpolated between the values for 350 and 1,000 years, and for intrusions occurring after 1,000 years, the release is assumed to be the same as at 1,000 years. For long-term release calculations, repository conditions are assumed to not change as a result of short-term releases, thus, repository fluid pressures and volumes are not reduced by the short-term losses.

3.12.2. Review of Criteria

3.12.2.1. Information Used to Develop the Conceptual Model

The principal elements of the conceptual model were developed by DOE in compliance with EPA requirements as summarized in Section 3.12.1 (40 CFR 194.33, Consideration of Drilling Events in Performance Assessments). Pursuant to this regulatory guidance, current borehole drilling, casing, and plugging practices were reviewed by DOE for hydrocarbon exploration boreholes in the Delaware Basin and this information was used as the basis for determining drilling frequencies and methods during the regulatory time frame. Although documentation of these studies was not reviewed by the Panel, the approach taken appears to have provided a reasonable and appropriate response to the regulatory requirements.

3.12.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.12.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the limitation of intrusion to hydrocarbon exploration drilling, use of the BRAGFLO code to simulate release, degradation of the continuous and upper cement plugs, degradation of the casing, permeability reduction in the borehole below the repository due to creep closure, and the assumptions used in modeling the continuous plug configuration. DOE's analysis of current drilling practices in the Delaware Basin, and the drilling frequency and plugging practice information developed from that analysis, are not considered to be conceptual models and were not reviewed by the Panel. An adequate technical basis for estimating the probability of encountering a pressurized brine reservoir in the Castile was not provided to the Panel and is addressed as an issue in Section 3.16 of this report. The method selected by DOE for randomly sampling borehole plugging configurations was also not available for review by the Panel and is not addressed here.

Several simplifying assumptions have been made by DOE that appear to be conservative and therefore acceptable for use in performance assessment. These include neglecting the effects of drilling mud loss into the repository at the time of penetration by an exploration borehole. The drilling mud would likely be a dense, low permeability, water-based brine weighted with bentonite or other additives that may partially fill available repository pore volume, reduce repository permeability, inhibit chemical degradation of the waste by limiting brine availability, and provide additional sorptive capacity for radionuclides. Although the mud could result in other, unforseen chemical reactions with the waste, the overall effect of drilling mud loss into the repository is expected to be beneficial.

The annular space between the borehole plugs is assumed in modeling to be open hole, but according to Thompson et al. (1996, p. C-3), standard practice in the Delaware Basin is to fill this space with a dense plugging mud that provides a platform for setting internal concrete plugs and remains as part of the plugging system. This mud is expected to have a low permeability and may be sufficiently dense to reduce long-term fluid movement through the sealed boreholes between the repository and a partially depressurized Castile brine reservoir. Ignoring this plug in the model may be overly conservative.

The range of permeabilities representative of a silty sand was checked against ranges given in three standard texts, and the results are tabulated below. As can be seen in Table 3.12.1, the values used in performance assessment are neither the highest nor the lowest and are appropriate.

Table 3.12.1. Range of Permeabilities

Source	Medium	High End Value (m^2)	Low End Value (m^2)
Freeze and Cherry 1979, p. 29	Silty Sand	1×10^{-10}	1×10^{-14}
USBR 1987, p. 98	Silty Sand	1×10^{-12}	1×10^{-17}
de Marsily 1986, p. 78	Fine Sand, Silt, Loess	1×10^{-12}	1×10^{-16}
WIPP Performance Assessment 1996	Silty Sand	1×10^{-11}	1×10^{-14}

The frequency of waste panel penetration by exploration boreholes is expected, on the average, to be about 6 penetrations per 10,000 years. This value is based on a waste panel target area of 0.125 square kilometers, which is the approximate area of the disposal rooms themselves and does not include the disturbed rock zone in the walls of the waste panel excavations. This disturbed zone will be fractured by spalling and halite creep and may have sufficient permeability to permit long-term hydraulic communication with the repository. Ignoring this zone in performance assessment reduces the effective area of the waste panels and decreases the frequency of penetration. This issue is discussed further in Section 3.15.

The exploration borehole is assumed by DOE to penetrate the repository within a waste panel. Although such a penetration would be expected to result in the greatest release potential, penetrations could also occur within the operations and experimental areas of the repository, where the greater area of excavations would lead to an increased frequency of penetration. Under long-term flow conditions, pressure is expected to equilibrate quickly throughout a sealed repository by relatively rapid gas movement, and advective brine movement may be small because of the low hydraulic gradients. Penetration of the operations and experimental areas could lower gas pressures throughout the repository, which is expected to be a beneficial result. Diffusive movement of dissolved radionuclides, however, could occur through the panel seals, allowing radionuclides to migrate into the other parts of the repository and be available for release through an exploration borehole. Also, an exploration borehole penetrating the operational area and pressurized brine in the Castile could release Castile brine into the operational, experimental, and waste panel areas and pressurize the entire repository.

Borehole plugs below the Salado are assumed by DOE to not degrade within the 10,000-year regulatory time frame. This lack of degradation is related to suppression of anoxic corrosion reactions, primarily by high hydrostatic pressures in the borehole, and preservation of the concrete plug by the longer term confinement offered by the casing (Thompson et al. 1996, Chapter 3). This approach is based on thermodynamic data and assumes that carbon dioxide and hydrogen disulfide will passivate and reduce the corrosion rate of steel surfaces, and that the buildup of hydrogen fugacity from the corrosion reaction will cause the conversion of iron to $Fe(OH)_2$, to cease at a pressure of about 45 atmospheres (4.5 MPa). Such a pressure is believed to prevent hydrogen bubble nucleation and loss of hydrogen from the chemical system and could be provided by brine inside the casing (Thompson et al. 1996, p. B-21). In the analysis of steel corrosion in the gas generation conceptual model, the DOE indicated that the hydrogen fugacity that would stop corrosion to $Fe(OH)_2$ was 70 atmospheres (7.0 MPa) based on another set of thermodynamic data, but that the corrosion reaction could not be counted on to stop at that pressure because the reaction could convert to Fe_3O_4 and continue until a pressure of perhaps 500 atmospheres (50 MPa) was reached. At these higher pressures, hydrogen bubble formation and loss from the system could occur down to the depths of the plugs below the repository, potentially resulting in their failure during the 10,000-year regulatory time frame. The potential for such failure is also indicated by Thompson et al. (1996, p. 17), where the two lower plugs are given median lives of about 5,000 years and a range of 500 to 50,000 years. The validity of DOE's assumed plug life in excess of 10,000 years is questioned in light of these alternative observations.

If the borehole plugs beneath the repository fail during the 10,000-year regulatory time frame, the role of Bell Canyon groundwater may become important. As previously noted, all exploratory boreholes are assumed to be drilled in search of hydrocarbon resources and all are therefore assumed to penetrate entirely through the Salado and Castile Formations into the Bell Canyon Formation. Although only about 10% of the holes drilled through the waste panels are assumed by DOE to encounter pressurized brine, 100% of the holes will penetrate the Bell Canyon and the plugs below the repository may be significant in isolating the repository from the Bell Canyon. Water pressure in the Bell Canyon is reported in Lappin and Hunter (1989, p. 3-151) to be insufficient to cause water to flow from the Bell Canyon to the Culebra in an uncased or leaky casing borehole if the increase in water density from salt dissolution in the Castile or Salado were considered. However, the potential for water movement to or from the repository horizon was not discussed. If borehole plugs below the Salado cannot be assumed to have functional lives exceeding 10,000 years with a high degree of certainty, the validity of the assumption that Bell Canyon groundwater can be ignored in the performance assessment analysis may be erroneous.

The assumption in BRAGFLO that the lower plugs need not be explicitly modeled in performance assessment may be valid only if the assumption that they will remain viable during the 10,000-year regulatory time frame is valid. Failure of the lower plugs would provide a low-permeability pathway among the repository, the Bell Canyon, and any pressurized brine that may be encountered in the Castile. *If a lifetime in excess of 10,000 years cannot be adequately supported, flow through the lower plugs may* have to be explicitly modeled in BRAGFLO.

The three-plug configuration is assumed by DOE to cause an E1 scenario to be equivalent to an E2 scenario by eliminating effects on the repository of encountering pressurized brine in the Castile. The rationale for this assumption, as summarized in Section 3.12.1, does not appear to consider the potential for Castile brine to enter the repository during drilling before the hole is cased through the Salado and Castile. Such an event could increase the brine saturation in the penetrated waste panel, and affect subsequent waste corrosion and gas generation rates. Such a scenario would occur before the plugs were emplaced and thus would be independent of plug degradation rates.

The use of reference conditions, rather than direct model results, as the final input for performance assessment calculations is acknowledged to be a necessary simplification given the thousands of model runs that are necessary to produce stable CCDFs; however, the sensitivity of the current performance assessment inputs to the assumptions inherent in this approach have not been presented to the Panel. The validity of this approach is of concern, particularly when only two release values (those at 350 and 1,000 years) are used to determine releases over a 10,000-year period. Sensitivity studies performed during earlier performance assessments showed this approach to be valid (see, for example, Helton et al. 1992); however, similar studies have not been performed to help assure the validity of this approach for the current performance assessment model.

3.12.2.3. Evaluation of Alternatives

The overall Exploration Borehole conceptual model has evolved over time along with the Repository Fluid Flow model, and has been the subject of extensive sensitivity studies in previous draft performance assessments as noted above. Based on these studies, the overall conceptual model has been shown to be adequate; however, the validity of certain assumptions regarding components of this model has been questioned as described in Section 3.12.3.2. These include: alternative borehole penetration locations in the repository; allowing for a more rapid degradation of borehole plugs below the repository horizon (including the effects of Bell Canyon groundwater and explicitly including borehole plugs below the repository horizon if adequate longevity of the lower borehole plugs cannot be reasonably assured); reevaluating effects on the repository from an E1 borehole and a three-plug configuration; and assessing the adequacy of the selected reference conditions.

3.12.2.4. Uncertainties

The principal uncertainties in model results are expected to stem from uncertainties in the parametric data base, in the performance of the borehole plugs, and in the accuracy of the reference condition approach to final performance assessment modeling. The principal uncertainties in the parametric data base are associated with the hydrologic properties of the repository materials and are addressed in Section 3.3, Repository Fluid Flow. The hydrologic properties of the seal materials are generally better known and have less uncertainty. Those parameters with the greatest uncertainty, such as the permeability of the silty-sand-like material derived from corrosion products that fill the borehole, are generally sampled from a range of values and their uncertainty is thereby reflected in the overall modeling results. The consequence of uncertainties in these parameters is ultimately to overestimate or underestimate radionuclide releases; however, many of these parameter values reflect best estimates of future conditions and are appropriate for use in performance assessment despite their high degree of uncertainty.

Uncertainty in the performance of the borehole plugs below the repository horizon is discussed in the preceding sections. Plug failure within the regulatory time frame could result in the need to explicitly model the plugs in BRAGFLO, and to consider the effects of a low-permeability pathway to the Bell Canyon Formation on flow into and releases from the repository.

The accuracy of the reference condition approach to final performance assessment modeling has not been demonstrated to the Panel. If sensitivity studies indicate that the present method is inadequate, a denser lookup table may be needed, consequently requiring more computer time to prepare the performance assessment.

3.12.2.5. Adequacy of the Conceptual Model

The conceptual model for exploration boreholes is fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.12.2.2) are associated with specific, but potentially significant, details of the model. The adequacy of the current model is not known because of the unresolved issues identified in Section 3.12.3.3. Further information is required to determine, for example, whether modeling results are sensitive to exploration boreholes that penetrate the operations and experimental areas of the repository, or to the presence of a low permeability pathway to the Bell Canyon Formation. Such changes would affect both the conceptual and numerical models. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.12.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.12.2.2 regarding model assumptions, the application of the conceptual model in the numerical models is adequate. Principal concerns are related to limiting borehole penetrations to the waste panel rooms, assuming no degradation of the lower borehole seals and, therefore, not explicitly modeling them or the Bell Canyon groundwater, and demonstrating the adequacy of the limited reference conditions used to provide input to the performance assessment.

3.12.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked; however, those areas where the modeling approach is questioned and could lead to inaccurate results have been identified as issues in this report.

3.12.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain pending resolution of the issues raised in Section 3.12.2.3. In summary, the following concerns remain.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures, by diffusion or other transport mechanisms, could be released to the ground surface, gas pressures could be relieved, and brine could migrate into those areas and then into the waste panels from a borehole penetrating a Castile reservoir or through degraded plugs from the Bell Canyon.

- The assumption that shorter (40-m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low-permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

3.12.2.9. Adequacy for Implementation

The Exploration Boreholes conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.12.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.12.2.10. Dissenting Views

There were no dissenting views for this model.

3.13. Cuttings/Cavings

3.13.1. Model Description

The Cuttings/Cavings conceptual model describes releases during drilling of exploration boreholes. It is one of several models that address the calculation of direct waste release to the ground surface if an exploration borehole inadvertently penetrates a waste panel, creating a possible pathway for transport of waste to the surface. Other associated models include those describing Exploration Boreholes, Repository Fluid Flow, Multiple Intrusions, and Spalling.

Of the possible pathways for release during the regulatory time frame, one of the most important is that caused by the inadvertent penetration of a waste storage room by an exploratory borehole. Normal oil and gas drilling practices can provide a means for waste to be released to the ground surface in the circulating drilling fluid (mud). From this intrusion, three mechanisms used by WIPP for waste movement are cuttings, cavings and spallings. Cuttings are waste particles released into the mud from the cutting action of the drill bit itself and from mechanical friction. Cavings are waste particles released by erosion of the borehole walls due to circulating drilling fluids. Spallings are those particulate materials removed and transported by the movement of gases.

The cuttings mechanism is the easiest to address because the volume of waste cuttings is a simple product of the borehole cross sectional area times the room height, and is equal to the waste volume produced by the drill bit moving through the waste. Cavings is somewhat more complicated as it must incorporate the erosional effects of the shearing action of the drilling mud as it moves up the borehole annulus. This shearing may be caused by either turbulent or laminar flow. Repository pressure can have effects on cavings, which is covered by the spalling process. Spallings will be discussed further as a separate model in Section 3.14.

Details of the Cuttings/Cavings model were in a state of flux at the time of this peer review and information describing the model was obtained from various sources, but mainly from the CUTTINGS_S User's Manual, several draft reports, and from numerous contacts, presentations, and discussions.

Releases of cuttings and cavings are calculated using analytical equations governing erosion by flow up through the hole bored in the waste room, based on laminar and turbulent flow (Bergland 1992) as implemented by the CUTTING_S code. This code calculates the final caved diameter of the borehole that passes through the waste by using appropriate input based on assumed physical properties of the waste and drilling parameters. Although DOE is continuing to question whether the flow of the drill mud is laminar or turbulent, and what the parameters should be, the basic model has been generally accepted. However, the amount of material predicted to be released by cavings can be small per penetration and, therefore, its contribution to surface release has not been considered critical relative to other contributions.

The WIPP repository will consist of a number of waste disposal rooms excavated in bedded halite (salt) approximately 650 m below the ground surface. Transuranic waste packed in 55-gallon drums or standard waste boxes will be placed in each room. The waste is expected to be slowly compacted vertically by salt creep, from an original waste room height of 4 m to a compacted height of 0.5 to 2 m in approximately 100 years. In unmodified form, the waste consists of a mixture of, for example, contaminated cloth, wood, rubber, plastics, metals, glass. After placement in the repository, the waste may become exposed to brine, which is expected to corrode the metals and generate hydrogen gas. Additional gas may be generated by the biodegradation of the organic materials. The gas volumes generated by corrosion and biodegradation are expected to increase continuously for hundreds of years and the pore pressure may become very high, possibly exceeding the lithostatic overburden stress. At some time within the 10,000-year regulatory period, it is probable that one or more exploration boreholes will be drilled into and through the vertically compacted waste and some of the waste will be carried to the surface. The volume of waste removed to the ground surface will depend on the physical properties of the compacted, decomposed wastes, the drilling procedures used, and the pressures encountered. The radioactivity of this waste is determined probabilistically, based on the distribution of waste radioactivity expected in the WIPP repository.

3.13.2. Review of Criteria

3.13.2.1. Information Used to Develop the Conceptual Model

Because the Cuttings/Cavings model is highly dependent on the borehole drilling process, it is important to understand the procedures used in drilling a gas or oil well. The current performance assessment model relies on the regulatory imposed assumption that future drilling techniques will be similar to those used today. When drilling commences, a conductor pipe is set in cement to prevent surface materials from sloughing into the wellbore during later drilling. Drilling is continued to the top of the salt section, using a large-diameter drill bit, where another steel casing is set. This "surface" casing is grouted into the hole and a blowout prevention tree is attached to the casing at the surface level. Drilling in the salt section uses drilling mud mixed in saturated brine to prevent dissolution of the salt.

Drilling mud is pumped from the reserve pit down through the drillpipe and drill bit, and up the annulus formed by the drill string and drilled hole. While drilling in the salt section, no formal attempt is made to monitor the character of the cuttings or the fluid volume of the reserve pit. (In the WIPP intrusion case, this can be an important input.) The drill string generally consists of a drill bit attached to long drill collars (heavy pipe) with a smaller outside diameter than the bit but a larger diameter than the following multiple sections of 4-1/2" diameter drillpipe. Once the drill has passed the salt section (1,375 m), the hole is again cased with cemented pipe. At this point, if the repository had been penetrated, no further contact would occur between the drilling mud and exposed WIPP waste.

Cuttings are a component of the direct brine release model, and cuttings releases are assumed to be the only drilling release to occur for repository pressures less than the hydrostatic pressure of the drilling mud (approximately 8 MPa). Because the volume of cuttings removed and transported to the surface is equal to the product of the drill bit cross sectional area, drill depth and waste porosity, it is only necessary to know these three parameters. The cuttings volume calculated becomes the lower bound to the total quantity of waste removed by drilling. The computation of cuttings release in the CUTTINGS_S code is performed within a module specific to cavings.

For the cavings part of the Cuttings/Cavings model, the erosion process is assumed to be driven solely by the shearing action of the drilling fluid (mud) on the waste as it moves up the borehole annulus between the drill pipe and the waste. For the purpose of the cavings calculations, it is further assumed that the repository is not excessively pressurized by either brine or gas (i.e., the repository pressure is less than the hydrostatic pressure of a brine column to the surface). In the annulus formed by the collars or drill pipe and the borehole wall, the flow of the drilling fluid has both a vertical and rotational component. This helical flow pattern generates shear stresses by the relative motion of adjacent fluid regions and by the action of the fluid on the borehole wall. It is assumed that if the fluid shear stress at the wall exceeds the effective shear resistance to erosion of the wall material (compacted repository wastes), erosion of the wall material will occur, increasing the diameter of the bored hole. The eroded material then will be carried onto the surface, entrained in the flowing drilling fluid. The code probabilistically determines the amount of material removed by the several release mechanisms, and decays the radionuclides release to simulate the source term at the time of intrusion.

3.13.2.2. Validity of Model Assumptions

Many of the principal assumptions used in developing the model are identified in Section 3.13.1. Overall, the assumptions are found to be reasonable and appropriate. Identification of and expansion on the key assumptions are discussed below.

The concept of release due to borehole drilling relies heavily on the assumption that future drilling techniques will be similar to those in use today. The basics of the drilling process are as outlined in Section 3.13.2.1, which comes from a large, well-tested body of experience that can be expected to be reliable.

It is implicitly assumed that the drillhole will encounter waste only as it penetrates the room. This is a simplifying assumption that is realistic but does not have to be absolute. For example, there can be a DRZ over the repository that could contain contaminated brines.

For this model it is assumed that the waste volume is probabilistically determined for each penetration. The Curie calculations are a direct computation from the amount of waste removed.

The cuttings portion of the waste material removed is assumed to be strictly the result of the neat volume of material cut away by action of the drill bit. The cavings portion accounts for the other mechanisms that complement the drilling action, such as frictional drill fluid erosion. These definitions of waste source from this model are inclusive and adequate.

It is assumed by the cavings portion of this model that the fluid shear stress at the waste surface must exceed the effective shear resistance of the waste wall for any release. This is valid since erosion occurs, increasing the diameter of the borehole with the eroded material being carried away by the circulating drilling fluid.

The equations governing waste erosion are based on laminar and turbulent flow, both of which are assumed to occur, depending on the velocity.

Among the basic assumptions made for the fluid flow calculations is that, in the absence of experimental data, the effective shear resistance to erosion of the repository waste is similar to ocean bay mud or montmorillonite clay. In the absence of accurate waste characterization or knowledge of the form this waste is in as the time of intrusion, this assumption appears appropriate because of the low shear strengths of these substances.

3.13.2.3. Evaluation of Alternatives

Only one issue is identified for which an alternative might be considered. It is a possibility that the environment for cuttings and cavings will be saturated with brine. If this becomes the case, this brine might be removed by the drilling action without the benefits of erosion or cuttings. This scenario does not appear to have been incorporated in the Cuttings/Cavings model and its significance is not known.

There are no meaningful alternatives for the cuttings and cavings model, except perhaps to consider using a finite fixed assumed input value, which would be more arbitrary.

3.13.2.4. Uncertainties

Several factors contribute to model uncertainty, principally the undefined nature and complexity of the waste, both in its initial and altered states. Information as basic as granular state, chemical form, decomposed form, density, and waste strength, is unconstrained. To conservatively treat these unknowns, property values of surrogate materials are selected to represent the worse case. As such, the accuracy of the model should be realistic, but on the conservative side. Uncertainty also may arise from inappropriate applications of turbidity resulting from assumptions in turbulent flow, which is a function of the Reynolds Number data on the transition from laminar to turbulence of the fluids. Within the full scope of exposure, however, any reasonable variation from probable waste volume removed would be confined to a restricted, relatively small volume and would not appear to lead to any significant consequences per penetration.

3.13.2.5. Adequacy of the Conceptual Model

This model is fundamentally appropriate. It is based on straightforward analysis, concepts, and technology that is well developed and believed to be adequate for depicting that part of the consequences of a waste room penetration by a borehole drill that is covered by this model.

3.13.2.6. Adequacy of Application

The CUTTINGS_S model contains well thought out and evaluated mathematics, based on researched and established fluid flow technology and science. The FORTRAN computer codes used to simulate the laminar helical flow in an annulus are documented and verified against published results. For turbulent flow, the results are highly dependent on the parameter values. The values given in the CUTTINGS_S User's Manual have resulted from significant research and are believed to provide adequate solutions. The turbulent flow is found to be dependent on absolute surface roughness and the value chosen for the calculation exceeds that of very rough concrete or riveted steel piping. As a result of these considerations, the Panel believes this model is adequate for application.

3.13.2.7. Accuracy of Results

The parameters for calculations were checked as presented in the CUTTINGS_S User's Manual and found to be appropriate. The drilling parameter values were obtained from surveying industry practices and as reported, the values are appropriate for a range of customary industrial size dimensions.

3.13.2.8. Validity of Conclusions

Physically, the conceptual process of this model is simple and valid. Some subjectiveness of validity exists in the questions of turbulent or laminar flow and the state of the waste for determining its resistance to removal by the caving process. The conservative values used in the calculations appear to alleviate these concerns, however. Therefore, the validity of this conceptual model appears to be acceptable within the uncertainties discussed in Section 3.13.2.4.

3.13.2.9. Adequacy for Implementation

This model is sufficiently developed and uncomplicated that no serious concerns were raised. The model appears to be capable of accurately representing the waste that might be removed during a drilling intrusion and is fully adequate for implementation in support of the WIPP performance assessment.

3.13.2.10. Dissenting Views

There were no dissenting views for this model.

3.14. Spallings

3.14.1. Model Description

The Spallings conceptual model is one of several that address the calculation of direct waste release to the ground surface if an exploration borehole penetrates a waste panel. Other associated models include Cuttings and Cavings, Exploration Boreholes, Repository Fluid Flow, and Multiple Intrusions.

Spallings are the particulate materials introduced into drilling mud by the movement of gas from the waste into the borehole annulus. At one time, spallings were conceived to involve three mechanisms: blowout, stuck pipe, and gas-induced spall. Because the latter two were perceived to produce insignificant releases, DOE determined that this model would concentrate on blowout. The repository pressure domain, where spallings are applicable, is above the borehole fluid hydrostatic pressure because it can occur only when the repository gas pressure is capable of countering and reversing the mud-laden drilling fluid during the drilling process. When the drillhole annulus around the drill pipe is cleared of drilling fluid, it becomes a conduit for free release of repository gases.

The principal parameters in the Spallings model are the gas pressure, the volume of gas in the repository when it is penetrated, and properties of the waste such as particle diameters and resistance to erosion.

Because the release associated with spallings is sensitive to gas pressure in the repository, it is strongly coupled to the BRAGFLO-calculated conditions in the repository at the time of penetration. In particular, the spall release may be sensitive to whether the repository has been penetrated previously by another borehole.

3.14.2. Review of Criteria

3.14.2.1. Information Used to Develop the Conceptual Model

This model was based on information on drilling practices, dimensions, and characteristics of drilling equipment parameters, and standard models for gas flow, as well as results of a simple laboratory test to examine some aspects of the conceptual model. Details of the Spallings model were in a state of flux at the time of this peer review. Information describing the model was obtained from various sources, mainly from the CUTTINGS_S Users Manual, several draft reports, presentations, and numerous personal contacts and discussions.

Because this source of release is somewhat dependent on the borehole drilling process, it will be instructive to understand the procedures utilized in drilling an oil or gas well, which the EPA has directed to be the standard for WIPP characterization studies. As described in Section 3.13.2.1, drilling produces a borehole into the repository room by a bit-cutting process that produces rock fragments. The fragments are removed by circulating a mud-laden fluid down through the drill pipe and returning it up the annular space between the pipe and the hole wall. The hydrostatic pressure of this mud column must be kept in balance with the pressure at the drill bit location. When an imbalance from overpressure in the repository occurs unchecked, the mud flow on the return side will be accelerated and ejected from the hole, creating a gas vent to the repository. Until this sudden uncontrolled venting is brought under control, violent escape of gas from the repository is expected to carry with it some of the stored waste, discharging it at the well head on the ground surface. Once gases begin to vent up the drill hole, repository room pressure gradients generated by the penetration of the repository cause a flow of gas toward the borehole that fractures the waste material, permitting the escaping gas to flow within fractures rather than through a porous waste matrix. Consequently, the intrinsic permeability of the matrix does not restrict the gas flow. Gas flow velocity up the borehole is governed by the isothermal flow of gas in a long annular tube of a given cross sectional area, tube roughness, and gas pressure at the borehole entrance. The gas pressure at the borehole entrance to the repository can be assumed to be the initial gas pressure in the repository. The mass-flow rate of gas in the fractured waste at any radial cross section is equal to the mass-flow rate up the borehole. Radial flow of gas within the fractures in the waste matrix erodes and widens the fractures. Erosion of the waste is assumed to occur if the fracture gas velocity exceeds a threshold velocity related to the terminal velocity of a waste particle at the fracture surface and to the cohesive strength afforded by moisture in the matrix.

A key part of the Spallings model is to determine how much of the waste will be lofted into the gas stream. With the uncertainty of the waste characterization (e.g., its state and chemical form), the premise that the spalling process is self-limiting is based on the assumption that particle movement will cease when the gas velocity, measured radially from the borehole axis, equals the critical entrainment velocity. All material close to the borehole is assumed to be eroded away and removed. A laboratory experiment was modeled to demonstrate a critical lofting velocity for sample materials as a function of particle size distribution. Different terminal velocities were associated with different particle diameters. Confirmative testing of the model was conducted with the standard that if the measured amount of lofted material was less than the predicted amount of erosion, the model was considered confirmed. Confirmation was not obtained because the tests showed the expected uniform gas flow through the waste was not occurring. Instead of a cavity forming around the borehole, flow channels formed that increased in width and length as erosion proceeded in the material. These results forced the latest iteration in the blowout model. The new model (WIPP PA User's Manual for CUTTINGS_S, Appendix A, Section 2.3.1.3), called the channel flow model, is the one used for CCA calculations, although it is the understanding of the Panel that the mechanisms of this model are yet to be confirmed.

A channel-flow mechanism in the model requires either precise definition of the number, geometric configuration, and location of all the channels before they form (which is not technically feasible), or scaling the model results in some manner to reflect the channeling process. The scaling method was adopted, adjusting the predicted releases to agree with experimental release observations in the laboratory test. This laboratory test was a simple, small-scale experiment that yielded useful insights, but it could hardly be an adequate representation of actual degraded waste materials. Although the uniform-flow model was independent of experiments, in the sense that release predictions did not require direct data from the tests, a coupling between experimental results and the model was necessary for scaling. This was accomplished by introducing certain experimentally determined scaling constants into the model (Lenke et al. 1996). Notwithstanding the use of these scaling factors, the model is based on well-defined first order physical principles and is applied to different gases and solid materials by prescribing well-defined material properties, such as particle size and density, viscosity, and cementation tensile strength. The scaling factors are the only parameters of the model not directly related to geometry or material properties, but they are necessary to represent the way channels for gas flow are likely to develop.

3.14.2.2. Validity of Model Assumptions

It is assumed that the repository pressure domain is above the hydrostatic head of the drill fluid column. This is reasonable because technically, a blowout should not occur at a lower pressure.

A simplifying assumption is that the driller does not have signs of the impending penetration and is unprepared to react. Therefore, the blowout is likely to occur and may be difficult to contain. Because of this, it is assumed that the release will be process-limited rather than operator-dependent.

An implied assumption is that the surface of the cavity will be cylindrical in nature.

The model's limiting characteristic is achieved by the derived equation's function of gas velocity and waste strength. As the velocity declines, the limiting parameter becomes the property of waste strength. The use of this property is valid, but its value is subjective because of the unknowns and uncertainties of the waste itself. In fact, this property is a function of the source of waste strength, such as cohesion, adhesion, or cementation. Cementation from a salt crystallization process in the stored waste is currently being considered as a mechanism that provides a strength value for waste that might be easily validated.

At this writing, it is assumed that the latest CUTTINGS_S model assures that the model relies on channel flow instead of a uniform low porosity flow toward the borehole. It is of concern to the Panel that the *mechanisms of this assumption are yet to be confirmed.*

3.14.2.3. Evaluation of Alternatives

The Spallings conceptual model has changed several times during its development. Early model development focused on transient, unrestrained outgasing leading to the spall (dynamic fracture) of porous cohesive granular media (Berglund 1992, Section 3.3). An experimental program related to model development focused on almost instantaneous depressurization and was limited to a one-dimensional linear sample configuration. The pore pressures required to cause spall or dynamic fracture could be closely approximated using the tensile strength of the porous soil medium (Berglund and Lenke 1995), but the model was complex and could not be directly related to an intrusion event. In addition, although the experimental observations showed fracturing under instantaneous release of gas pressure, sample-preparation factors were largely responsible for the locations of the fractures. The fracture patterns also depended on the one-dimensional nature of the experiments, and the model did not adequately explain how the fractured material was removed.

After extensive discussion, the dynamic fracture model was replaced with a more general three-part model based on the premise that the waste could be removed by any one of three mechanisms: blowout, stuck pipe, and gas-flow assisted erosion (as the result of gas-induced spall) (Butcher et al. 1994). Which mechanism will dominate depends on the permeability and pressure drop at the borehole. Well blowout, an uncontrolled gas release from the borehole, was considered the dominant mechanism. The remaining two mechanisms, stuck pipe (waste loosened and moved while attempting to dislodge a stuck drill pipe), and gas-flow assisted erosion, were not thought to be important because they would only occur at waste permeabilities of less than 1×10^{-16} m^2. The gas-flow assisted erosion is now the basis for the channel flow modeling in the Spallings model.

3.14.2.4. Uncertainties

Development of this model is not sufficiently complete to determine uncertainties specific to the channel flow movement of waste to the existing borehole. The lack of adequate waste characterization may also provide a set of uncertainties. Other uncertainties concern the state the waste is in at the time of intrusion, which may not be feasible to ascertain.

3.14.2.5. Adequacy of the Conceptual Model

The Spallings model gives a good conceptual view of how solid waste can be removed by gases that are being rapidly vented. The latest model is most realistic mechanistically because it is predicated on the concepts of moving particles via gas movement. The original model, which relied on instantaneous decrease in gas pressure, was judged by DOE to be unrealistic because of waste permeability and gas flow considerations. The latest model appears to be the most applicable of those that have been considered to date. Notwithstanding the need for establishing two scaling parameters and a waste strength factor, this model is conceptually appropriate, but the Panel could not find sufficient information to determine its adequacy.

3.14.2.6. Adequacy of Application

Integration of the Spallings model into the CUTTINGS_S code is a relatively simple exercise, although the equations governing the waste availability for removal do not appear to be fully developed at this time. While the concept of scaling parameters, which are intended to address waste strength by providing factors of resistance to erosion or lofting, is appropriate, the proposed parameter value has yet to be validated. Therefore, until these details are resolved, it will not be possible to assess the adequacy of application for this model.

3.14.2.7. Accuracy of Results

On testing the latest modeling efforts for confirmation of principle, additional information was gained that should be pursued before further confirmation is sought. It seems plausible that the performance assessment exercise might use an assumed entrained waste content for a given time period and sample several scenarios for concentration and time domain. Another simplistic approach might be to assume a certain waste volume around the borehole that would be removed. Given the importance to overall performance assessment of results from this model, any laboratory tests could be supplemented by a scaled-up testing demonstration that will more convincingly verify the model. At this time there is not enough information to determine the accuracy of results from the Spallings model.

3.14.2.8. Validity of Conclusions

In the opinion of the Panel, the model development is now on an appropriate path to produce a valid outcome. However, the available information was not sufficient to present a compelling argument that adequate work has been done to confirm that the conclusions would be valid. Additional testing is required to firm up the conceptualization of the channel flow scenario.

3.14.2.9. Adequacy for Implementation

Because of perceived inability to defend a time limit for release, it became necessary to implement a model that provides a self-limiting process for waste removal. It is not reasonable to expect that the entire room would be excavated by the blowout process. If this were possible, a model would not be necessary. *Because of its unconfirmed state of development, this model is not adequate for* implementation at this time.

3.14.2.10. Dissenting Views

There were no dissenting views for this model.

3.15. Direct Brine Release

3.15.1. Model Description

The Direct Brine Release conceptual model describes short-term releases of brine from exploratory boreholes that penetrate waste panels in the repository. The model addresses releases from both single and multiple intrusions. Long-term flow from single intrusions and the assumptions regarding the physical aspects of the boreholes are addressed in the Exploration Borehole conceptual model, and long-term flow from multiple intrusions is addressed in the Multiple Intrusions conceptual model. Other related models include Repository Fluid Flow, Castile and Brine Reservoirs, and Actinide Transport in the Salado. The related Cuttings/Cavings and Spallings models address releases of solid waste materials following borehole intrusions, but do not address brine releases. The details of the Direct Brine Release model were still under development at the time of this peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 22 May 1996 Draft CCA, Sections 6.4.7.1, Releases During Drilling (DOE 1996, pp. 6-65 to 6-70), from verbal descriptions, and from the cited references.

Releases that may occur during and immediately following drilling are modeled in accordance with regulatory guidance, assuming that present standard rotary drilling practices will be used. This assumption was used by DOE to establish borehole geometry during drilling, as well as the drilling, casing, and sealing practices (Thompson et al. 1996). To help prevent blowout, the density of the drilling mud is controlled by drillers based on the fluid pressures expected at the drilling depths. Gas, as well as brine, may enter the borehole from the waste panel if the driller is unable to control the pressure in the borehole. If fluid pressures in the waste panel are sufficiently high, brine or a brine-gas mixture may flow to the ground surface. The boreholes are assumed to be cased from the ground surface to the lower Rustler before entering the Salado; thus, brine flowing up the borehole during drilling would reach the surface, but not enter the Culebra or the other permeable horizons above the Salado. The frequency with which exploration boreholes will penetrate the waste panel area is estimated based on a long-term average of 47 boreholes per square kilometer per 10,000 years, and the size of the waste panel area. This is further discussed in Section 3.12.

Before brine can flow from a waste panel to the ground surface, mobile brine must be present in the waste panel and the pressure of the brine must be greater than the pressure of the drilling mud at the repository depth. Brine is expected to enter the waste panel as seepage from the surrounding halites, anhydrite beds, and through the shaft seals, and will also enter if pressurized brine is encountered in the Castile. Mobile brine will be present in the waste panel if it has not been previously consumed by the corrosion reaction and if there is enough remaining to exceed the residual brine saturation of the waste. The residual brine saturation is the percent saturation below which the brine occurs discontinuously in the porous waste and will no longer move. The residual brine saturation in the waste panel is uncertain and is randomly sampled in performance assessment from the range of zero to 0.552 (DOE 1996, Table 6-6). The drilling mud is assumed to exert a pressure of about 8 MPa at the repository horizon; thus, for brine to be released to the ground surface its pressure in the repository must exceed this value.

In accordance with regulatory guidance, DOE does not assume that a direct brine release would be noticed by the driller, or that the driller is aware of the presence of the repository. The driller is assumed to be exploring for hydrocarbon resources, and after taking normal steps to deal with any brine releases or drilling fluid losses at the repository horizon, would continue drilling to customary depths below the Bell Canyon. Based on a review of current practices in the Delaware Basin, DOE has assumed that direct brine releases to the surface will be stopped by the driller 44 hours after penetrating the repository. Borehole plugs are assumed to be installed in three alternative configurations, and to degrade as discussed in Section 3.12. Because of the assumed degradation rates of the various plugs, only the two-plug and three-plug configurations are of consequence to direct brine releases.

Encountering pressurized brine in the Castile in a borehole is not considered by DOE to result in a direct release of repository waste. The Castile brine will be uncontaminated and, to result in a direct release, would have to be of sufficient pressure to eject the drilling mud from the borehole. Because the repository is likely to have been depressurized a short time before when it was penetrated by the same borehole, the repository pressure is expected to be lower than the Castile brine pressure and initial hydraulic gradients would be from the borehole into the repository. The longer term migration of Castile brines into the repository are addressed in the long-term BRAGFLO calculations and would affect both the long-term releases and the initial conditions (such as waste panel brine saturations and gas pressures) for the next short-term release. Direct release of waste solids by borehole wall erosion from Castile brine moving up the borehole is assumed by DOE to be negligible.

Short-term releases of dissolved or suspended radionuclides contained in brine are modeled using a two-dimensional, two-phase, transient horizontal plane model of the waste panel area, developed using the BRAGFLO code specifically for estimating short-term, direct brine flow. This model has not been specifically named, and for purposes of this report will be called the BRAGFLO-DBR model. Radionuclide transport is calculated using the PANEL code. This code conservatively assumes complete mixing in the waste panels and is further discussed in Section 3.8. BRAGFLO-DBR explicitly models all disposal rooms, pillars, panel closures, and the associated disturbed rock zone within the waste disposal area of the repository.

A one-degree dip in the repository corresponding to the average one-degree dip to the south in Salado bedding is included in the model. Including this dip has been found to be important in modeling results because of the effects of gravity. Gas movement in the anhydrite beds tends to be to the north toward areas of lower pressure, while brine tends to accumulate in the southern or lower end of the waste disposal area. Material properties in BRAGFLO-DBR are generally consistent with those in the standard version of the BRAGFLO model (called BRAGFLO in this report) used to model repository fluid flow (Section 3.3), with the exception that the intact Salado halite is assumed to be impermeable and forms an outer no-flow boundary for the model.

BRAGFLO-DBR takes its initial and boundary conditions from BRAGFLO, CUTTINGS_S, the WIPP data base, and an analytical correlation to simulate flow up the open borehole. Fluid pressures, saturations, permeabilities, porosities, two-phase flow properties, and other repository properties are determined at the time of penetration by the standard version of the BRAGFLO code. The borehole flow model has been developed from a multi-phase vertical pipe flow analysis used in the petroleum industry. Total flux and transport are determined based on a flow duration of 44 hours.

For calculating short-term releases, borehole penetrations are assumed in BRAGFLO-DBR to occur in two reference locations, at an updip location in the center of the waste panel area, and at a downdip location in the southwestern waste panel. Multiple borehole penetrations of the same waste panel are always assumed to occur at the southwestern end of the repository because the reference conditions for multiple intrusions are developed from the standard BRAGFLO model, which conservatively places the single waste panel and intrusion borehole at the downdip end of the waste panel area. Actual intrusion locations are selected randomly, but the boreholes are then assigned standardized reference locations depending on whether they penetrate the waste or a salt column, whether they are updip or downdip, whether they are E1 or E2, and whether they are the first intrusion or a subsequent intrusion of the same waste panel. Modeling results have indicated that the effects of borehole intrusions on the repository are not significant beyond the waste panel that was penetrated; thus, second and subsequent intrusions into the same waste panel are treated separately in the model.

For the first borehole penetration in a particular waste panel, the initial and boundary conditions are determined by interpolation from reference conditions determined from undisturbed BRAGFLO results at approximately six reference times ranging from 100 to 10,000 years. BRAGFLO-DBR is run for each of these sets of reference conditions to establish a data base for interpolating short-term releases from first penetrations occurring during the regulatory time frame. Conditions for first penetrations are assumed to be the same for E1 or E2 boreholes, because at the time of penetration neither would have been drilled past the repository. Initial conditions for downdip borehole locations are taken from conditions in the single waste panel in BRAGFLO, which is at the downdip end of that model. Initial conditions for updip borehole locations are taken from the "rest of the repository" in BRAGFLO, which is at the updip end of that model.

Conditions for second penetrations are determined based on the date, type, and location of the first penetration, as well as the date, type, and location of the second penetration. Different sets of reference conditions are established for second penetrations depending on whether the first penetration was an E1 or E2, whether the second penetration occurs in the same panel or a different panel, and the lag time between the first and second penetrations. Subsequent penetrations are addressed following similar logic. Reference conditions for second and subsequent penetrations are determined from BRAGFLO calculations for E1 and E2 intrusions occurring at 350 and 1,000 years, as described in Section 3.12.

Changes in repository pressure, fluid saturation, and other repository conditions resulting from the short-term releases are not considered in the long-term flow calculations. Such effects are considered negligible by DOE over the long term because of their transient and local nature.

3.15.2. Review of Criteria

3.15.2.1. *Information Used to Develop the Conceptual Model*

The Direct Brine Release conceptual model was developed based on a combination of conceptual models for repository design and two-phase fluid flow, the physical and hydrologic properties of Castile brine reservoirs, current drilling and borehole sealing practices in the Delaware Basin, fluid flow in open boreholes, and borehole plug degradation rates. Current practice has provided elements of this model, in accordance with regulatory requirements. This information base is considered reasonable and appropriate.

3.15.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.15.1, and are critically reviewed here. Most assumptions are reasonable and appropriate and include the general approach taken to modeling fluid flow within the boreholes and repository, treatment of borehole sealing practices, and use of reference conditions to address alternative intrusion scenarios. The frequency of drilling and the time required for a driller to control a direct brine release are based on DOE analysis of current practice and are not reviewed here. Reference conditions for direct brine releases are determined at a greater frequency than for the exploration boreholes or multiple intrusions models, and are expected to be adequate for performance assessment. The assumptions related to repository fluid flow, the physical aspects of the boreholes and borehole seals, and the characteristics of Castile brine reservoirs are discussed in Sections 3.3, 3.12, and 3.16, respectively. Changes in these assumptions would affect the approach taken to model direct brine releases. Several assumptions in the Direct Brine Release model that are potentially important to radionuclide containment and are not adequately supported are discussed in the following paragraphs.

No radionuclide release is assumed to occur from direct discharge of Castile reservoir brine in a borehole penetrating a waste panel. The rationale for this assumption does not appear to be supported by an analysis of the potential for brine mixing and borehole wall erosion. This could be more significant for penetrations occurring before complete water panel closure, when waste has not yet been fully compacted. Because the Castile brine would pass directly through a waste panel, the potential consequences of an error in this assumption could be significant.

The potential for entraining waste room brine in rapid gas flow from the waste panel is not considered in the conceptual models for either spallings or direct brine release. The Spallings model considers only the entrainment of solid particles in single-phase gas flow, and the Direct Brine Release model considers only dissolved and colloidal radionuclide transport in brine released to the surface. Brine entrainment in the gas can occur by transport of droplets or, more importantly, by air-lifting brine and waste particulates in a closed-wall pipe (the coffee percolator effect). The air-lift is in fact a method of well completion where the violent surges from air pumped down a well are used to scour the borehole production zone and remove fine-grained sediments to enhance well production. Depending on the flow velocity in this two-phase brine/gas system, the erosional forces could be greater than for either gas or brine flow alone.

Boreholes penetrating areas of disturbed rock in the walls of the repository excavations do not appear to have been considered in performance assessment modeling. The walls will have a tendency to bow inward under the lithostatic stress, resulting in both micro- and macro-fracturing in the halite. Hydrologic tests in repository walls have shown pore pressure depressurization and reduced permeabilities within 10 m of the workings, most likely in response to halite deformation. Within this zone, pore pressures appear to have dropped to near zero at some locations, and permeabilities nearly three orders of magnitude higher than the high end of the undisturbed halite range have been measured (Lappin and Beauheim 1996). Hydrofracture measurements in horizontal boreholes within the repository have indicated that stress effects from repository excavations may extend on the order of 50 m from the end of a drift (Wawerski and Stone 1986). Boreholes very near the excavation wall could, therefore, encounter open fractures and permeabilities equivalent to those of the waste, while boreholes 10 m or more from the excavation may encounter essentially undisturbed halite. The higher permeabilities encountered in boreholes penetrating the disturbed rock zone in the excavation walls could lead to increased short- and long-term releases.

3.15.2.3. Evaluation of Alternatives

The overall conceptual model for direct brine releases is based on standard hydrogeologic and petroleum industry practices and is appropriate for use in performance assessment. Alternatives to this model may be considered, however, in the details of its application. Three fundamental issues have been identified: waste transport during the direct release of Castile brine, the entrainment of brine and waste solids in two-phase gas/brine flow from the repository, and boreholes penetrating disturbed rock in the excavation walls.

3.15.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying fluid flow theory and analysis methods, from uncertainties in the input data, and from the validity of assumptions regarding the conceptual models. The underlying theory is widely used in the petroleum industry for evaluating oil reservoirs and provides a reasonable and appropriate approach to studying direct brine releases. Although the uncertainty in the input data are occasionally high, the parameter values have generally been appropriately selected for performance assessment. The three additional processes discussed in Section 3.15.2.2 are similar in that they each address processes that were not considered by DOE. The consequence of neglecting these processes is to potentially underestimate radionuclide releases.

3.15.2.5. Adequacy of Conceptual Model

The conceptual model for direct brine releases is fundamentally sound, with the possible exception of the three processes identified in Section 3.15.2.2. These processes were not included in the conceptual model for performance assessment, and if valid, could be important to cumulative radionuclide release. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.15.2.6. Adequacy of Application

With the exception of the issues raised in Section 3.15.2.2 regarding model assumptions, the internal consistency of the conceptual model and its application in BRAGFLO-DBR is logical and is adequate for performance assessment. The simplifications required to model a complex set of conditions in an efficient manner appear to be appropriate.

3.15.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. Although the modeling results were not available for review and could not be checked, the density of reference conditions is expected to provide performance assessment inputs of suitable accuracy.

3.15.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.3.2.3. In summary, the following concerns remain.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases if releases do, in fact, occur through this mechanism.

- Radionuclide transport through entrainment of brine and waste solids in rapid gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

3.15.2.9. Adequacy for Implementation

The Direct Brine Release conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.15.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.15.2.10. Dissenting Views

There were no dissenting views for this model.

3.16. Castile Formation and Brine Reservoir

3.16.1. Model Description

The Castile Formation and Brine Reservoir conceptual model addresses the hydrologic characteristics of the Castile Formation and the occurrence, size, hydrologic, and chemical characteristics of brine reservoirs that may underlie the repository within the Castile Formation. Associated models include Exploration Boreholes, Multiple Intrusions, and Repository Fluid Flow. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Section 6.4.8, Castile Formation and Brine Reservoir (DOE 1996, pp. 6-75 to 6-79), from verbal descriptions, and from the cited references.

The Castile Formation consists of a 360-m thick series of halite and anhydrite beds underlying the Salado Formation. Although few tests have been performed, by analogy to the Salado, the Castile is conceptualized as a very low permeability formation whose primary importance to WIPP performance assessment stems from the hydrologic isolation it provides the repository and from the pressurized brine reservoirs that have been encountered during deep drilling.

Deep exploratory boreholes that penetrate both the repository and the underlying Castile Formation may encounter a pressurized, higher-permeability, brine-filled region called a brine reservoir. If encountered, the fluid pressure in such a reservoir would be sufficient to cause brine to flow at potentially high rates and high pressures through the repository and from the wellbore at the ground surface. The consequences of such flow are addressed in the Exploration Borehole and Multiple Intrusion conceptual models.

The brine reservoir is conceptualized by DOE as a heterogeneous, discontinuously fractured zone of limited extent within the Castile anhydrites. Transmissive pathways for brine and gas movement are provided by interconnected, primarily vertical fractures whose origin may be related to structural deformation. Fluid in the reservoirs is pressurized by the weight of the overlying geologic media and averages about 67% of the lithostatic pressure within the Delaware Basin (Freeze and Larson 1996).

Brine reservoirs are occasionally encountered during deep drilling in the Delaware Basin and, when allowed to flow, may discharge at rates estimated at 1,000 to 2,000 barrels (150 to 300 m^3) per day and last up to 4 to 5 days (Silva 1994). The observation that flows stop by themselves supports the concept that the size of individual brine reservoirs is limited. Brine reservoirs were penetrated by two boreholes (ERDA-6 and WIPP-12) drilled for WIPP site characterization purposes. The pore volumes of these reservoirs were estimated to be about 96,000 m^3 and 2,700,000 m^3, respectively, although the uncertainty in these estimates is large (Popielak et al. 1983). A geophysical survey, using time domain electromagnetic methods, completed over the WIPP-12 brine reservoir and the waste disposal panels, detected a conductor interpreted to be the WIPP-12 brine reservoir, and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels (Earth Technology Corporation 1988).

The chemistries of the brines from the ERDA-6 and WIPP-12 reservoirs were studied by Popielak et al. (1983) and found to be distinctly different from each other and from local groundwaters, supporting the concept that the reservoirs are isolated from each other and from local groundwaters. The major and minor element concentration ratios were interpreted by Popielak et al. to indicate that the brines originated from ancient seawater. Based on the geochemical and hydrological information, DOE believes the brine in the Castile reservoirs has not mixed to any significant extent with other waters and has not circulated within the Castile. Further, the brines are nearly saturated with halite and have little potential to dissolve additional halite.

The WIPP performance assessment requires information on the hydrologic characteristics and likelihood of encounter for a brine reservoir beneath the waste disposal area. Many of the characteristics of the reservoir penetrated by WIPP-12 have been used as a basis for modeling the hypothetical reservoir underlying the waste. The WIPP-12 reservoir is the best characterized, it is relatively large and permeable, and it is the closest identified reservoir to the site. Relatively little gas has been found in the Castile reservoirs and the analyses of WIPP-12 have only considered single-phase brine flow.

The parameters needed to determine the hydrologic characteristics of the hypothetical reservoir beneath WIPP are described in several supporting documents. Reservoir pressure is described in Freeze and Larson (1996) as a distributed parameter with an expected value (12.7 MPa) equal to the estimated pressure of the WIPP-12 reservoir, and a range (11.1 to 17.0 MPa) based on pressures in other reservoirs encountered in the Delaware Basin. Reservoir porosity is described in Freeze (1996a) as a distributed parameter with a mean value (0.009) determined from laboratory measurements of intact anhydrite core from ERDA-6 and WIPP-12. Although the porosity values have not been finalized, they are currently proposed to be treated as a distributed parameter with a range of 0.001 to 0.02. Average fracture porosity in the WIPP-12 reservoir is estimated by Popielak et al. (1983, pp. G-44 to G-48) to range from 0.004 to 0.011, and is similar in magnitude to the intact rock porosity. A fracture porosity of 0.008 was used by DOE in estimating reservoir pore volume.

Bulk rock compressibility is described in Freeze (1996c) as a distributed parameter with a mean of 1×10^{-10} Pa^{-1} and a range of 5×10^{-12} Pa^{-1} to 1×10^{-8} Pa^{-1}. These values were determined as a best estimate considering compressibilities for intact anhydrite computed from elastic theory, compressibilities determined from the results of borehole hydrologic tests in disturbed Salado halites, and literature values for the compressibility range typically associated with fractured rock.

Reservoir permeability is described in Freeze (1996b) as a distributed parameter with an expected value of 1.6×10^{-12} m^2 and a range of 2.0×10^{-15} m^2 to 1.6×10^{-10} m^2. The expected value was derived from a GTFM analysis of Flow Test 3 in WIPP-12 (Reeves et al. 1991, Appendix A). This was a long-term test and the results best represent the average permeability across the volume of the reservoir. Permeability and rock compressibility are strongly coupled in hydrologic test analysis. In a low-porosity medium, their product should be maintained approximately constant for accurately simulating flow from a specific source; however, their ratio should be maintained approximately constant for accurately simulating pressure fluctuations. The most accurate characterization of these parameters is considered to be that which best matches both pressure and flow fluctuations. Because the expected value of rock compressibility used in the GTFM analysis of 1×10^{-9} Pa^{-1} was decreased in the performance assessment to 1×10^{-10} Pa^{-1}, the expected value of permeability used in performance assessment was increased from

1.6×10^{-13} m^2, determined in the GTFM analysis, to 1.6×10^{-12} m^2 to maintain good estimates of fluid flow. The low end of the range of permeabilities was based on the lowest value obtained in flow tests in ERDA-6, and the high end was based on the near-field high permeability zone encountered in WIPP-12.

The pore volume of the WIPP-12 reservoir was estimated using rock compressibility and porosity data and pressure changes measured in response to reservoir flow. The uncertainty in the volume estimate is largely derived from the uncertainty in rock compressibility. Estimates of the WIPP-12 reservoir pore volume are presented by Larson and Freeze (1996) as ranging from 32,000 m^3 to 64,000,000 m^3. This estimate is based on the nearly four order of magnitude range in compressibility used in performance assessment, and an estimated anhydrite reservoir fracture porosity of 0.008. A WIPP-12 reservoir pore volume of 3,200,000 m^3 was estimated for the expected compressibility of 1×10^{-10} Pa^{-1}.

The pore volume of a potential brine reservoir beneath the WIPP disposal panels was estimated by Larson and Freeze (1996) to range from 32,000 m^3 to 160,000 m^3. The lower end of this range was based on the minimum pore volume estimated for the WIPP-12 reservoir. The upper end of this range was based on the size of a reservoir that would extend beyond the perimeter of the WIPP disposal area. Assuming that the anhydrite layer containing the WIPP-12 reservoir is from 7 m to 24 m thick (Reeves et al. 1991, p. 2-10) and is analogous to the hypothetical reservoir beneath the site, the radius of a circular reservoir with a pore volume of 160,000 m^3 would range from about 510 m to 950 m. Larger reservoirs would likely extend beyond the limits of the waste panels, which have a perimeter of about 600 m by 800 m. Based on regulatory guidance, DOE assumes that the waste panels are partially protected from drilling by active and passive institutional controls for 700 years after repository closure. The larger reservoirs would underlie areas that are not protected by such controls and are assumed to be partially depleted by exploratory drilling penetrations before drilling over the waste would occur. In view of this depletion, the larger reservoirs are not considered in performance assessment because a smaller, undepleted reservoir is considered by DOE to be more significant to performance assessment than a larger, partially depleted reservoir.

Exploration boreholes are assumed to occur both in the waste itself and in the surrounding waste panel walls and room pillars. The probability that a borehole will encounter pressurized Castile brine beneath the WIPP disposal area is tentatively assumed in the WIPP performance assessment to be 10%. This probability is primarily based on a geostatistical analysis of the spatial distribution of known Castile brine reservoirs in the Delaware Basin and on the assumption that because of the primarily vertical orientation of known fractures in the Castile anhydrites, the potential exists that a vertical borehole could penetrate the area of a reservoir without intersecting conductive fractures and, therefore, without encountering significant brine flow. A discussion of the development of this probability is presented in the 23 May 1996 Draft CCA, Section 6.4.12.6, Probability of Intersecting a Brine Reservoir (DOE 1996, pp. 6-109 to 6-110).

Boreholes randomly selected to penetrate the waste panel area and encounter pressurized brine in the Castile are assumed to contribute to the depressurization of that reservoir. Depressurization is currently assumed by DOE to occur to the extent that the reservoir no longer affects the repository after two penetrations for the smallest reservoir size (32,000 m^3), ranging up to ten penetrations for the largest reservoir size (160,000 m^3). Boreholes penetrating the walls and pillars of the waste panel area are assumed to result in no waste release, but will contribute to reservoir depressurization if they are randomly determined to encounter pressurized brine.

Numerical simulations of short-term and long-term flow from a Castile brine reservoir into the repository, to units overlying the Salado, and to the ground surface are handled by the BRAGFLO-DBR and BRAGFLO codes for single or multiple intrusion scenarios. These codes have the capability to model two-phase brine and gas flow, and it is anticipated that this capability will be applied to Castile brine reservoirs. Short-term flow is addressed in the Direct Brine Release conceptual model, and long-term flow is addressed in the Exploration Borehole and Multiple Intrusions models.

3.16.2. Review of Criteria

3.16.2.1. Information Used to Develop the Conceptual Model

The Castile Formation and Brine Reservoir conceptual model draws heavily on the properties of the WIPP-12 brine reservoir in developing characteristics for the hypothetical reservoir that could be encountered beneath the WIPP waste panels. Information is also taken from other brine reservoirs within the Delaware Basin, with emphasis on the ERDA-6 reservoir. Details on the sources and use of this information are presented in Section 3.16.1. Use of Delaware Basin reservoir information and emphasis on the WIPP-12 and ERDA-6 reservoirs are appropriate because of the increased relevance of local information and the relative wealth and accuracy of data from the two specific sources.

3.16.2.2. Validity of Model Assumptions

The principal assumptions used to develop the model are identified in Section 3.16.1 and critically reviewed here. Most assumptions are reasonable and appropriate and include the conceptual hydrologic role of the Castile Formation (exclusive of the brine reservoirs), consideration of the WIPP-12 reservoir as analogous to the hypothetical reservoir beneath the WIPP disposal area, the concept of a brine reservoir as a heterogeneous, discontinuously fractured zone of limited extent within Castile anhydrites, two-phase treatment of reservoir flow, and the selected values for reservoir pressure and porosity.

Bulk rock compressibility data were developed from a variety of sources including elastic modulus values, disturbed Salado surrogates, and literature values. Although the high end of the range (1×10^{-8} Pa^{-1}) is considered appropriate, the low end of the range (5×10^{-12} Pa^{-1}) and the mean value (1×10^{-10} Pa^{-1}) may be unrealistically low. The mean and maximum permeability values used in the performance assessment were adjusted upward by an order of magnitude from the original GTFM analysis of WIPP-12 to compensate for an order of magnitude downward adjustment in the original value of rock compressibility. The result of these adjustments is to decrease the storage capacity, increase the permeability, and increase the maximum size of the potential reservoir underlying the site. The estimated minimum size of the WIPP-12 reservoir directly supports the performance assessment and remains unaffected by the decrease in the mean compressibility. Although the assumption of a lower mean compressibility for the brine reservoir is not fully supported, the effects of this assumption appear to be conservative and therefore acceptable.

The assumption that reservoirs with pore volumes greater than 160,000 m^3 can be ignored is not adequately supported. Although sufficiently large reservoirs would extend beyond the area assumed to be protected by institutional controls for 700 years after closure, and could be intersected and partially depressurized by exploratory boreholes before boreholes are drilled over the waste panels, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumption that reservoirs will be depleted by two to ten penetrations by exploration boreholes is also not adequately supported. Although the concept of depletion is rational, no supporting studies of the effects of this scenario have been presented to the Panel.

The assumed 10% probability of encountering pressurized Castile brine in an exploratory borehole is based on a geostatistical analysis of reported brine encounters, consideration of the relationship of brine reservoirs to geological features or processes, and on the assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine. The adequacy of the assumption that significant brine releases are routinely documented was checked with Paul Knautz, a geologist with the New Mexico Oil Conservation Division in Hobbs (telephone 505-393-6161). Mr. Knautz indicated his confidence that the reporting requirements for significant releases were met by the operators. He stated that when encountered with a brine reservoir, the operator must report brine volume and pressure by telephone, and must truck the brine to a proper disposal facility.

Although no documentation of the geostatistical analysis was available for Panel review, preliminary results were verbally presented by DOE. The value of the results of this analysis was seriously weakened by a lack of data in the vicinity of the WIPP. The validity of the spatial correlations relied on the assumption that the geologic conditions supporting reservoir development at the WIPP site were similar to those in areas where hydrocarbon exploration boreholes were numerous and where a number of brine reservoirs were encountered. Unfortunately, there is little direct evidence to support or refute this assumption, but regional trends support the hypothesis that the probability of encountering brine decreases to the west. The kriging results on which the estimate of probability of encounter would be based were sensitive to historic brine encounters. The single encounter near WIPP (at WIPP-12) changed the probability over the waste panels from near zero to about 8%. A second encounter could have an equally dramatic effect. Due to the lack of data and the consequent sensitivity of the estimated probability, little credibility can be assigned to either value.

The assumption that not all boreholes penetrating through the area of a reservoir will necessarily encounter brine is reasonable, given that fractures in the anhydrite reservoir rock appear to be predominantly sub-vertical. However, this assumption must be quantified to be of more than conceptual value to performance assessment, and no basis for such quantification, nor of the way in which this concept has been used in developing the final probability value, has been presented to the Panel.

The approach for estimating the probability of a brine encounter apparently does not quantitatively consider the TDEM geophysical results reported in Earth Technology Corporation 1988, which suggest the presence of brine pockets beneath the waste panels and provide an alternative, site-specific approach for estimating the probability of encounter. In considering the reported uncertainty of ±75 m in estimated depth from the geophysical results (Earth Technology Corporation 1988), Borns (1996) estimated the proportion of waste panel area underlain by a potential brine reservoir to range from 10% to 55%, with an expected value of 25%. A similar study performed on an alternative contouring of the original TDEM data for the 1992 WIPP preliminary performance assessment (WIPP Performance Assessment Department 1992b) identified a maximum proportion of 40%. Although these values may be reduced by evidence that a borehole penetrating the area of a reservoir may not actually encounter pressurized brine, or discarded based on evidence that the geophysical results are quantitatively unreliable, such evidence has not been presented to the Panel.

3.16.2.3. Evaluation of Alternatives

Although the fundamental hydrological behavior of the Castile Formation and its brine reservoirs is conceptually sound, concerns have been identified in Section 3.16.2.2 regarding the manner in which the encounter of pressurized brine is handled in performance assessment. Three fundamental issues are identified for which alternatives may be considered. These are alternative limits on the maximum reservoir volume, alternative concepts for reservoir depletion, and alternative probabilities of encountering pressurized brine.

3.16.2.4. Uncertainties

Uncertainty in model results stems from uncertainties in the validity of the underlying theory and from uncertainties in the input data. Although the underlying theory is widely used in the petroleum industry for evaluating oil and gas reservoirs and provides the best currently available approach, the results must be considered approximate, as illustrated by the high degree of uncertainty in the results presented, for example, by Popielak et al. (1983) and Spiegler (1982). Uncertainties associated with specific input parameters and assumptions are more tractable to address, and the key uncertainties are associated with the three principle issues identified in Section 3.16.2.3. Uncertainty in the two-phase flow parameters used in the analysis cannot be addressed because the values of these parameters had not been selected at the time of this review (see CCA Table 6-yz, draft of 5/23/96).

The uncertainty associated with rock compressibility is approximately one order of magnitude. Although this parameter is coupled with permeability, as previously discussed, the uncertainty in permeability is approximately two orders of magnitude. Uncertainties in compressibility propagate through the calculations and affect the estimates of both the permeability of the hypothetical reservoir at the site and the volume of the WIPP-12 reservoir. Because the uncertainty in permeability is even greater than the uncertainty in compressibility, the consequences of the uncertainty in compressibility may not be significant to the overall performance assessment. Uncertainty in permeability may have a greater consequence in overestimating or underestimating flow rates from the reservoir if flow rates are controlled by the reservoir rather than by the borehole dimensions or plugging materials. High degrees of uncertainty in the related parameters of compressibility, permeability, and reservoir volume are not readily avoidable and stem from the wide range of values these parameters can have and from limitations in the state-of-the-art in measuring them.

The consequences of assuming a relatively small maximum size for a hypothetical brine reservoir beneath the site are not known because modeling results are not available, but could result in underestimating the volume of brine that could potentially be released. Alternatively, the modeling results may show that the volume of brine released during the 44-hour flow period assumed by DOE is relatively insensitive to reservoir volume if the reservoir volume is significantly greater than the volume of brine released from the reservoir. In this event, larger reservoir sizes may have little effect on performance assessment.

An unrealistically low probability of encountering pressurized brine could lead to underestimating radionuclide releases resulting from flow from Castile brine reservoirs. The consequences of underestimating this probability would be identified in modeling results, which were not available for review by the Panel.

The consequences of overestimating reservoir depletions by boreholes that do not penetrate a waste panel would be to underestimate reservoir and repository releases by boreholes that do penetrate a waste panel. The issue of reservoir depletions is tied to reservoir volumes, compressibility values, reservoir sizes, and the probability of encounter. Changes in any of these parameters would require modifications throughout the conceptual model.

3.16.2.5. Adequacy of the Conceptual Model

The hydrologic aspects of the conceptual model for the Castile Formation and Brine Reservoirs are fundamentally sound, and the issues raised in the validity of model assumptions (Section 3.16.2.2) are associated with the details of its application. With appropriate resolution of the issues raised in this report, the adequacy of the current model would be acceptable.

3.16.2.6. Adequacy of Application

The internal consistency of the conceptual model is adequate, based on the interdependence of expected or mean values of the parameters as described in Section 3.16.2.1. Although consideration could be given to correlating values during statistical sampling, such as permeability with compressibility, the uncertainties in these values is such that it would be difficult to judge whether any combination were totally unreasonable. The correlation of porosity and reservoir volume in BRAGFLO is considered to be an artifact of the fixed model cell volume and not a true parametric correlation based on conceptual model principles. The integration of the conceptual model with the BRAGFLO and BRAGFLO-DBR codes is addressed under the Exploration Borehole (Section 3.12), Multiple Intrusion (Section 3.17), and Direct Brine Release (Section 3.15) conceptual models.

3.16.2.7. Accuracy of Results

The data base calculations were spot-checked and found to be accurate. The parameter values were also checked against values estimated by other investigators (Popielak et al. 1983; Spiegler 1982; Reeves et al. 1991) and found to be acceptable, given the ranges of uncertainties in the input parameters. The accuracy of integration with the BRAGFLO and BRAGFLO-DBR codes is discussed in Sections 3.12, 3.17, and 3.15.

3.16.2.8. Validity of Conclusions

The validity of the conceptual model is uncertain, pending resolution of the issues raised in Section 3.16.2.3. In summary, the following key assumptions have not been adequately supported in information provided to the Panel, nor do sensitivity studies appear to have been made.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

3.16.2.9. Adequacy for Implementation

The Castile Formation and Brine Reservoir conceptual model is not currently adequate for implementation because of the validity issues raised in Section 3.16.2.8. The conceptual model would be considered adequate for implementation if the validity issues were successfully resolved.

3.16.2.10. Dissenting Views

There were no dissenting views for this model.

3.17. Multiple Intrusions

3.17.1. Model Description

The Multiple Intrusion conceptual model is an extension of the Exploration Borehole model that describes fluid flow between the repository and multiple exploratory boreholes penetrating a single waste panel. The borehole drilling methods and frequencies, borehole plugging, and plug degradation discussed in the Exploration Borehole model in Section 3.12 are the same for multiple intrusion boreholes. Short-term flow through unsealed boreholes is addressed in the Direct Brine Release conceptual model in Section 3.15. Other related conceptual models include Repository Fluid Flow, Castile Formation and Brine Reservoirs, Cuttings/Cavings, Spallings, and Actinide Transport in the Salado. The details of this model were still under development at the time of the peer review, and information describing the model was obtained from a variety of final and draft reports and memoranda, and from verbal descriptions provided by DOE. The following model description was prepared from information presented in the 23 May 1996 Draft CCA, Sections 6.4.13.6 and 6.4.13.7 (DOE 1996, pp. 6-119 to 6-121), from verbal descriptions, and from the cited references.

The proscriptive requirements of 40 CFR 194 for exploration boreholes also apply to multiple intrusion boreholes. The focal point of the Multiple Intrusion model is the E1-E2 scenario (worst case), wherein more than one exploration borehole penetrates a waste panel and at least one of those boreholes also encounters pressurized brine in the underlying Castile Formation. However, the Multiple Intrusion model also addresses multiple intrusions by other combinations of boreholes.

Multiple intrusions are modeled by the same two-dimensional version of the BRAGFLO code used to model repository fluid flow and single borehole intrusions. Use of this model is supported by preliminary analysis of modeling results, indicating that liquid flow through the panel closure seal between the isolated, single waste panel in the model and the "rest of the repository" is slow enough that each waste panel is effectively independent from the rest of the repository. Thus, for a multiple intrusion to occur, two or more boreholes must penetrate the same waste panel. Gas flow does occur between panels, and for this reason short-term releases are calculated separately. However, for long-term brine flow from a single waste panel, the BRAGFLO model is considered adequate. Because the panels behave independently, different configurations of boreholes may occur in different panels. The model computes releases from these configurations separately and adds them to estimate a total cumulative release.

To accommodate the limitation in the BRAGFLO model of being configured to represent only one borehole column, the boreholes are assumed to be drilled in a series of specific sequences, with shifts in material properties in the upper and lower parts of the single modeled borehole at specific times. Background information on the development and use of reference conditions and on borehole plug degradation assumptions is presented in Section 3.12. Because 90% of all deep boreholes are assumed by DOE to be of the E2 type (DOE 1996, p. 6-119), it is most probable that the first borehole to penetrate a waste panel will be of this type. The approach taken by DOE in analyzing multiple intrusions has therefore been built around this E2-E1 scenario, which occurs under the following assumptions.

The first borehole is assumed to be an E2 type that penetrates the waste panel 800 years after closure. At 1,000 years after closure the upper seal in this borehole fails and the borehole is filled with a material that has the properties of silty sand. At 2,000 years an E1 borehole penetrates a waste panel and encounters pressurized brine in the Castile. This borehole is assumed to be sealed with the two-plug configuration, the only configuration considered in performance assessment that allows flow to occur between a Castile brine reservoir and the waste panel (Section 3.12). At 2,000 years the properties of the modeled borehole column below the repository are changed to represent an open borehole, while the properties of the borehole column above the repository are unchanged and continue to represent the long-term properties of the earlier E2 borehole for the duration of the modeling. At 2,200 years the upper plug in the E1 borehole fails and the properties of the borehole below the repository are changed to those of silty sand. At 3,200 years the permeability of the borehole below the repository is reduced by one order of magnitude to represent the effects of pore volume reduction due to creep closure. No further changes in material properties occur for the duration of the modeling.

The aforementioned series of assumptions is valid given DOE's plug degradation assumptions, with the exception that after 2,200 years the upper plugs in both the E2 and E1 boreholes have failed and two pathways, rather than one, are available for brine migration to the Culebra. The assumption that only one of these two pathways conducts flow in this scenario is considered by DOE to be consistent with the assumption of complete mixing of brines within the waste panel, which requires that flow from the brine reservoir in the E1 borehole pass through the waste panel and exit through the E2 borehole, rather than through the upper part of the E1 borehole. However, multiple borehole pathways to the Culebra are included in scenarios involving multiple E1 boreholes because flow through the repository and consequent mixing can then occur among multiple boreholes.

The foregoing scenario of an E2, followed by an E1, establishes the basis for determining a standard reference cumulative radionuclide release to the Culebra, assuming an E2 borehole drilled at 800 years is followed by an E1 borehole drilled at 2,000 years. In this drilling sequence the rate of release jumps dramatically at 2,000 years because of pressurized brine flowing from the Castile reservoir. In an actual scenario the randomly selected drilling dates for these two boreholes are likely to be different. In that event, the cumulative release is calculated using the release rate from a single E2 borehole (Section 3.12) up to the date of the E1 penetration, and then applying the reference release rate starting at the time of E1 penetration in the standard E2-E1 scenario to approximate the jump in release rate that would occur at the actual date that the E1 borehole is drilled. In this approach, the brine fluxes after penetration by an E1 borehole are those occurring at the 2,000 year date of penetration assumed in the standard E2-E1 scenario, rather than the fluxes that would have been modeled at the actual date of penetration; however, the radionuclide releases associated with those fluxes are corrected for radionuclide decay and progeny production.

If the first two boreholes are randomly selected to penetrate the waste panel in a different sequence, the following rules for determining reference conditions for long-term flow are applied.

Radionuclide transport is modeled by the NUTS code for single borehole intrusions and by the PANEL code for multiple intrusions (Section 3.8). While the NUTS code is directly coupled to BRAGFLO and uses BRAGFLO's computed velocity field vectors, PANEL is a separate model that conservatively assumes complete mixing in the waste panel. PANEL is used when two or more boreholes penetrate a panel and at least one of those boreholes is an E1 type. In applying the PANEL code, the multiple intrusions are implicitly assumed to occur in different parts of the waste panel so that cross borehole flow and mixing will occur. The PANEL code is used for transport calculations in the standard E2-E1 scenario, and use of that scenario for multiple borehole intrusions is conservative.

Table 3.17.1. Rules for Determining Reference Conditions for Long-Term Flow

Sequence of First Two Boreholes	Basis for Brine Flux	Basis for Radionuclide Transport
E2 followed by E1	Single E2 flux followed by E2-E1 flux at time of E1 penetration	Single E2 transport followed by E2-E1 transport at time of E1 penetration
E1 followed by E2	Single E1 flux followed by E2-E1 flux at time of E2 penetration	Single E1 transport followed by E2-E1 transport at time of E2 penetration
E1 followed by E1	Single E1 flux plus E2-E1 flux at time of second E1 penetration	Single E1 transport plus E2-E1 transport at time of second E1 penetration
E2 followed by E2	Single E2 flux	Single E2 transport

The first two borehole sequences in the foregoing tabulation (E2 followed by E1 and E1 followed by E2) both assume sequential calculation of flux and transport by jumping from single borehole behavior to E2-E1 behavior at the time of the second penetration. The sequence of two E1s, however, is treated by adding the E2-E1 flux and transport to the single E1 flux and transport, beginning at the time of the second E1 penetration, because flow from two brine reservoir penetrations can circulate and mix within the repository and leave through two boreholes to the Culebra. As previously mentioned, in cases where there is only a single E1 penetration, the brine is considered by DOE to be more likely to circulate within the repository, adequately mix, and then leave only through the E2 borehole to the Culebra. In cases of two E2 penetrations, long-term brine release volume is assumed to be the same as for a single E2 penetration because flow will be controlled by the rate at which brine can be supplied by the Salado halites, rather than the rate at which brine can flow in the borehole. In cases where at least one of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, additional E2-E1 flux and transport values are added to the cumulative release. In cases where none of the boreholes previously penetrating the panel is an E1 and an additional E1 is added, the flux and transport sequentially shift to the E2-E1 values. However, if only E2 boreholes are present, additional E2 boreholes do not increase the flux and transport rates. In all cases, adjustments are made for radioactive decay and progeny generation to account for the times of waste panel penetration in the cumulative releases.

3.17.2. Review of Criteria

3.17.2.1. Information Used to Develop the Conceptual Model

The information used to develop the Multiple Intrusion model is essentially the same as that used to develop the Exploration Borehole and Repository Fluid Flow models. The Multiple Intrusion conceptual model becomes active at the time that two or more boreholes are randomly selected to penetrate a single waste panel. Alternative reference conditions, repository mixing, and transport models are employed for the Multiple Intrusion model, as described in Section 3.17.1. The information used to develop the conceptual model is reasonable and appropriate.

3.17.2.2. Validity of Model Assumptions

The principal assumptions used to develop the Multiple Intrusion model are identified in Section 3.17.1 and are critically reviewed here. Assumptions related to borehole drilling methods and frequencies, borehole plugging, and plug degradation are the same as those reviewed for the Exploration Borehole model in Section 3.12. The principal assumptions specific to the Multiple Intrusion model are reasonable and appropriate for performance assessment applications and include use of the two-dimensional BRAGFLO model for this application, the somewhat gymnastic but conservative assumptions made to accommodate the single borehole column in the model, and the mixing assumptions in the model.

The assumption that only a single borehole conducts brine to the Culebra in an E2-E1 scenario is troublesome; however, the potentially nonconservative nature of this assumption is compensated by the highly conservative assumption of complete mixing of Castile brine with waste panel brine. In reality, the Castile brine would flow through the waste panel to the exit borehole by preferentially following high conductivity flowpaths with relatively little volume compared with the waste panel pore volume, and consequently with relatively little mixing. Even less mixing would occur in brine flowing from the E1 in the bottom of the waste panel and out the same E1 through the top of the waste panel.

The use of reference conditions, rather than direct model results, as the final input has been handled in a relatively conservative manner. The appropriateness of assuming that the flux associated with the E1 penetration at 2,000 years in the standard E2-E1 reference case is representative of the flux into an E1 penetration at other times has not yet been directly supported by sensitivity studies using current performance assessment calculations, but by analogy to the results of such studies performed for the

1991 draft performance assessment, such an assumption is expected to be appropriately conservative (Helton et al. 1992, Chapter 4).

3.17.2.3. Evaluation of Alternatives

The approach taken to address multiple intrusions in performance assessment is reasonable and appropriate considering the complexity of addressing the many possible scenarios in an efficient manner. Further investigation into the approaches taken have indicated that they are adequate and that no alternative approaches are required. However, the validity of the current approach is based on acceptance of DOE's assumptions regarding borehole plug degradation rates. These assumptions were questioned in Section 3.12, and if those assumptions are changed, many of the basic assumptions used in the Multiple Intrusions model should also be changed. For example, if plug degradation allows fluid to flow into the waste panel from the Bell Canyon Formation through an E2 borehole, the significance of the E2 borehole in performance assessment will become more like that of an E1.

3.17.2.4. Uncertainties

The principal uncertainties in model results stem from the same types of issues that were raised for the Exploration Borehole model and are addressed in Section 3.12.2.4. No additional significant uncertainties have been identified that are specific to the Multiple Intrusions model.

3.17.2.5. Adequacy of the Conceptual Model

The conceptual model for multiple intrusions is fundamentally sound and appropriately conservative, given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.6. Adequacy of Application

The application of the conceptual model to the numerical model is adequate, again given the simplifications that are required to model a complex set of conditions in an efficient manner.

3.17.2.7. Accuracy of Results

Individual parameter values supporting the conceptual model were checked and found to be reasonable. The modeling results were not available for review and could not be checked.

3.17.2.8. Validity of Conclusions

The validity of the conceptual model is expected to be adequate for performance assessment; however, modeling results have not been observed by the Panel and have not been checked through sensitivity studies similar to those used in previous performance assessments. Many of the modeling assumptions were based on borehole plug degradation assumptions whose validity was questioned in Section 3.12. If those assumptions are changed, many of the basic assumptions used in the Multiple Intrusion model would be questioned.

3.17.2.9. Adequacy for Implementation

The Multiple Intrusion conceptual model is adequate for implementation in performance assessment. However, the results of the model have not been checked by the Panel because sensitivity studies similar to those used in previous performance assessments have not yet been performed.

3.17.2.10. Dissenting Views

There were no dissenting views for this model.

3.18. Climate Change

3.18.1. Model Description

The long periods of time over which the isolation of radioactive waste must be considered stimulates concern over climatic cycles and occurrences that may impact the long-term performance of the disposal system. The Climate Change conceptual model provides quantitative consideration about the degree to which future climates may contribute to the uncertainty of estimates of potential radionuclide releases from the WIPP repository. The model does not attempt to predict or simulate a future climate, but intends to implement climate change effects into the performance assessment through a parameter named the Climate Index.

The formulation of the conceptual model for climate change (Climate Index) began with the screening out of the direct effects of climate change that do not involve groundwater. Factors such as wind patterns and thermal effects do not impact the WIPP due to its depth below the ground surface. Additional aspects of climate change were eliminated through the FEP screening process and the conceptualization of climate change impacts focused on reasonably foreseeable events and the effects of these events on groundwater flow.

A three-dimensional regional groundwater basin model (Corbet and Wallace 1993) was employed to assist in characterizing the natural hydrogeologic processes as they could occur over geologically significant periods of time in the Delaware Basin. The model was bounded on the bottom by "impermeable" rock, on the top by the ground surface, and on the sides by groundwater divides. The upper boundary of the flow domain is the water table and differences in the elevation of the water table across the basin are assumed to be the driving force for groundwater flow. Other notable but standard assumptions are stratigraphic homogeneity and ignoring the unsaturated zone with respect to timing of infiltration (dry to wet periods). The results suggest that flow in the Culebra Dolomite Member of the Rustler Formation is strongly influenced by the water table elevation and the infiltration (recharge) rates associated with that elevation. Infiltration was varied as a step-function of average amounts of moisture reaching the water table. The model results indicated that changes in infiltration rates of tenths of a millimeter per year had significant impacts on flows in the Culebra. The basin modeling and later analyses (Corbet 1996b) approximated recharge rates that maintained the water table at or near the ground surface (maximum recharge situation) and the relationships between the various recharge rates and lateral-flow ratios. The assigned distributions of lateral-flow ratios became the Climate Index. The Climate Index is therefore a factor by which the lateral flow rate in the Culebra is uniformly increased to account for increases in recharge rates.

Two future climate or recharge patterns were evaluated: the step recharge function, with a 0.25 probability of representing the future, and the Holocene recharge function, with a 0.75 probability of occurring. The step recharge function (similar concept to Corbet and Wallace 1993), which represents a steady increase in heads and recharge rates into the future with the lateral-flow ratio reaching its maximum in 10,000 years, is assigned Climate Index values of 1.5 to 2.25. The Holocene pattern of future recharge results in periodic increases and decreases in heads and recharge rates that are assigned Climate Index values of 1.0 to 1.25. These two Climate Index ranges are sampled during each realization of disposal system performance, with each realization representing a different approximation of future climate.

3.18.2. Review of Criteria

3.18.2.1. Information Used to Develop the Conceptual Model

An extensive reference list supports the process of formulating the conceptual model for climate change. Wood (1994) and Campbell (1995) include isotopic quantification of recharge flux, and Corbet and Wallace (1993), Knupp (1995), and Wallace (1994) address groundwater modeling and hydraulic test interpretation. Swift (1992) and Powers (1990) discuss and include additional references on sedimentology, regional geology and geologic history, long-term climate variability, and climatic records. In addition to references used in conceptualizing climatic change at the WIPP, EPA criteria and guidance (EPA 1996), FEP screening references, performance assessment documentation, and evaluation of groundwater flow models developed in support of climate change conceptual model formulation document in detail the data and information used. Documents and reports produced internally to summarize studies and present results of studies relevant to the WIPP performance assessment (e.g., SAND Reports, professional society papers, DOE-WIPP, FEP, memos) were extremely valuable as they summarized data used and explained concepts applied. The information used to develop the conceptual model for climate change is extensive, referenced, available for review, and adequate.

3.18.2.2. Validity of Model Assumptions

The conceptual model for evaluating the effects of future climate change on the long-term performance of the WIPP began with a detailed examination of a great deal of literature, evolved through an understanding of past changes and situations/conditions of future change, and is now implemented through a dimensionless index that is used to change groundwater flow velocity in the Culebra Dolomite. The relationships between climatic extremes and such parameters as temperature, wind, precipitation, evapotranspiration, and vegetation cover have been researched, and the impacts of such factors on recharge have been evaluated. Since recharge impacts groundwater flow and flow characteristics are required by EPA for a compliance application, the Climate Change conceptual model formulation focused on evaluating the effects of climate change on flow characteristics of the Culebra Dolomite and Dewey Lakes Redbeds. After screening was completed (Corbet 1995a), effects evaluations were limited to the Culebra Dolomite. An extensive list of assumptions would be required to cover all of the modeling and evaluations conducted to represent real events and related climatic factors. The conceptual model for climate change assumes to represent ranges of conditions that are not related to specific events or the interactions between climatic factors, but represent reasonable extremes of potential future climates.

In addition to assuming that the climate will change over the next 10,000 years, the conceptual model of climate change assumes that periods of maximum precipitation are also periods of maximum recharge and that during such maximum situations, recharge is sufficient to maintain the water table at the land surface. A supporting (or bounding) assumption is that recharge in the late Pleistocene was sufficient to maintain the water table at the land surface. The conceptual model assumes that the range of recharge rates (0.1 to 5.0 mm/yr) represents the appropriate range of hydrologic conditions and the Climate Index factor distributions represent these conditions appropriately. A key assumption that is not clearly within the conceptual model or its implementation concerns representing three-dimensional flow in the Rustler Formation with a two-dimensional model of the Culebra Dolomite.

To invalidate the assumption that climate change will occur would require an assumption that the climate will remain constant for 10,000 years. This invalidating assumption would be inconsistent with the scientific view of climate. The assumptions of maximum precipitation/maximum recharge and that recharge could be sufficient to maintain the water table at the land surface are defensible, but not unconditionally validated as representative of a future extreme climate. These assumptions are supported by interpretations of sedimentary records (Swift 1992), isotopic analyses (Campbell 1995 and Wood 1994), paleo-environmental records, and other evaluations that estimate the characteristics of groundwater during varying climates. The assumed range of recharge rates is supported by isotopic recharge dating and rate estimation. The support documentation for the two-dimensional assumption is FEP NS-9 (Corbet 1995b).

The Panel members conclude that the main objectives of the conceptual model for climate change at this time are to incorporate uncertainty about the effects of future climates into the performance assessment and meet EPA expectations with regard to the effects of climate change on hydrological conditions and future state assumptions. Since the range of recharge rates represents the reasonable extremes of potential future climates and the climate index carries the representation into the implementation, the assumptions are valid in terms of the usefulness of the conceptual model, as is the Climate Index.

3.18.2.3. Evaluation of Alternatives

The conceptual model for representing the effects of climate change on the WIPP is a result of an evolution of thought requiring the characterization of climatic factors and simulating their effects. While interest in the possible effects of climate change has, historically, been in terms of recharge and groundwater, early interest considered increased rates of salt dissolution, fracture filling in the Culebra and changes in groundwater flow direction. Early assessments of system performance did not consider that climate change could alter the transport of radionuclides in groundwater. Later performance assessments considered transport effects but as a function of head change. Sensitivity analyses conducted for the 1991 and 1992 preliminary performance assessments determined that cumulative radionuclide releases were not sensitive to head variation as applied, and the boundary-head approach was abandoned.

Alternative approaches to the characterization of climatic effects on groundwater and modeling groundwater flow have been considered and ruled out for conceptual and technical reasons. Alternatives to representing the factors of climate change have also been considered, ruled out during analyses, and screened out through the FEP screening process. In many cases, alternative approaches that attempted to closely relate climatic factors to hydrogeologic effects introduced additional uncertainty, and could have made the overall conceptual approach less defensible. The 1996 EPA guidance presented recommendations for the consideration of future climates in a compliance application. The guidance focuses considerations on natural processes, potential impacts to recharge, and groundwater flow, and indicates that effects on hydrogeologic conditions are expected to be analyzed and demonstrated in compliance and performance assessments. The selection of the Climate Index to implement the effects of climate change through direct scaling of groundwater velocity in the Culebra allows for the uncertainty of effects of future climates to be incorporated into the performance assessment. Multiple realizations provide for a representative range of future climate effects to be included in disposal system performance.

3.18.2.4. Uncertainties

Many obvious uncertainties accompany the interpretation of the magnitude and temporal aspects of historical climatic factors and the representation of such factors at the WIPP site 10,000 years into the future. The uncertainties are less overwhelming when climates are limited to those reasonably foreseeable, and the absolute timing of alternative climates is of less importance than the range of magnitude of the relevant climatic or climate-induced factors.

A primary objective of the Climate Change conceptual model is to incorporate uncertainty about future climates and their potential impacts on radionuclide releases from the disposal system. The conceptual model for climate change is implemented through a single parameter index that scales groundwater flow in the Culebra Dolomite. Key uncertainties concern whether or not climate will change, if index values represent the appropriate range of changes, and whether or not implementation realizations sample the index in a manner representative of the range of climate change.

The uncertainties related to whether or not climate will change and the representativeness of index values are a result of predictions, analyses that are imprecise, and conclusions about the future based only on the past. While these uncertainties remain, the conservative assumption for performance assessment is that the climate will change, including periods of both drier and wetter conditions. The only relevant uncertainty with respect to the index is whether or not reasonably foreseeable climates are represented by the range of index values. It is the intent of the index to be bounded by the wet extreme of the Pleistocene glaciation and by another climate where there is little or no climatic effect on groundwater flow. Panel members conclude that significant scientific effort has been expended to characterize the periods bounding the index value and relate relevant climatic factors to the index, and that the index is appropriately conceptualized. Uncertainty with respect to implementation of the climate change model cannot be completely addressed by panel members since a detailed analysis of the implementation models and computational scheme is not within the scope of this review. However, even though climate change preliminary calculations resulted in relatively small increases in flow rates, decreased travel times had a large impact on normalized radionuclide releases under certain conditions (calculations performed for the 1992 performance assessment) (Corbet 1995a). Based on the potentially large consequence demonstrated, climate change has been tentatively retained for inclusion in performance assessment calculations.

3.18.2.5. Adequacy of the Conceptual Model

The climate change conceptual model represents a reasonable and defensible range of potential future climate extremes for incorporation into the performance assessment. The conceptual model includes a range of conditions, bounded by reasonably foreseeable future climates and their effects, that are adequate to represent impacts to groundwater flows in the Culebra Dolomite Member of the Rustler Formation. In addition to providing adequate representation of conditions for implementation, the background research and analysis supporting the formulation of the conceptual model for climate change provides adequate information for satisfying EPA guidance.

3.18.2.6. Adequacy of Application

The conceptual model for climate change is implemented through the Climate Index. This index is a dimensionless factor through which direct scaling of specific discharge for the Culebra Dolomite is accomplished in the SECOFL2D code (Section 4.1). The range of sampled index values available for realization of disposal system performance has been verified through modeling to represent the range of recharge impacts that reasonably foreseeable future climates would create. As such, the conceptual model is implemented through an acceptable and adequate performance modeling element.

The conceptual model for climate change is compatible with the closely related model of the steady-state groundwater velocity field for the Culebra, which it directly scales through the index. The relationship is simple and should be adequate for its intended use, assuming that the implementing computational scheme operates as designed.

3.18.2.7. Accuracy of Results

Model formulation results, as well as model application/implementation results, must be reviewed in assessing the overall accuracy of results for the conceptual model for climate change. The accuracy of model formulation results is judged on how well descriptions and descriptive write-ups present the conceptual model. In the case of the climate change model, background research and analysis, history of model development, screening and verification, descriptions of model parameters, assumptions, and an implementation scheme were available. Panel members were required to consult numerous sources for a comprehensive description of the conceptual model but, overall, the model formulation results were judged accurate.

As discussed in Section 3.18.2.6, the application or implementation of the conceptual model for climate change is conducted with the Climate Index. This dimensionless factor is sampled over its distribution and represented by direct scaling of the steady-state groundwater velocity field in SECOFL2D for the Culebra Dolomite. For performance assessment realizations of disposal system performance, each realization represents the effect of a different climate. The model is judged as capable of producing accurate results through implementation if realizations of disposal system performance adequately represent the range of future climates available within the distribution of the index.

While the scope of this conceptual model review did not include verification of realization computations, a single CCDF calculated to address FEP NS-8b had interesting results. The FEP NS-8b, summary memo of record (SMOR) of 21 September 1995, stated that on the basis of relatively small increases in flow rates expected from including climate change in the performance assessment modeling system, and the associated low consequence of omitting the factor, climate change could be screened out. The SMOR also presented that a single CCDF calculated to address the FEP illustrated that screening out climate change would not be of low consequence. The CCDF illustrated that velocity fields that decreased travel times (increased flow rates) by a factor of 2 resulted in three orders of magnitude increases in releases for release probabilities less than 0.1. The reason for the large impact was not clear, but this quantitative evaluation of the climate change subsystem resulted in the retention of climate change for inclusion in future performance assessment calculations. While the quantitative subsystem evaluation did not prove the accuracy of implementation of the conceptual model, it is indicative and supportive of performance assessment sensitivity.

3.18.2.8. Validity of Conclusions

The results of the implementation of the conceptual model for climate change are the representation of the effects of a reasonably foreseeable range of future climates within realizations of disposal system performance. While Panel members found no documentation of the results of the application of the Climate Index in disposal system-scale performance assessment calculations or conclusions drawn, the FEP screening process (Corbet 1995a) SMOR addressed a quantitative analysis. The SMOR, discussed in Section 3.18.2.7, presents that the results of the quantitative evaluation stimulated the conclusion to retain climate change for inclusion in future performance assessment calculations.

The evaluation presented in the SMOR could not support conclusions to the degree possible from results of disposal system-scale performance assessment calculations and sensitivity analyses. In the absence of results from repository/disposal system-scale realizations and sensitivity analyses, no definitive, valid conclusions can be made. However, the evaluation at the subsystem level did support conceptual model sensitivity and uncertainty assessment and a valid conclusion was drawn on the basis of results of the evaluation.

3.18.2.9. Adequacy for Implementation

The conceptual model for climate change, as discussed in Sections 3.18.2.1 through 3.18.2.8 and defined for implementation by the Climate Index, is adequate for implementation. The Climate Index is capable of representing uncertainty about future climates and their potential impacts on disposal system performance. While the conceptual model has been judged adequate for implementation, the mathematical representations in the computer code have not been reviewed and no conclusions can be made as to the overall adequacy of the applications/implementations.

3.18.2.10. Dissenting Views

There are no dissenting views for this model.

3.19. Creep Closure

3.19.1. Model Description

The Creep Closure model is part of a complex of submodels that are combined to effect the porosity surface lookup table. This table combines gas pressure, room closure, and waste compaction to pre-calculate repository void space for inclusion in several other performance assessment models. The Creep Closure model is reviewed here and other aspects of the porosity surface are discussed in support of that review. The Creep Closure model has a complex history of development, which extends into the period of review. The generic creep model impacts both the room closure and the development of the DRZ surrounding the repository openings. The DRZ models are discussed elsewhere.

Closure of the repository occurs naturally in the Salado halite as a response to the imbalance of forces created by excavation of the repository rooms and passages. Weak and plastic rock salt begins immediately to flow into the excavated spaces by processes dominated by creep. The rate of closure is the combined result of creep rates inherent to salt, repository temperatures and pressures, and resistance provided by repository contents. The creep rate proceeds to the limits determined by resistance from gas, brine, waste, backfill, or other contents in the repository until the void space is closed to the final porosity dictated by waste and seal material properties, contained fluid pressure, and lithostatic pressure. Roof fall in the disposal rooms, which may have significant impact on flow at least in the short term, is not included in the model.

Both brine and gas content of the repository vary with time. Brine inflow/outflow is partly controlled by gas pressures. The relationship between gas outflow rates and gas generation rates influences pressures within the repository. Gas pressure results from the alteration of waste by biogenic and corrosion-based processes. The rate of the corrosion process is dependent on brine availability. Repository gas and brine pressures are limited by the minimum pressures at which gas or brine would be forced out of the repository via identified flowpaths through fractured interbeds within the Salado. The threshold pressures for initiation of outflow through these fractured anhydrite interbeds are therefore a key consideration in limiting resistance to closure due to gas and brine pressures. The fractures in the interbeds are essentially horizontal, so the pressures necessary to open the fractures or to initiate new fractures must be greater than the lithostatic load. Further, some resistance to gas release may result from travel through the fractured, rock-bolted halite between the repository and the interbeds. Resistance to gas outflow due to stress cage effects at the repository boundary and gas pressures necessary to maintain very extensive fractures may result in repository pressures larger than interbed threshold pressures. Gas pressures, which are some amount greater than the lithostatic pressure, are therefore possible at some times during the repository gas generation history. Internal gas pressures greater than the stress imbalance that drives creep inflow are conceivable. Internal pressures may contravene stresses in the salt and repository closure may cease, or repository inflation may occur in some scenarios. The stoichiometric treatment of time histories of gas generation and the volumetric model based on creep closure rates and waste compaction are combined in the SANTOS computer code to provide repository void volume estimates through time as part of lookup tables called the "porosity surface."

In the present WIPP performance assessment calculations (using BRAGFLO), the details of the mechanics of disposal room closure and/or eventual expansion are not explicitly calculated. Instead, the room-rock system behavior is obtained from the porosity surface. In this table, the three dimensions are time, total room porosity, and mass of gas in the room. The porosity surface is itself calculated prior to the BRAGFLO runs using the SANTOS code. This procedure is followed to avoid the massive computational effort that would be required to fully calculate (in an iterative sense) the mechanics of room closure for each performance assessment realization. At first, this may seem to be an invalid decoupling of the external environment and the disposal room. However, if the room porosity can be shown to be described with sufficient accuracy as a variable dependent only on time and gas mass (which is itself dependent only on time in the current model), then this approach is quite justified in view of its simplicity and efficiency. Note that brine content of the room is not mentioned at this point, nor are there any brine parameters on the porosity surface parameter list. This is a consequence of the calculation method and interaction with BRAGFLO, and is discussed below.

The porosity surface calculations using SANTOS are described by Stone (1996). The main features of these plane-strain calculations are a simplified stratigraphic model with boundaries at 50 m from the disposal room, the inclusion of the main clean halite and argillaceous halite layers, and the inclusion of the two anhydrite layers of influence (MB 139 below and anhydrite a above), but no clay seams. The waste drums are lumped into a single rectangular mass, bounded by slip surfaces, that correctly reproduces the initial porosity and density. The simplified geometry used (as compared to the reference stratigraphy) is justified in Stone (1996), with supporting calculations given by Osnes and Lebreche (1995). In justifying the simplification, it is shown that including two types of salt and the anhydrite beds are necessary to provide the model sensitivity needed to support observations, but that the clay seams and additional complexities do not contribute. Thus, only halite and anhydrite properties are included as material properties in the parameters listed for the porosity surface. No roof failure of the room is considered in the porosity surface calculations. The porosity surface and its parameters have also been discussed in Butcher (1996), and Butcher et al. (1995).

The first full explanation of the porosity surface and its justification of use appears in Butcher and Mendenhall (1993). Since the pressure in the room depends on the amount of gas and the room pore volume, and this pressure creates the "back stress" resisting closure, the porosity surface can uniquely represent the room behavior if the relationship between gas volume and time is known. Since that relationship is specified (by corrosion rates and/or intrusion scenarios) the porosity surface can be used as prescribed.

A complication occurs, however, when brine is allowed to flow into or out of the room. Then, the porosity evaluated from the porosity surface must be treated as the gas-filled porosity and added to the brine-filled porosity to become the total porosity required in the performance assessment calculations using BRAGFLO. Furthermore, BRAGFLO, which is a fluid flow code, must be used to provide the brine content of the room for this iterative calculation. This coupling is only valid if the fluid flow is slow, which is a good assumption in the case of WIPP. Also, it must be assumed that the brine pressure is the same as the gas pressure within the room, which is true for high waste permeability.

The resistance to closure resulting from the compaction and consolidation of backfill and waste is based on empirical relationships derived from experimental studies. Some experimental laboratory and *in situ* experiments on crushed salt compaction for shaft sealing studies may provide definitive property assessments for backfill, although the final makeup or certainty of use of backfill materials is not known at this time. Limited experiments involving the compaction of waste-filled drums and simulated waste provide the basis for empirical estimates of waste behavior. The variable nature of waste form and inventory lends a large uncertainty to the definition of waste physical behavior. The models of waste properties and mechanical behavior are reviewed elsewhere in this document.

The volumetric plasticity model has evolved significantly since it was proposed in its initial form by Kreig (1984). This formulation consisted of a synthesis of published empirical creep constitutive models, the geometry of material distribution, a calculated initial stress condition, and a set of creep constitutive properties derived from laboratory creep tests at SNL. Morgan et al. (1985) applied this initial formulation of the model to closure records from the south drift and found that it significantly under-predicted closure rates. Sjaardema and Kreig (1987) proposed that the characterization of Young's Modulus was the source of error in the initial model. They suggested an empirically derived reduction (division) of Young's Modulus by 12.5, which improved the performance of predictive calculations based on the model to satisfactory levels for use in crushed salt compaction tests for seals and subsequent closure observations. This model has been called the Reduced Modulus (RM) model in subsequent work.

Munson et al. (1989, 1991) undertook to resolve the empirically altered model with a "first principles" model derived from a set of more process-based rock mechanics theories. He demonstrated that a reliance on Von Mise's flow rule was less appropriate than that of Tresca, revised salt property estimates based on elimination of excavation strain from laboratory results, reevaluated creep parameters for argillaceous salt, added a term for primary creep, and improved the micro-mechanical creep models. These modifications enabled the steady-state creep response model (the MD model) to match observed closure rates at WIPP within 10%.

As it is presently formulated, the MD model does not include a treatment of the tertiary creep domain. Tertiary creep may be characterized as an acceleration in creep strain rate, accompanied by extensive microfracture, leading to macrofracture and failure. Chan (1996) has developed an amended version of the model (MDCF model), which includes tertiary creep for prediction of the formation of a DRZ around repository openings. The room closure model does not include tertiary creep on the grounds that all of the acceleration of strain (above the steady state rate) is due to microfracture and is recovered during the final stages of room closure due to DRZ healing. This concept is part of a larger concept called the conservation of void space. Because of void space conservation, no increase of gas pressure in the repository is attributed to this increase of strain rate.

The conservation of void space is only partly proven (experimentally or observationally) and is largely based on theoretical assumptions. In the case of tertiary creep of salt, the primary assumption is that all of the acceleration in strain rate during tertiary creep results from the onset of microfracture generation caused by the accumulation of intracrystalline lattice damage. The accumulation of lattice damage within individual crystals often results in work hardening and the elevated local stress levels may result in the initiation of strain by a "new" mechanism or mechanisms. However, no clear evidence exists that fracture is not accompanied by an undefined intracrystalline micromechanism, which may account for part of the change in the tertiary creep rate. The concept of continuation of unchanged steady state creep by micromechanisms that are unaffected by the damage accumulation to which the onset of fracture is attributed, seems incompatible. A more complex micromechanical model, which might include some acceleration due to non-fracture (plastic) processes, is not ruled out by any of the evidence. None of the closure observations at the WIPP occur over periods of time long enough to encompass the complete creep cycle observed in other salt mines.

Munson et al. (1995) estimates that only about 3% of the total creep strain is attributable to tertiary creep. The MD model matches short-term steady-state creep rates to within approximately 10%. If all or some part of the tertiary creep is not attributable to recoverable microfracture, the MD model may only be able to predict long-term closure rates to about 13% at best. Associated gas pressure changes through the porosity surface calculation are impacted by the inherent uncertainty in closure rates represented by the creep closure model predictions.

3.19.2. Review of Criteria

The room closure model includes the creep closure model (MD), the porosity surface lookup table, and interaction with BRAGFLO to iteratively specify brine inflow volumes. The porosity surface is constructed within the SANTOS model and consists primarily of creep closure, waste compaction, and gas pressure to estimate repository void space versus time. This review concentrates on the adequacy of the creep model (MD) with reference to the other associated models (e.g., BRAGFLO, SANTOS, porosity surface, gas generation) only as necessary to evaluate uncertainties.

3.19.2.1. Information Used to Develop the Conceptual Model

The initial version of the creep closure model was developed from published creep constitutive relationships and rock salt properties from intact rock salt deformation experiments at the SNL Rock

Mechanics Laboratory. The model was revised on the basis of short-term measurement of closure rates when the WIPP experimental rooms were opened. Both empirical revisions of elastic constants, based on closure rates, and revisions to the constitutive model, based on refinement of the understanding of deformation processes and flow rules, contributed to the development of later versions of the model.

Resistance to room closure (backstress) is the result of brine and gas pressure in the repository and of the strength of waste and backfill. Gas pressures used in the model are the result of the interplay between the time history of gas generation, the time history of void volume due to salt creep, and the threshold pressures governing gas outflow along the fractured anhydrite interbeds. Brine inflow is partially controlled by gas pressures. Repository pressure is modeled by an interplay between BRAGFLO and SANTOS, and interactions between gas pressure and creep are presented in the lookup table called porosity surface. Gas generation and brine inflow information are the product of other models. Threshold pressures for gas outflow in the interbeds are taken from packer tests of those horizons (Salado model). Strength of salt backfill is available from extensive experimental work done for the shafts and seals model. Waste strength may be the most uncertain type of information used in modeling room closure. Some experimental waste compaction has been done, but variation in waste form and inventory may make the characterization of waste physical properties highly variable. The creep closure model depends on the waste to resist closure and suppress rockfall and also contributes to the generation of an estimate of final waste porosity for waste dissolution estimates.

3.19.2.2. Validity of Model Assumptions

With the exceptions of the creep model, most of the assumptions in the global room closure conceptual model, as represented by the porosity surface calculation, are discussed in the consideration of other models (e.g., Gas Generation, Repository Fluid Flow). Many of the assumptions in the creep model were modified and tested during the development of the second iteration of the constitutive (MD) model. This redevelopment of the model was driven by the failure of the preliminary model to acceptably predict the short-term rates of closure of WIPP rooms. The redeveloped model contains a new flow rule and refinements of other model elements. The new model predicts short-term, steady-state salt creep rates (room closure rates in the WIPP excavations) acceptably (within 10%) implying that the principal assumptions are correct. No such correlations have been made for the transient (tertiary) creep behavior of the repository because of the limited observation times of room closure behavior. Tertiary creep is neglected in the MD creep closure model because of the assumption that all strain rate acceleration (above the steady state rate) is due to microfracture and that the porosity caused by microfracture is recoverable during DRZ healing. This assumption is referred to as "the conservation of void space" and is largely unproven.

Because of the complexity of the natural environment and number of parameters evaluated, several assumptions are required to make the process of modeling and mechanical parameter evaluation possible. The most important of these appear to be:

- Thermal effects can be ignored since little waste heat generation is expected. This assumption is reasonable.

- Halite and anhydrite layers can be treated as continuous. This assumption is probably necessary in view of current computer modeling methods. It is also reasonable, in view of program requirements and data accuracy. However, discontinuous surfaces certainly exist within the assumed continuous layers. A good example is given by the few "anomalous" creep results reported by Senseny (1986), which were not included in the final creep parameter determination. Some of these occurred in samples that contained distinct linear clay seams. The effect of ignoring such data and other similar effects by assumption is not severe with regard to the final results, but should not be forgotten.

- Size scale effects can be ignored. Most geologic media exhibit a size scale effect. More often than not, this takes the form (in mechanical properties) of module reduction with size. In the case of WIPP, one might also expect an increase of creep rate with size. A hint of size effect is noted by Munson et al. (1989) but no model changes are proposed. Such effects are frequently attributed to discontinuities, which have differing properties as functions of scale. The assumption of no size scale effects therefore ties in with the continuum assumption discussed previously. Despite these cautions, ignoring scale effects seems reasonable within the realm of available data and accuracy of prediction required for these massive formations.

- The "unknown" long-term creep mechanism can be described by a standard equation and its parameters determined by relatively short-term tests. Virtually all of the halite creep during the lifetime of the repository will occur in response to a mechanism labeled as unknown. Therefore, the equation used for this mechanism, although a standard and acceptable activation equation, must also be labeled as unknown. This may have consequences with respect to long-term predictions. From the viewpoint of repository performance, the consequences are probably not severe since the parameters of the unknown mechanism have been empirically determined with some confidence.

- The presence of water can be ignored as an explicit mechanical properties material parameter. In most geologic media, saturation state strongly affects material properties. Here, with small amounts of water, one can argue that the explicit effects can be ignored. It does not appear that the WIPP project has investigated this, but the results are probably not severe. One area of caution is the possible conversion of anhydrite to gypsum on water absorption. This event, if it occurs, will make the affected anhydrite zone softer and more plastic than now calculated. However, since the anhydrite beds tend to be zones of weakness to begin with, a severe adverse effect on subsequent modeling is not anticipated.

3.19.2.3. Evaluation of Alternatives

Alternative forms of the creep model were evaluated and compared to repository behavior during the redevelopment of the preliminary (Sjaardema and Kreig 1987) model. The empirical model, which was a version of the preliminary model with elastic modulus modified (RM model) on the basis of observed repository behavior, was used as a stop-gap model to allow the seals and backfill evaluation experiments to move forward. A more process-based model was ultimately developed which utilized a different flow rule and other refinements. This model (MD model) permitted a better understanding of the interaction of individual flow processes and could be more confidently extrapolated to differing initial and environmental conditions than the empirical version. The two models, one empirical (RM) and the other a process-based model (the MD model), agree well and are mutually supportive.

3.19.2.4. Uncertainties

The Creep Closure model contains two of the most important and sensitive variables involved in the potential release of radionuclides. Gas pressure resulting from the compression of gases in the repository from reduction of void volume and gas generation are the principal driving forces capable of pushing brine and dissolved and particulate waste out of the repository toward the accessible environment. Waste consolidation controls the pore space in the waste, which regulates the available surface area across which brine can dissolve radionuclides. Gas pressure is regulated by a complex set of model interactions. Permeability regulates gas outflow via fractured interbeds, and gas generation rates and rate of closure are the primary controls of gas pressure maxima. Gas pressures that exceed lithostatic pressures, sufficient to slow, stop, or reverse repository closure, are credible.

Timing of release relative to a complex interplay of variables controlling gas pressure, void volume, brine volume, residence time, and the reactivity of waste and brine as controlled by brine availability, waste permeability, and porosity are important in determining released brine radionuclide concentration and volume. The assessment of the interplay of timing of multiple processes is controlled by the stochastic manipulation of the processes by SANTOS and is preserved in the porosity surface lookup table. If the latin hypercube sampling strategy adequately addresses the timing issues, as claimed by DOE, consequences of uncertainty in the conceptual models are minimized if the assumed limits of variability in processes are conservative. Only in the case of waste compaction and its influence on the degree of radionuclide entrainment and solution in brine is the conservatism of assumptions not verifiable. This is because the physical and, to a lesser degree, the chemical character of the waste is essentially unknowable within wide bounds. The consequence of this uncertainty is significant only if release impact is dominated by concentration of released radionuclides rather than by volume of released brine. Those aspects of the consequences of release are considered in other conceptual model reviews. Uncertainty associated with the room closure model (minimum of about 13%) must be evaluated through its sensitivity in the porosity surface calculation, and primarily impacts gas pressures.

3.19.2.5. Adequacy of the Conceptual Model

The adequacy of the Creep Closure conceptual model is demonstrated by its predictiveness of room closure in existing WIPP excavations. The uncertainties inherent in the model must be assessed through the sensitivity of the porosity surface calculation. The model appears to be adequately predictive.

3.19.2.6. Adequacy of Application

Integration of the Creep Closure model with the other component models and submodels to represent repository room closure is contained in the SANTOS code generation of the porosity surface lookup table for a large number of stochastically defined combinations of conditions, and appears to be adequate for performance assessment use.

3.19.2.7. Accuracy of Results

Accuracy of results for the salt creep conceptual model has been demonstrated to be adequate within the sensitivity of the overall room closure model by its ability to predict short-term closure rates in empty WIPP rooms and drifts (10%). The accuracy of the combined model of room closure with, for example, waste, backfill, and gas pressures, cannot be demonstrated at this time. Butcher (1996) claims that the sensitivities to undemonstrated variables in the combined model are low.

3.19.2.8. Validity of Results

The validity of the global room closure model cannot be assessed at this time in the absence of long-term room closure observations of filled and closed rooms, or of analogues or observations of releases from similar structural systems, particularly in the undisturbed scenario. This is ameliorated by the approach adopted in the generation of the porosity surface lookup table, which addresses the complexities of room closure processes and timing among the principal dynamic processes. The Room Closure model appears to be valid as part of the porosity surface calculation for performance assessment purposes.

3.19.2.9. Adequacy For Implementation

Implementation appears to be adequate. The porosity surface calculation appears to address the complex issues of timing among processes and provides a means of choosing representative parameters for individual processes with respect to uncertainty about process results and timing during dynamic process evolution. The creep closure model (MD) appears to be acceptably adequate to the approximation of timing among room closure, gas generation, waste compaction, and brine inflow for performance assessment purposes.

3.19.2.10. Dissenting Views

There were no dissenting views for this model.

3.20. Shafts and Shaft Seals

3.20.1. Model Description

Four existing shafts connecting the repository to the surface, which will be used in the operational phase, are represented in performance assessment by a single shaft with a cross section and volume equal to the total cross section and volume of the four real shafts. This composite shaft is modeled as separated from the waste regions in the model by the distance from the waste to the present waste handling shaft. On closure of the repository, the shafts will be sealed as described below and as represented in performance assessment by nine materials occupying 11 model regions in the shaft, as shown in Figure 3.2. The materials are earthen fill from the surface to the Rustler Formation; a clay region in the Rustler; asphalt at the top of the Salado; three concrete sections within the Salado; an upper clay region within the Salado; a thick section of compacted crushed salt; a lower clay section separated into upper and lower segments; and a concrete monolith at the repository horizon.

Conceptually, the shafts are assumed to be surrounded within the Salado by a DRZ with properties that vary with depth, time, and type of adjacent seal material. The performance assessment calculation grid represents only the cross sectional area of the shafts, and the permeability values for the various seal components at different times have been adjusted to account for the presence of the DRZ. Therefore, the DRZ is not represented explicitly in the BRAGFLO calculation. Thus, the flux that would occur through a shaft and its surrounding DRZ can be modeled equivalently using the shaft cross-sectional area with a higher permeability.

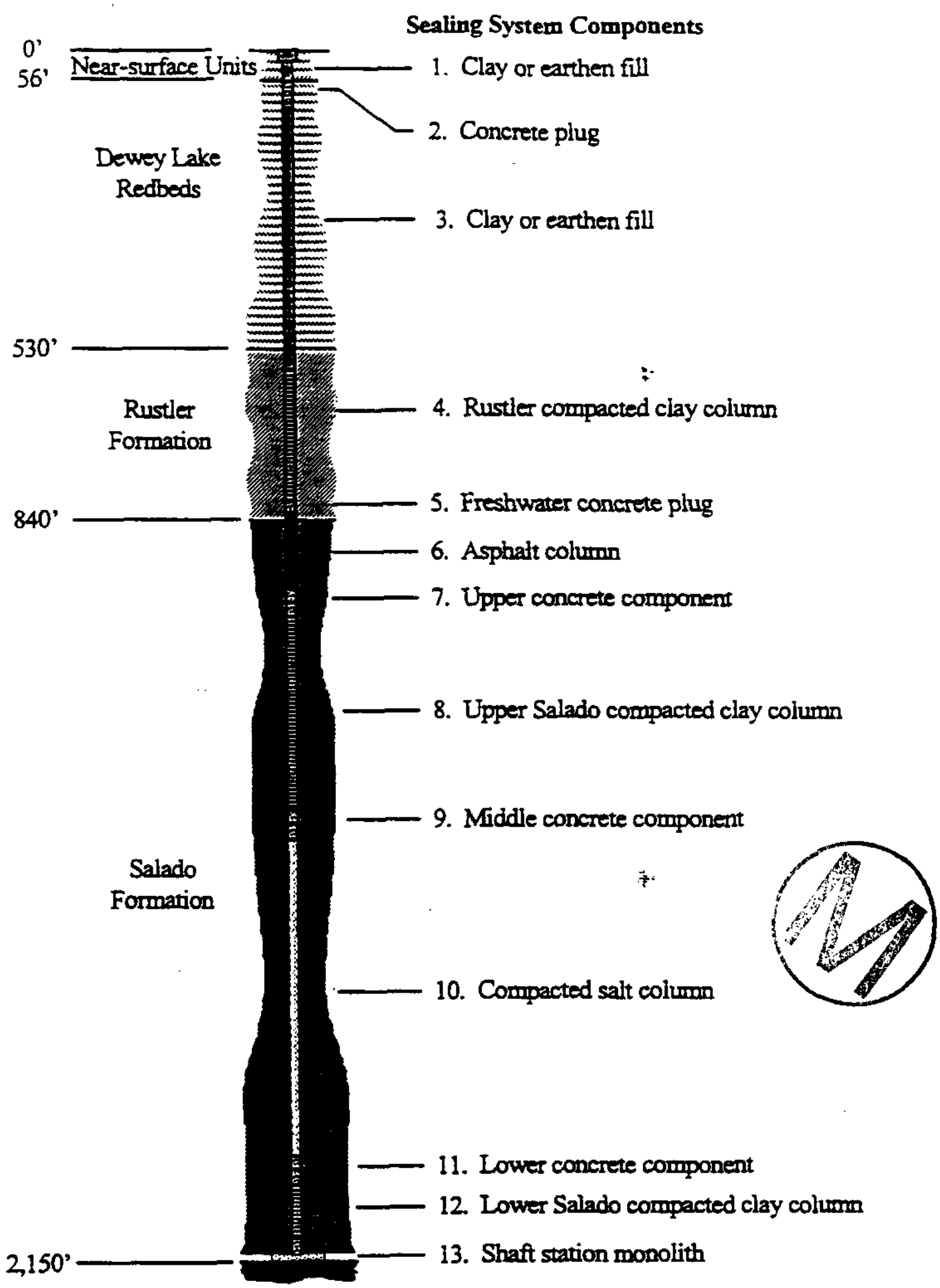


Figure 3.2. Arrangement of the Air Intake Shaft Sealing System

As described by Knowles (1996b), the shaft DRZ permeability is incorporated into the shaft permeabilities by a sampling and calculation process. DOE studies showed that the permeability can vary over an order of magnitude across the DRZ. Test data showed it is greatest near the excavation surface and decreases outward into the rock. To determine the effective permeability of the shaft DRZ, an equation was derived using the assumption that the permeability change is log linear. This equation has as variables a sampled inner DRZ permeability, intact salt permeability, shaft radius, and outer extent DRZ radius. A permeability value is computed for each shaft DRZ. A composite shaft DRZ permeability is then calculated by summing the individual products of the permeabilities and respective areas and dividing by the summed areas. Finally, the adjustment to the shaft zone permeability to account for the DRZ is computed similar to the previous step. The final shaft zone permeability is the sum of the composite permeability times the area of the combined shaft DRZs and the permeability times areas of the summed shaft area divided by the modeled shaft area. The modeled shaft area is assumed to be 95 m^2, which is the computed sum of the areas defined by the shafts' radii. The shaft seal permeability (including the DRZ) is sampled and is temporal in the BRAGFLO calculations.

3.20.2. Review of Criteria

3.20.2.1. Information Used to Develop the Conceptual Model

The conceptual model for the shafts and shaft seals used in the performance assessment has been chosen to provide a reasonable and realistic basis for simulating long-term fluid flow in either direction through the shaft seal system between the repository and brine bearing units and the surface, and to allow evaluation of the effect that uncertainty about the long-term properties of the shaft seal system may have on cumulative radionuclide releases from the disposal system.

Parameters used to characterize the shaft seal system are described in Section 6.4.4 of the CCA and in Appendix PAR. The principal parameters of interest are the permeabilities and porosities of each seal component. For salt, concrete, and clay components, permeabilities are assumed to change with time. Permeabilities are constant for asphalt and earthen fill components. These parameters include the time-dependent properties of the DRZ around the shafts to determine the hydraulic properties of the shaft seal system through time. Other parameters specified for the BRAGFLO model include pore-volume compressibility, two-phase flow parameters, and initial conditions.

The FEPs associated with model development include:

- SP-1, Mechanical Effect of Gas Generation.
- SP-2, WIPP Shaft Seal Degradation.
- SP-4, Other Physical Degradation Mechanisms (Cracking Concrete, Erosion of Seals).
- SP-5, Chemical Degradation of Seals (Alkali-Aggregate, Cement Sulfate, Cement Pore Water).
- SP-6, Differing Thermal Expansion.
- SP-7, Concrete Hydration.
- SP-8, Effects of Microbial Growth on Concrete.
- SP-9, Effect on Groundwater Chemistry.
- SP-10, WIPP Investigation Boreholes.
- SP-11, Evaluation of Full Shaft Conceptual Model Seal System.

This information base appears to be adequate for the intended use.

3.20.2.2. Validity of Assumptions

The basic assumptions pertinent to this model concern the applicability of the findings from the test program. Key among these are healing of the DRZ, recompaction of salt (which has application in the shaft sections filled by this material), adequately qualified parametric values for each seal component, a short-term seal to assume appropriate permeability until the salt column is reconsolidated, and implementability of the seal components.

The healing mechanism is discussed in more detail in Section 3.7 of this report. Tests are quite positive in supporting this conclusion, with the most significant of these being the results of testing the zone around a rigid inclusion in salt (Knowles et al. 1996). Recompaction of salt has been demonstrated and concerns are detailed below. Parametric values of components have been scrutinized by a qualification process for adequacy. Implementability of the seal components, as most recently described in the Draft WIPP Shaft Seal System Compliance Submittal Design Report, Appendix B, appears to be readily achievable. All of these assumptions are sufficiently supported to be acceptably valid.

3.20.2.3. Alternatives

The shaft seal system design has evolved over time (Borns and Stormont 1988; Nowak et al. 1992). The Initial Reference Seal System Design proposed a two-phase sealing strategy: short-term concrete and clay seals and a long-term crushed salt seal. The use of native rock (i.e., crushed salt) as a permanent sealing material is considered the most effective means to eliminate the shafts as a preferred pathway for migration of hazardous constituents. Due to the time necessary for the crushed salt to reconsolidate to sufficiently low permeabilities, short-term seals were incorporated as a means to prevent fluid migration during the interim. Estimates of this interim period ranged from 100 to 200 years.

Results of the scoping calculations (CSDR 1996, Appendix D) showed that low-permeability materials were required for the shaft seals. However, the simplicity of the conceptual model limited the applicability of results to the current detailed seal system design. A comparison of the scoping calculations to the seal system design proposed for the last CCA was found in a memorandum to performance assessment (Knowles 1995a).

The current conceptual model of the WIPP shaft seals is documented in a memorandum to performance assessment (Knowles 1995b). The conceptual model is directly related to the detailed seal design both visually and technically, with all materials and components of the engineered seals being included. Parameters for the materials were developed from field and laboratory testing, literature searches, and numerical modeling. Documentation of the parameter development process is to be published.

3.20.2.4. Uncertainties

The conceptual model of the seals is based on results of detailed numerical models of the shaft seal system design that were developed to evaluate the performance of the shaft system under a range of conditions. Both fluid flow and structural response of the system were evaluated. Principal uncertainties evaluated and incorporated in the model include: 1) reconsolidation of the crushed salt component; 2) construction, permeability, and gas threshold pressure of the clay components; and 3) damage, permeability, healing, and character of the Salado and Rustler disturbed rock zones.

The consequences of uncertainty in seal component performance were a primary motivation in the development of the proposed seal system design. Although there is uncertainty in many of the materials and models, the shaft will be completely filled with high-density, low-permeability materials. The use of multiple materials and components for each sealing function resulted in a robust system. The shaft seal system being evaluated makes no distinction between "short-term" and "long-term" seal components. Instead, time dependency is incorporated directly into the model through temporal variation in seal properties. On general overview, the uncertainties that emerged in the shaft seals program appear to have been dealt with adequately.

3.20.2.5. Adequacy of the Conceptual Model

Details concerning a description of the sealing materials and why they are expected to function as expected are to be presented in the WIPP Shaft Seal System Compliance Submittal Design Report, currently in draft. The materials include compacted earthen fill, concrete, compacted clay, asphalt, and compacted salt. These different materials are used to reduce uncertainties in performance. All materials are expected to maintain their integrity for very long periods, although for design purposes longevity only is assumed for those materials with strong scientific justification. Concrete plugs with impermeable water stops located in the Salado provide early low permeability, and the rigid support to promote healing of the DRZ. In approximately 100 years (design provides for 100 to 200 years), the compacted salt column will be sufficiently compressed to have a low permeability, thus replacing reliance on the concrete plug. The asphalt is functional as a nonpermeable plug to prevent water flow, and as a water stop within the seals in the Salado Formation. These water stops, backfilled in a one-radius kerf cut surrounding the shaft in the salt, are expected to be highly effective in deterring water flow in the DRZ surrounding the shaft. The Compliance Submittal Design report will describe the processes showing feasibility of achieving adequate placement of these seals (initial drafts appear convincing). Except for confirmation of the compactability performance of salt, this model appears to be fully adequate for implementation.

3.20.2.6. Adequacy of Application

The properties of the designed seals are realistic, achievable, and allow for controllable application. The only relatable issues for application concern the performance of recompacted salt (as discussed in Section 3.20.2.8), and performance of the DRZ. The latter issue regards the accuracy of the assumption that the DRZ will heal and accordingly can be disregarded as an explicit component of performance assessment calculations. This assumption stems from tests showing that with time, the permeability of a DRZ decreases as confirmed by tests when a stiff support is placed in an opening. The property of salt creep forces the fractures to close and original conditions to be re-established (Knowles et al. 1996). As a result of these findings, it can be assumed that following the placement of seals, the DRZ will quickly heal to create a permeability that is lower than the shaft seals provide (Chiesler 1996). Hence, it is argued that by adjusting the permeability of the seal components upward in the model, it will compensate for the additional low flow in the DRZ, and the DRZ can be removed as an explicit input to the performance assessment calculations. Because of the relatively large extent of the DRZ and its capability of being a potential pathway for releases, this concern bears its rightful recognition in the accuracy of results.

3.20.2.7. Accuracy of Results

The results from development of the shaft sealing system pose questions of achievability, which obviously are subject to incorporating ensured quality in the design and implementation processes. On one hand, a concern may exist that the quality of materials placement might cause performance problems, and on the other hand the system is sufficiently tangible that problems can be resolved provided there is an assurance program that identifies problems in time to be addressed. Only two concerns appear to impact the concepts as discussed relative to accuracy. The first is discussed in Section 3.20.2.8, concerning establishment of a consistent and appropriate permeability value for compacted salt. The second consideration is the reliability of the expected DRZ healing process, which is an assumption of significant proportion, as discussed in Section 3.20.2.6. The results of studies, calculations, test programs, and engineering principles all appear to produce results favorable to achieving the construction of competent seals in the WIPP shafts.

3.20.2.8. Validity of Outcome

A principal conclusion from the studies and design of the WIPP shaft sealing system is that an effective and implementable design has been documented. Existing technology and use of common materials make this engineered barrier system tangible and realistic. This Panel's evaluation confirms that these attributes are fulfilled and the concepts forwarded are believed to be valid.

Two caveats were identified; however, neither threaten the validity of this model but they warrant further investigation to assure the integrity of the system. First, while the tests showing compactability of the halite adequately demonstrate the principle, to date it has not been possible to qualify an established permeability value in this medium. The principle reason lies with problems in interpretation of the test data, believed due to experimental conditions. Furthermore, having recognized that the halite is capable of being recompacted, it appears that the method of compaction by repetitive dropping of a heavy weight could cause an inhomogeneous, nonuniform packed bed. No evidence could be found that addresses this question as a requirement, as a phenomenological process, or experimentally.

The second caveat concerns the shaft monolith placed in the drift at the base of the sealing column. No evidence could be found that any analysis was made concerning whether this monolith could cause a stress condition at the shaft perimeter interface, which might create a shear zone there. The basis for this concern lies with the reality that the dimension of the monolith is sufficiently large that it creates a base platform supporting what appears to be a rigid column in a viscoelastic medium. Its effect will be that the base will be fixed at the floor datum, which might be upward moving, while the salt above in the far field is flowing downward. It appears that an analyses is warranted to assure that this is not a problem.

3.20.2.9. Adequacy for Implementation

Comments concerning two issues from the preceding section are also applicable to the model's adequacy for implementation: 1) further analysis of the salt compaction data base, firmed up with additional data, is important to support parameter permeability values, and 2) an analysis has not been found to assure the shaft monolith does not create a shear zone at the shaft perimeter interface. Aside from these, the foregoing discussions outline an insightful piece of scientific and engineering work. The shafts and seals program is well thought through and the areas of perceived concern have been addressed to various degrees of detail, each believed sufficiently adequate to support qualifying this model as adequate to proceed in supporting performance assessment.

3.20.2.10. Dissenting Views

There were no dissenting views for this model.

3.21. Gas Generation

3.21.1. Model Description

Gas generation within the disposal rooms after closure was identified as an important process to be considered in analyzing both the undisturbed and disturbed performance at WIPP. The principal features of the model are the production of hydrogen from the corrosion of iron in the waste and containers and production of carbon dioxide, methane, nitrogen and hydrogen sulfide from possible microbial degradation of cellulose, rubber, and plastics in the waste. These reactions are assumed to occur under anoxic conditions after the repository is closed and brine enters the disposal rooms and contacts the waste materials. The model also covers the removal of carbon dioxide from the gas phase by absorption and reaction with a chemical getter, magnesium oxide.

Ten to fifteen years ago it was thought that little water would be available in the dry salt to support either significant corrosion or microbial degradation of cellulose in the waste and that any gas that might be produced would be absorbed into the surrounding salt rock. However, observation of water in the underground workings, seeping from clay seams and in drilled holes, and the results of analyses and hydrologic experiments showed that interstitial water can flow into the repository. This lead to the serious consideration of corrosion and microbial action, through assessments that included laboratory analyses, some of which are ongoing. Three conceptual models have been used to describe gas generation: the so-called rates-and-potentials model, the average-stoichiometry model, and the reaction path model. These are further discussed in Section 3.21.2.3.

The amount of gas production in the repository is of considerable interest to assessment of repository disturbed and undisturbed performance. Gas pressure can counteract the brine inflow from salt, relating it to the Fluid Flow in the Salado model. Gas pressure can also drive brine out of the repository, relating it to the Actinide Transport in the Salado model. It can potentially counteract the closure of the salt around the waste, relating it to the Creep Closure model. It includes reactions that relate to the repository Chemical Conditions model and it can, thereby, also affect the Dissolved and Colloidal Actinide Source Term models. It also can affect the integrity of the Shaft Seals model. Under the various intrusion scenarios, gas is a driving force for potential releases, so it inputs to the Direct Brine Release model, as well as to the Cuttings/Cavings and Spallings models, and provides input material to the Culebra Flow and Actinide Transport models.

3.21.2. Review of Criteria

3.21.2.1. Information Used to Develop the Conceptual Model

The information used to develop the model included the quantities and compositions of the transuranic waste, particularly the quantities of radionuclides and corrodable steel and aluminum, and the quantities of water, cellulose material, and plastics, as well as any chemicals and sludges that could provide nutrients for microbial degradation of these materials. Other important information sources were the observation of brine inseepage into the underground salt cavities, and determination of the chemical compositions of brine in the Salado, in the Castile below, and in the Culebra above the repository. Direct observations were made of halophilic microbes in salt lakes in Nash Draw near the site and in repository inseepage water. Information was also obtained on corrosion-induced hydrogen generation experiments at other sites, measurements of radiolytic gas generation from plastics and water, and controlled measurements of oxic and anoxic corrosion and microbial degradation rates of cellulose using representative brine and cultured microorganisms from the repository brine. These measurements were done for Sandia at Lawrence Livermore National Laboratory and Brookhaven National Laboratory. There is some ongoing experimental work in this latter area at the Idaho National Engineering Laboratory using actual transuranic waste materials. There is little information on the microbial degradation of plastics.

The information on brine compositions, microbe presence and populations, and the controlled experiments of corrosion and microbial processes are very useful. Due to the length of time of the experiments, no evidence for likelihood of self-limiting conditions on corrosion or microbial action were observed, although it is logical that there will be some self-limiting features that would prevent complete reaction of metal, cellulose, and plastics. A determination of whether microbial action on cellulose would have a net production or consumption of water could not be made from the information available. Experiments of potential radiolysis of water do not appear to allow direct differentiation of gas generation from dissolved versus wet particulate alpha-emitting radionuclides. The ongoing longer term experimental work being conducted at the Idaho National Engineering Laboratory could provide improved resolution of some of this information. However, overall there appear to be adequate data to develop a meaningful conceptual model of gas generation.

3.21.2.2. Validity of Model Assumptions

Regarding hydrogen generation by metal corrosion, a key assumption is that hydrogen is generated by corrosion of steel in waste drums. This is certainly valid. The model also assumes that carbon dioxide and hydrogen sulfide generated by microbial degradation will not passivate steel, which appears very valid based on the corrosion experiments and the addition of magnesium oxide as a carbon dioxide getter. Rates of steel corrosion are assumed to be higher for waste inundated or wetted in brine at the bottom of the room, and rates are somewhat lower for metals above the brine level resulting from wicking. These assumptions appear reasonable based on the direct experimental evidence. In fact, assumed rates based on the reasonably short-term iron corrosion experiments could be somewhat conservative with regard to the timing of gas generation, but probably valid for the overall amount of gas from corrosion of this source of metal.

The model ignores corrosion of aluminum, steel in rockbolts and steel netting, and other equipment to be left in the underground workings. This seems to represent an implicit assumption that corrosion of these materials will not contribute to gas generation and is based on the relatively small amounts of these materials. Aluminum is apparently on the order of 10% by mass of the steel, based on the summary data in the 1995 Baseline Inventory Report. Aluminum is quite corrodable in brine, and rockbolts can directly contact water seeping from the anhydrite interbed above the disposal rooms. The molar quantity of hydrogen produced per mole of aluminum corrosion would be 1.5, due to the stoichiometry involved. Therefore, it seems only logical to include these materials in the corrosion model to avoid a bias.

The model also assumes that the chemical reaction representing the stoichiometry of anoxic corrosion of iron is

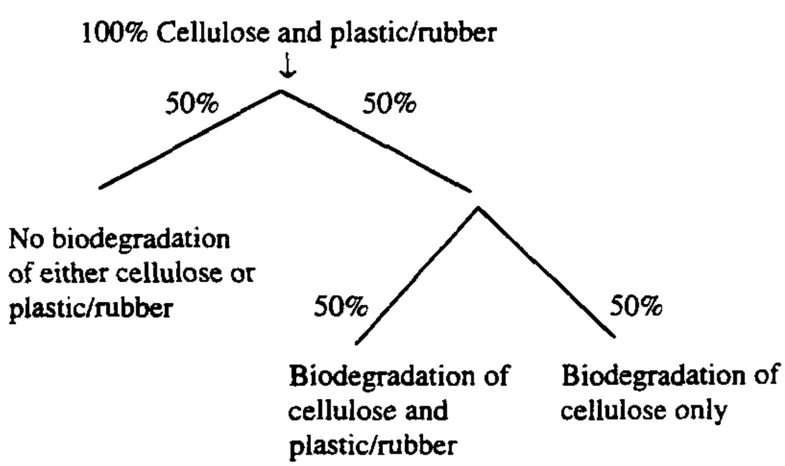
$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H2$$

thereby yielding one mole of hydrogen per mole of iron reacted, and consumption of two moles of water. The model assumes that the corrosion of iron is not represented by the reaction

$$Fe + 4/3H_2O \rightarrow 1/3Fe3O4 + 4/3H2$$

as this reaction is not expected at low temperatures, and the amount of hydrogen generated in experiments was consistent with the first equation. Except for the initial period after repository closure, when oxygen is available, this appears valid and reasonable, especially since the chemistry conditions model predicts reducing conditions in the repository.

Regarding microbially induced gas generation, the model assumes that the probability of degradation of cellulose and plastics/rubber will be 50% and that in the event that biodegradation occurs there is a 50% probability that plastics and rubber will also be degraded. This assumption is shown schematically in the diagram below.



This assumption is based on major uncertainties that are described in Section 3.21.2.4 below, and represents a judgment. For performance assessment purposes, this assumption will result in less gas generation than if one were to assume total consumption of all the organic material. There is apparently no scientific evidence that plastics/rubbers degradation will occur at all with certainty, based on contemporary experience. The possibility that products from microbial degradation of cellulose, and perhaps radiolysis by alpha irradiation, could combine to break down the relatively stable plastics polymers to more consumable fragments suggests the probability should be non-zero. It is difficult to argue for a value higher or more precise than 50%, unless there were more robust long-term data, or experience with plastics degradation in, for example, landfills. Therefore, for performance assessment purposes, the assumption regarding plastics/rubber appears to be adequate.

With regard to the degradation of cellulose, the long list of uncertainties identified in Section 3.21.2.4 below suggests that less than full probability of significant microbial degradation of this more readily consumable material is a reasonably valid assumption. Also, it does not appear scientifically valid to assume that either all or none of the cellulose will be degraded in light of the significant uncertainties that microbial populations would remain viable to the extent of complete cellulose degradation. DOE is not seeking a worst case in performance assessment. Therefore the 50% probability is a reasonable assumption for modeling purposes.

3.21.2.3. Evaluation of Alternatives

The Average Stoichiometry model currently used has been in use since 1991. Its principal features and assumptions have been described in the previous sections. Two alternatives that have been seriously considered are the Rates and Potentials model from about 1989 through 1991, and the Reaction Path model, which was developed between 1992 and 1995, but has not been used.

The Rates and Potentials model used measured rates of gas generation from microbial processes and corrosion and the total potential for gas generation from the available amounts of metal and cellulose. This model assumed no gas generation from plastics, which was controversial. The results of use of this somewhat less involved model demonstrated that gas pressures could have a significant effect on the performance of the repository. This stimulated development of more complex analyses methods involving coupling gas generation with brine flow and incorporating processes of fracturing due to gas flow into the Salado anhydrite beds. The Rates and Potentials model gave way to the Average Stoichiometry model.

The third model that has been considered is the Reaction Path model in which the reactive gases, carbon dioxide, and hydrogen sulfide produced by microbial action, were assumed to interact with and potentially passivate the surfaces of steel, thereby reducing or potentially stopping the rate of corrosion. Although some passivation was observed in experiments, corrosion films were not judged to be sufficiently adherent. Also, analysis of rates of microbial production of carbon dioxide and hydrogen sulfide showed they would not be present in sufficient quantities to provide passivation. Therefore, the reduced corrosion rates indicated could not be demonstrated reliably and effort on this model was stopped in late 1995. Furthermore, the use of a chemical getter such as magnesium oxide would absorb the carbon dioxide, raise pH and lower actinide solubility, reduce carbon dioxide pressure buildup, and somewhat lower steel corrosion rates at the higher pH.

The alternative models that were seriously considered did not offer sufficient benefits to performance assessment. However, the thermodynamic elements of the more complex Reaction Path model could, in the future, offer improved understanding and more rigorous ability to understand the complex chemical behavior in the repository room. Nevertheless, the purpose of the Gas Generation model to provide input gas generation to other models is adequately met by the Average Stoichiometry model.

3.21.2.4. Uncertainties

There appear to be greater uncertainties in the submodel describing microbial degradation than in the submodel describing metal corrosion. Uncertainties, which have been stated relative to microbial degradation, include the following:

- Will there be adequate populations of microbes capable of surviving for long periods in the disposal environment?
- Will there be adequate nutrients and electron acceptors available from the waste over long periods of time?
- Will sufficient brine enter the room to support the microbes?
- Can chemically toxic metals or radiation destroy or retard otherwise viable microbe populations?

- Will microbial degradation of plastics and rubber occur at all?
- What are the relative amounts of the various gases produced, and will microbes be net producers or consumers of water?

Despite these significant uncertainties, the Gas Generation model will predict significant but not total degradation of cellulose and plastics/rubber. Thus, these uncertainties appear to have been resolved in a conservative manner.

Uncertainties in the submodel describing corrosion-induced hydrogen gas buildup include the amount of metals present; the use of short-term metal rates of corrosion; the potential for oxic corrosion to continue due to radiolysis of water; and the potential for increased amounts of corrosion products from aluminum corrosion or increased rates from iron/aluminum galvanic couples and from corrosion of steel in the repository rock bolts and netting. It is judged that the only one of these that is potentially significant is the amount of added corrosion-induced gases from aluminum in waste and from rock bolts and netting. Another issue is whether some Fe+3 would be produced during the initial period after closure, and later due to continued generation of oxygen from radiolysis, thereby effecting actinide oxidation states.

The radiolysis of water in the waste and in brine, as well as radiolysis of plastics and rubbers, have separately been judged to have an insignificant effect on gas generation compared to the other gas generation mechanisms, and are not included in the gas generation model. For alpha particle irradiation of plastics and rubber, the measured G values (molecules of gas per 100 electron volts) were quite variable over time, leading researchers to conclude that depletion of available hydrogen atoms in plastic/rubber polymers around radioactive particles would stop the generation of such gases. However, over the long term, this conclusion is questionable since the radioactivity and waste can move around and be deformed by salt creep and gas and brine movement. Furthermore, the reported experiments involving radiolysis of brine have used soluble alpha emitters. In this situation the approximately 5 Mev per disintegration would all be dissipated in water. Depending on the solubilities, much of the actinides could remain undissolved. The review of this issue did not cover radiolysis by wetted particulate radioactive materials. This omission could be rather significant. If a significant portion of actinides are not dissolved but remain in small particulate materials that become wetted, a significant portion of the alpha energy could still be deposited in water and generate hydrogen and reactive oxygen species.

A project decision was recently made to add magnesium oxide to buffer the brine pH (in the range of approximately 10) to limit actinide solubility. The model assumes that all carbon dioxide is quickly dissolved in brine and precipitated as magnesium carbonate, thereby also reducing gas pressure and buffering the pH at 10, rather than about 4 to 5. While this appears clearly desirable, there are significant uncertainties as to whether these benefits will be completely realized. No results have been presented of any consideration of phenomena that could limit the effectiveness of the magnesium oxide. Likewise, there have been no laboratory or pilot scale tests to demonstrate effectiveness. Some potential adverse scenarios that might be considered are as follows:

1. Brine, which slowly enters the room, bypasses the getter and penetrates the drums from below. The current design has no getter beneath the drums.

2. Carbon dioxide, which initially reacts directly in the gas phase with the magnesium oxide getter, creates an insoluble crust around the outer surfaces of the getter, thereby limiting further access of brine and carbon dioxide to the getter. Such a crust might also occur at the water level in the bags of getter stacked around the periphery of the waste rooms.

Thus, the assumption of complete and rapid removal of carbon dioxide appears quite uncertain and, for modeling purposes, seems unjustified in light of such uncertainties. The benefits being counted on in the Chemical Conditions model are extremely significant, which carries with it a very significant obligation to demonstrate the validity of this assumption.

Another uncertainty is whether the heats of the corrosion reactions, and the microbial degradation of the cellulose, will result in elevated temperatures. Analyses of thermal effects of radiogenic heat in contact-handled transuranic waste have shown this source of thermal energy is small. Likewise, analyses of radiogenic heat in remote-handled transuranic waste can result in 38-65°C in the area of canisters but only about 4°C in the repository overall. However, no thermodynamic analysis has been provided to support the single-statement conclusion in the FEP screening document that corrosion and biodegradation do not affect repository temperature due to low enthalpies of the reactions. Heat generated in contact-handled transuranic waste could not dissipate as readily as in remote-handled waste, because of the large mass and dimensions of these relatively low-conductivity wastes. Significant temperature increases could accelerate corrosion rates in the presence of brine and potentially affect other processes, such as creep closure and brine flows. This uncertainty could be resolved readily through a numerical evaluation.

3.21.2.5. Adequacy of the Conceptual Model

The Gas Generation model would represent a reasonable approximation of the most significant processes represented at the conceptual level, were it not for the four potentially significant uncertainties described above. Some modest effort to resolve these uncertainties is needed, as discussed in Section 3.21.2.8.

3.21.2.6. Adequacy of Application

The gas generation model results are applied to the overall performance modeling system known as BRAGFLO, as well as to the Chemical Conditions model. Gas pressures are calculated from molecules of gas produced and assume a reasonable equation of state. As indicated earlier, the assumption that all carbon dioxide is rapidly removed from the gas phase appears somewhat unreasonable in the absence of better chemical and engineering justification for this important assumption. Therefore, this currently represents a discontinuity in the modeling system. The processes not included in the model, including gas generation from aluminum and rock bolts and from radiolysis, represent potential changes in the model but do not affect the modeling application per se. However, if greater thermal effects due to heat generation from corrosion and biodegradation were found through analysis, this could in turn affect other system parameters and processes outside the Gas Generation model.

3.21.2.7. Accuracy of Results

In the absence of key results of the model, it is difficult to draw definite conclusions about what the accuracy of the results will be when implementing a conceptual model. If one were to properly represent the conceptual model in equations, and then properly implement the equations in a numerical system using appropriate data on parameters, the accuracy of results would presumably be that associated with the uncertainties and biases in the conceptual model above, as well as any introduced during implementation, to get numerical results.

The uncertainties and potential biases that have been identified for this model are judged to have a potentially significant effect on its accuracy in predicting gas pressures and other parameters, such as pH and actinide solubilities. However, this judgment could be tempered somewhat if key results of analyses and sensitivity studies were to indicate that the identified uncertainties and biases taken collectively were to show that the effects on waste systems releases under disturbed and undisturbed conditions were small. If this were not the case, changes to the model to account for such effects would be needed. Therefore, it is suggested that results of implementing the Gas Generation model would be useful, including sensitivities among Gas Generation model variables and brine inflow calculations, and resulting pressure buildup over time. Also, the sensitivity of gas generation to the amounts released from human intrusion scenarios would provide useful information. Such information is believed necessary to make a more useful and informed judgment on accuracy.

3.21.2.8. Validity of Conclusions

There are two issues of concern here, first, whether the predicted outcomes in terms of inputs to other models are valid, and second, whether the outcome of larger issues on disposal system releases are valid in light of remaining issues with the Gas Generation model. A definite conclusion on either point would be somewhat speculative, at least without resolution of several of the issues raised and possibly of the results of sensitivity studies identified. One would also not want to speculate on the validity of conclusions without seeing what the conclusions might be. The following issues have not been adequately resolved:

- Analysis of hydrogen generation by corrosion of metals other than the steel in the waste is inadequate. Ignoring gases generated by corrosion of other metals could result in underestimating the gas pressure in the repository.

- Temperature increases in the repository due to corrosion and microbial degradation are not sufficiently analyzed or characterized. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

- Due to uncertainties about the effectiveness of the magnesium oxide getter to completely remove CO_2, significant uncertainties exist regarding pH, CO_2 pressure, and actinide solubilities. The chemical conditions in the repository would significantly change if the MgO did not function as planned, and could result in underestimating radionuclide releases.

- Hydrogen and oxygen gas generation from radiolysis of dissolved and wetted particulate actinides have not been adequately evaluated. Radiolysis of cellulose and plastics without assuming local hydrogen depletion has also not been adequately evaluated. Ignoring the gases generated by these effects could result in underestimating the gas pressure in the repository.

3.21.2.9. Adequacy for Implementation

At the conceptual level, without consideration of the integration, accuracy, and conclusions criteria, the conceptual model would be adequate if the significant issues raised above are resolved. However, a bottom line assessment on whether the Gas Generation model, as used in the compliance application, represents a complete reasonable approximation of the actual disposal system, is premature unless the significant issues raised above are resolved and some key results and conclusions are available.

3.21.2.10. Dissenting Views

There were no dissenting views for this model.

3.22. Chemical Conditions

3.22.1. Model Description

This conceptual model has been developed to standardize the chemical conditions of the repository. As such, the data generated by this model are used as input parameters to other conceptual models.

The chemical conditions of the repository are a major influence on actinide solubility. It has been estimated that under specific chemical conditions (low pH), the actinide solubility may increase over expected values by up to five orders of magnitude. This model has used engineering systems to limit such variability. DOE has assumed that equilibrium has been established between the brine in the repository (Castile or Salado), waste forms, and primary minerals. In addition to this basic chemical assumption, a series of other assumptions were made to help facilitate computer code calculations. The assumptions are discussed in further detail below. The defense of model assumptions is presented in Appendix SOTERM, which was not available for the peer review.

Major variables in this conceptual model include brine compositions (fixed chemistry Salado and Castile brines), ligand concentrations, pH, fCO_2, oxidation conditions, mineral stabilities, cement inventories, actinide inventories, and MgO backfill. Of these variables, some can be held constant because of the MgO backfill. The reaction of MgO and CO_2 acts to buffer the pH of the repository and allows other variables to be fixed. The two major variables that will now be constrained are fCO_2 (low fugacity) and pH (between 9 and 10, depending on brine composition).

Certain assumptions are critical to this model. Brine and waste are modeled as a uniform mix of dissolved and solid phases. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions amongst the actinides. Further, chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions. Chemical microenvironments are not believed to persist for this reason. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time. Temperatures will increase a total of approximately 5.4°C (radioactive decay and exothermic reactions), and it is assumed that there will be negligible effects due to this increase.

DOE believes that calculating mixing of brine from different sources is not amenable to performance assessment. Therefore brine compositions are fixed by performance scenarios. Undisturbed performance and E2 scenarios dictate the use of Salado brine. This is because the Castile Formation is not penetrated. Scenarios E1 and E1-E2 use Castile brine as the solvent for chemical conditions.

Oxidation states of the repository are believed to be reduced. This judgment is based on the thought that available oxygen will be consumed early by oxic corrosion or aerobic microbes. Furthermore, large quantities of iron from 55-gallon drums are consumed by anoxic corrosion, producing hydrogen gas and ferrous iron. Although reducing conditions are expected, redox reactions between dissolved actinides in possible oxidation states are not addressed. DOE assumes this will produce conservative results and increase the total dissolved actinide source term.

Experimental data have shown that acidic conditions greatly enhance the solubility of actinides. Although cement materials in the waste will hydrate to $Ca(OH)_2$, CO_2 produced by microbial degradation of cellulosics will overwhelm this component and force the brine to low pH values. To reduce the potential for highly accelerated actinide dissolution, DOE decided to add MgO to the repository as backfill. The simplified reactions of concern are:

$$MgO + H_2O = Mg(OH)_2$$

$$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$$

In large enough quantities, the backfill will act as a getter of CO_2 and thereby buffer the liquid, produce low CO_2 fugacities, and provide alkaline conditions in the repository.

Because the addition of MgO will buffer the CO_2 fugacity, many processes that create time-dependent changes in the repository have been negated. The other assumptions imparted on the chemical conditions model, such as fixed ligand inventory, mineral equilibrium (halite, anhydrite, brucite), fixed brine compositions, and fixed actinide inventories have produced a fairly simple system. There is no need for a large computer code to replicate the conditions of the repository. Rather, fixed or calculated (EQ3/6) parameters (pH, fCO_2, phase equilibria, buffering equilibria) from this model are used as input to other, more complex conceptual models.

3.22.2. Review of Criteria

3.22.2.1. Information Used to Develop the Conceptual Model

Information used to define the Chemical Conditions conceptual model fall into four main categories: thermodynamic considerations, experimental results, numerical simulations, and results of literature reviews. The first major consideration of this model, equilibrium conditions, is a cornerstone of physical chemistry. The model uses equilibrium conditions between brine and minerals as a given; however, it dismisses the concept of redox equilibrium conditions between dissolved actinide species. The second category, experiments used in the WIPP project (especially gas generation and actinide source terms), have identified significant factors affecting the room chemistry. A clear example is that of WIPP-specific microbes generating large amounts of CO_2 gas. The third major information source is supplied by numerical modeling. Two of these examples are listed. Mineral precipitation sequences were developed from EQ3/6 computational runs. Cement inventories were produced by simple algebraic formulas. The fourth information source came from peer reviewed journal articles. An example would be that of mineral equilibria, such as Felmy and Weare (1986).

The nine FEPs were also used in the development of this conceptual model are:

1. DRG-13, Effects of chemical changes due to gas generation and corrosion.
2. Heat from exothermic reactions and concrete hydration.
3. SP-7, Heat from concrete hydration.
4. Effect of thermal gradient.
5. DR-15, Electrochemical effects.
6. DR-16, Other second-order FEPs similar to electrochemical effects.
7. RNT-25, Electrochemical effects in the repository.
8. SP-5, Chemical degradation of seals.
9. SP-8, Effects of microbial growth on concrete.

It has been decided that this gathering of information is adequate.

3.22.2.2. Validity of Model Assumptions

The major assumptions of the Chemical Conditions conceptual model have been listed in the model description above. To summarize, the assumptions are as follows:

1. Brine and waste are modeled as a uniform mix of dissolved and solid phases.

2. Thermodynamic equilibrium is assumed for dissolved actinides but not for redox reactions among the actinides.

3. Chemical homogeneity and solubility equilibrium are assumed. This allows for the assumption of instantaneous reactions.

4. DOE assumes there will not be conditions whereby supersaturation can exist for long periods of time.

5. It is assumed that there will be negligible effects due to the temperature increase (by radioactive decay and exothermic reactions) of approximately 5.4°C.

6. Brine compositions are fixed by performance scenarios.

7. Oxidation states of the repository are assumed to be reduced.

8. All CO_2 will be fixed by available $Mg(OH)_2$, thereby buffering the pH of the repository.

9. Actinide and ligand inventories are fixed.

Assumption (1) is reasonable when one considers the time frame involved for mixing and the difficulty of trying to numerically represent heterogeneous waste forms. Thermodynamics relies on the principal of equilibrium and, therefore, assumption (2) provides a mixed interpretation. Assuming equilibrium for dissolved actinides is valid; however, DOE claims conservatism by not assuming redox equilibrium. This cannot be considered valid without further explanation and demonstration of the conservatism. Equilibrium of solubilites and chemical homogeneity are a simplifying assumption (3) that should be wholly valid over the time frame involved. The corollary of this assumption, that reactions are instantaneous, is wrong. The effect of kinetics was never taken into account in the model.

Assumption (4) is valid as a simplifying assumption. The trade-off between long-term saturation versus supersaturation and precipitation is valid for modeling. Although assumption (5) may be valid, verification calculations that prove negligible differences have not been provided. Assumption (6) is valid for the scenarios described. In effect, these two brines provide end-member compositions for a complete solution series. Assumption (7) is valid after approximately 100 years beyond closure. In the short term, oxidizing conditions would prevail. The limits allowed for total waste to be entombed at WIPP provide for assumption (9) to be valid.

Assumption (8) is probably the only assumption in this conceptual model that is physically unfounded and very problematic. From a thermodynamic viewpoint, the reactions are proper and the buffering capability is valid. However, there is no physical evidence that the MgO pellets will be allowed to completely react with the CO_2 generated by microbes. Reaction rims forming on the extremity of the MgO packages may not allow the majority of the backfill to be available for interaction. Such a chemical system would then not be buffered and the brine would become acidic. Studies have not been performed to demonstrate that the present engineering design will in fact work and allow all the MgO to react with CO_2 until the gas is exhausted. This is also discussed in Section 3.21, the Gas Generation conceptual model.

3.22.2.3. Evaluation of Alternatives

The majority of the chemical alternatives are described in Section 3.23.2.3 (Dissolved Actinide Source Term). By fixing many of the chemical parameters at reasonable values for repository conditions, the need for alternative models was not required. The primary alternative that is discussed in this section is *whether a chemically reactive backfill is required.*

In the early 1990s, no backfill was anticipated for emplacement in the repository rooms. When the test plan for soluble actinides was initiated, a large range of CO_2 pressures and pH values was anticipated. High CO_2 generation would produce sufficient carbonic acid to lower the brine pH to approximately 4 or 5. The basic conditions of the natural Salado Formation brine (9.4) would only allow restricted dissolution of the actinides. Under acidic conditions (pH 4) in experiments, actinide solubility was found to increase by approximately 5 orders of magnitude over that of the natural Salado brine. Such a *solubility increase could conceivably present problems to the overall project.*

It was then decided to buffer the chemistry of the repository and brines by addition of a reactive backfill. The addition of copious amounts of MgO as backfill is designed to react with the microbially generated CO_2 and buffer the overall chemical conditions of the repository. This would, in effect, fix both the pH and fCO_2 of the brine.

3.22.2.4. Uncertainties

Uncertainties associated with this conceptual model fall into three categories. General uncertainties associated with dissolved or colloidal actinides are discussed in Sections 3.23.2.4 and 3.24.2.4, respectively. This section is restricted itself to uncertainties associated with assumptions presented in Section 3.22.2.2 and the uncertainty of whether phase stability has been adequately characterized. In Section 3.22.2.2., four of the assumptions presented (1, 4, 6, and 9) were deemed to be valid.

The five remaining assumptions presented by DOE were not clearly shown to be valid. The point to keep in mind is what magnitude of uncertainty is associated with each assumption. Although DOE has not validated the assumption of redox disequilibrium (assumption 2), the partitioning of oxidation states into lower and higher oxidation states for model runs has effectively addressed this uncertainty. Assumption 3, that chemical reactions are instantaneous, is not valid. The impact this assumption creates on the conceptual model may be significant. Reactions that are relatively fast present no problem at all. Reactions that take a couple thousand years probably introduce very little uncertainty to the model. It is those chemical reactions that never go to full completion that may invalidate the model. This uncertainty with regard to assumption # 8 is dealt with in detail below.

Assumption #5, that a 5°C increase over STP conditions is negligible, is probably correct. Any uncertainty with this assumption could be clarified with a few verification calculations. The other assumption that contains only a small uncertainty (#7) deals with anoxic conditions in the repository. Even if oxic conditions prevail for the first 1% of the regulatory time frame, only a very small amount of iron would be tied up as oxidized iron oxides (hematite, goethite, leucophane). Although these mineral phases do not react back to reduced phases due to kinetic effects, this is not expected to have any significant effects.

The assumption that $Mg(OH)_2$ will absorb all available CO_2 generated in the repository (assumption #8) contains a very large uncertainty. As mentioned above, there is no uncertainty that the chemical reaction pathway is indeed correct. The uncertainty is whether the engineering design will be effective. If a large portion of the MgO never reacts with CO_2, then the carbonic acid will remain unbuffered and the dissolved actinide source term may increase (depending on model scenario) by up to 5 orders of magnitude. This could be considered a significant uncertainty.

The final uncertainty to be commented on is that of mineral phase stability in the repository. Although the EQ3/6 computer code has been used to qualify which phases will precipitate from solution, no formal phase-stability study has been conducted. There may be phases present that have been overlooked and the consequences of that oversight would impart an unneeded uncertainty. Schreinemakers diagrams have not been calculated to determine the phase-stability fields present in the repository.

3.22.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. Since this model strictly consists of a number of chemical condition parameters, it should be easy to evaluate whether the model is valid. It is concluded that the majority of parameters for this model are both reasonable and adequate. For the present model, the uncertainties of the previous section must be dealt with to prove that the model is adequate. Even when one considers the potential uncertainties listed in Section 3.22.2.4, only two could severely impact the adequacy of the Chemical Conditions conceptual model. These are the rigorous treatment of phase stability (Schreinemakers analysis) and the ability for the backfill to sequester the CO_2. For phase-stability analysis, only the omission of a major phase from the stability fields could jeopardize the validity of the conceptual model.

Conversely, the backfill parameter is so key to the model that without test validation that the $Mg(OH)_2$ will work as a getter, the model will not be adequate. The reason is that too many other parameters of this model hinge on the pH and fCO_2 values being fixed.

3.22.2.6. Adequacy of Application

This conceptual model does not flow as total input to a single computer code, rather it functions to set the parameters and boundaries for other conceptual models. As such, the conceptual model does not integrate to larger computer models (e.g., BRAGFLO) in the typical way. Any chemical values or constraints that the model generates should be readily integrated into other conceptual models. If the model provides a specific chemical parameter, that quantity could plug directly into performance assessment codes.

3.22.2.7. Accuracy of Results

This section discusses whether the results of performance modeling using the conceptual model within the performance system are sufficiently accurate to adequately represent the chemical processes occurring. In essence, this question is not applicable to the model in review. There should be no opportunity to corrupt or distort parameter values from the chemical conditions conceptual model to the performance assessment model. However, this idea has not yet been confirmed by test runs of the performance assessment.

The other manner by which the performance assessment could derive inaccurate results from this conceptual model is to portray thermodynamic assumptions incorrectly. There is no way to judge whether this has happened without viewing the results of the performance assessment runs.

One would assume that the WIPP project can transfer chemical parameter values correctly from the conceptual model to the performance assessment, and that thermodynamic assumptions can be accurately implemented in the same fashion.

3.22.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Chemical Conditions conceptual model in the modeling framework are valid. The conclusions presented here rely heavily on the assumption that $Mg(OH)_2$ buffers the chemistry of the repository and that all stable equilibrium phases have been identified and appropriately considered. If the MgO backfill works as proposed, and all stable phases have been appropriately considered, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.22.2.9. Adequacy for Implementation

The Chemical Conditions conceptual model utilizes a strategy common to the physical sciences, fixing well defined parameters to allow the study of unknowns. For the most part, the model has done a very adequate job of simulating certain physical characteristics of the repository and then determining a reasonable median value. This value has become the fixed parameter (e.g., Salado brine composition) that is then passed on to other models.

To better document that a slight temperature increase in the repository beyond standard temperature and pressure (STP) conditions does not affect the repository chemical conditions, it would be reasonable to validate the assumption with a series of appropriate thermodynamic calculations.

The assumption that chemical reactions are instantaneous led to the belief that all CO_2 released to the brine would be consumed in the repository by MgO. However, this critical chemical process (MgO backfill as buffer) has not been field tested sufficiently to be confident it will work. If the technique does not perform correctly, then the total model would fail. At a less critical level of model completeness, there is no documentation that a phase-stability review (Schreinemakers analysis) has been performed for the chemical system in question. For these two reasons, and especially that MgO has not been tested as a buffer under WIPP-like conditions, the conceptual model is not yet adequate for implementation.

3.22.2.10. Dissenting Views

There were no dissenting views for this model.

3.23. Dissolved Actinide Source Term

3.23.1. Model Description

This model is based on thermodynamic laws to predict chemical phenomena affecting dissolved actinide concentrations in the presence of actinide-bearing solids. The actinides deemed important to the performance assessment of WIPP are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). The dissolved actinide source term determines the concentration of each actinide in solution by combining the oxidation state distribution of each actinide with the modeled solubility of that oxidation state at repository conditions and the appropriate scenario brine composition (Salado or Castile).

Several oxidation states can be screened out or substantially constrained. Oxidation states initially screened out are Np (+6), Pu (+5), Pu (+6), and Am (+5). The screening rationale are described in Appendix SOTERM (not provided to the Panel for review). Actinides limited to a single oxidation state are Th (+4), Am (+3), and Cm (+3). The model then assumes that the remaining three actinides will exist in only one oxidation state, but is unsure which of two possible states it will be. Therefore, the modeling assumes half the realizations will be in the reduced state (U +4, Np +4, and Pu +3) and half in the more oxidized state (U +6, Np +5, and Pu +4).

The factors controlling dissolved actinide concentrations are equilibrium with anhydrite, halite, MgO, actinide-bearing solid phases, appropriate brine, and water-soluble ligands.

The ligand concentrations used in the calculations are based on the Baseline Inventory Report and are reported to be acetate, citrate, oxalate and EDTA. The concentrations used represent dissolution of the entire ligand inventory. DOE believes this is a conservative approximation for the following two reasons: (1) it does not reduce the ligand inventory by destruction mechanisms, and (2) although all ligands will dissolve in the first brine volume, the ligand concentration will stay constant for the full simulation.

Folded within the dissolved actinide conceptual model are several conceptual submodels. The solubility submodel is the Fracture-Matrix-Transport (FMT) model, which is based on the Pitzer activity coefficient model of the thermodynamics of highly concentrated electrolytes. This model uses an adaptation of the Harvie-Moller-Weare/Felmy-Weare (HMW/FW) data base. FTM parameters are fitted using the code NONLIN, which calculates the Pitzer parameters. No redox equations are used in FMT; instead, an oxidation state analogy and oxidation distribution state submodel are used.

Soluble actinide concentrations are based on solubility limits (maximum concentrations), or when a cell is partially depleted, by inventory limits. The actinide inventory is depleted on a cell-by-cell basis for the undisturbed, E1, and E2 scenarios. Processes affecting dissolved actinide concentrations in a computational cell are: dissolution of actinide solids, advection of dissolved actinides by brine flow from neighboring cells, diffusion or dispersion from neighboring cells, and interaction with colloidal particles. The E1-E2 scenario assumes homogeneous mixing within the panel for dissolved actinides moving up the borehole.

As mentioned above, the dissolved actinide source term model incorporates a very critical assumption, that of oxidation state analogy. It assumes that all actinides in the same oxidation state (ex. +III) will form the same aqueous species and isostructural solid phases. There is said to be a large data set confirming this for the 3+ oxidation state, but fewer data exist for the 5+ and 6+ oxidation states. It is also noted that such an analogy may not hold to be strictly true for the 4+ oxidation state. The rationale for using the oxidation state analogy is to allow a great reduction in the number of experiments that must be conducted.

A second assumption is that actinide precipitates formed in laboratory experiments will allow the crystallinity to mature with time. Since solids are typically less soluble than amorphous precipitates, laboratory solubility studies can then provide an upper concentration limit. The exception may be that radiolysis could cause certain solids to become more soluble.

A third assumption in the dissolved species model is that no adsorption will occur with immobile substrates in the disposal rooms. DOE however may take credit for adsorption of dissolved actinides to mineral phases in the Culebra Formation, via the Transport of Dissolved Actinides in the Culebra model.

A fourth assumption considers that dissolved actinide concentrations are also coupled to brine compositions in the disposal rooms. DOE expects this capability to greatly enhance their ability to look at site-specific solubilities based on disposal room brines and the effect of engineering modifications on dissolved actinide concentrations.

A fifth assumption centers on the presence of anoxic conditions in the repository setting. Actinide oxidation state distributions are presently unknown, since redox couples are not in equilibrium in low temperature systems. Although it is believed reasonable to expect the actinides to exist in their most reduced state because of anoxic conditions, alpha radiolysis oxidizes Am (III) to Am (V), and Pu (VI) is stabilized in the presence of carbonate. Another potential problem with the assumption is that the repository is actually under oxic conditions for the first few tens of years, due to relict atmosphere and nitrate reactions, and oxidized actinides may encounter kinetic effect problems in attaining their final reduced oxidation state.

3.23.2. Review of Criteria

3.23.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are classical thermodynamics, information gleaned from appropriate journal articles, and experimental programs. The discipline of thermodynamics as a portion of the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions. The conceptual model has made liberal use of research published in the journals. Items transferred to the dissolved actinide conceptual model from journal articles range from algorithms (Harvie et al. 1987) to phase equilibria fields (Felmy and Weare 1986) to individual thermodynamic parameters (Pitzer 1991). Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Argonne National Laboratories, Lawrence Berkeley Laboratory, Pacific Northwest Laboratory, and Florida State University.

Nine FEPs are used in the development of this conceptual model. These FEPs are: effects of chemical changes due to gas generation and corrosion (DR-13), electrochemical effects (DR-15), second order FEPs similar to electrochemical effects (DR-16), effect of thermal gradient (GG-4), heat from exothermic reactions (GG-7), chemical degradation of seals (SP-5), heat from concrete hydration (SP-7), effects of microbial growth on concrete (SP-8), and electrochemical effects in the repository (RNT-25). Information gleaned from the FEPs was instrumental in both model conceptualization and test plan development.

3.23.2.2. Validity of Model Assumptions

The dissolved actinide source term model is extremely detailed, complex, and contains many implicit and explicit assumptions. One of the most significant of these assumptions is that equilibrium is maintained. Such an assumption is a basic part of thermodynamics and is considered valid only if firmly held to. However, this model picks and chooses when the concept of equilibrium is used. An example is that dissolved actinides are assumed to be in equilibrium with solids; however, redox reactions among actinides and supersaturation are not assumed to be in equilibrium. Such a philosophy may be correct for this model (it builds in conservatism) but each variance must be defended and justified adequately.

The ten other major assumptions are: (1) lack of adsorption onto immobile substrates; (2) anoxic conditions will dominate; (3) dissolved actinide concentrations are based on repository room brine compositions; (4) metastable phases in laboratory experiments become more stable with time; (5) all actinides in the same oxidation state will form the same aqueous species and isostructural solid phases; (6) the oxidation state analogy holds true; (7) experimental runs reached equilibrium; (8) fluids obtained in 1-liter experiments are representative of the tests; (9) all stable phases have been identified; and (10) the hydrogen fugacity system is completely buffered by $Mg(OH)_2$ - $MgCO_3$.

Assumption 1 is probably not valid, but by assuming so in the Salado, DOE has built a conservative estimate. Anoxic conditions in the repository (assumption 2) are valid in the long term, however short term oxidation phases were not considered. This is because activation energies needed to reduce certain oxidized phases may not occur in the repository, and the effect would be to isolate certain phases in an oxidized state. Assumptions 3 and 7 are considered valid. Assumption 4 (metastable phases become stable with time) is not a valid assumption. Time is not the only constraint on the stability of a phase, and there is no documentation that other criteria have been considered. Assumptions 5 and 9 are intimately tied together. The information provided does not confirm that an exhaustive phase equilibria stability study has been performed for this chemical system. In essence, DOE has not proved that the actinides will form the same aqueous species or solid phases, or that all phases have been identified. Regarding assumption 6, the oxidation state analogy is not truly valid. However, the assumption is oft times conservative. This is the case for the +4 oxidation state that assumes Th solubility values. In the +3 oxidation state, however, values were obtained from another oxidation state (+5) and were not proven to be correct. The test runs for +6 phase (U) could not generate Pitzer parameters or characterize the associated solid phase. In an overall sense, it is probably inaccurate to assume the oxidation state analogy holds true. Assumption 8 (whether final liquids of 1 liter experiments are representative) is not valid due to microdomains and the absence of equilibrium conditions. However, it is not clear that these results were used in the final lookup tables. Finally, assumption 10 is only valid if the CO_2 gas is able to react completely with the $Mg(OH)_2$ backfill. As yet, no discussion exists that sufficiently assures that the reaction will go to completion. There is an equal chance that reaction rims will occur early in the process, isolate a large proportion of the backfill, and not allow the system to be buffered (see also Section 3.21.2.4).

3.23.2.3. Evaluation of Alternatives

The Dissolved Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as dissolved species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over 18 years, six alternative models were proposed: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with Realistically Conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4 and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, the Fresh Water Estimate model was essentially undeveloped, and sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory Limits model was complete and defensible but highly conservative. The model that until recently was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium Model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The other realm where a series of alternatives were considered was that of thermodynamic models for activity coefficients. Four modeling approaches were considered by DOE: the Pitzer model, Harned's

Rule (ion pairing), a hybrid of ion pairing and Pitzer formalism, and specific ion interaction (SIT) ion-pairing approach. Harned's Rule was only used for dilute solutions and not for brine more concentrated than 2 molal. Therefore the model was rejected. The SIT model assumes only species with opposite charges interact, and is limited to concentrations up to 3.5 molal. This model was also rejected because of its limitations. The Pitzer-SIT hybrid model did not compare the calculated lanthinide solubilities with data, so the hybrid model was dismissed. The Pitzer formalism has been applied frequently to concentrated electrolyte solutions and is backed by considerable peer reviewed journal articles. This model was therefore judged the most applicable format for characterizing the actinide solubilities in WIPP brines.

3.23.2.4. Uncertainties

There are five groups of relative uncertainty associated with the dissolved actinide source term conceptual model. The first uncertainty involves the experimental results produced by the Actinide Source Term (AST) program, while the other four uncertainties relate to how the experimental results are applied to the conceptual model.

The results of the experimental program exhibit a relatively small uncertainty (Novak 1995; Novak and Roberts 1994). When the solubility data and Pitzer coefficients from the experiments are implemented in FMT, the model results predict an uncertainty of an order of magnitude or less for the chemical conditions tested. The results of FMT modeling also compare favorably with the data of Kim et al. (1985).

The four uncertainties arising from FMT applications to the conceptual model are as follows: (1) is dissolution/precipitation steady state obtained, (2) can FMT data be extrapolated outside the realm of test parameters, (3) is the oxidation state analogy valid, and (4) are WIPP chemical conditions adequately defined? These uncertainties are much more difficult to quantify, therefore, a short discussion of each is given below.

Because of constraints imposed on the time involved in the performance assessment, the uncertainties of dissolution/precipitation steady state are fairly simple. The model assumes a long period of time in which brine will be in contact with waste and this would allow both dissolution and precipitation to equilibrate. Other assumptions that lower the uncertainty of this issue are reduced conditions, lack of supersaturation, ample solid materials for nucleation and sorption, and brine homogeneity due to long-term mixing. All these assumptions reduce the uncertainties of achieving steady state conditions to a low level.

The second uncertainty, that of extrapolation beyond the realm of test results, has been significantly reduced by the use of MgO backfill. Originally, the experimental tests were carried out over a range of fCO_2 values, but did not entirely cover the conditions expected in WIPP. The use of MgO backfill to provide an $Mg(OH)_2$-$MgCO_3$ buffer has negated this uncertainty. The only potential problem would be if the buffer in effect did not work (see Section 3.23.2.3).

The uncertainties associated with the oxidation state analogy are more ambiguous. Actinides in the +3 state do show the same limited set of solubilities. The +5 (Np) and +6 (U) oxidation state analogies are based on experiments using those specific actinides. The remaining uncertainties all center on the +4 oxidation state analogy. Thorium was used as the test analog and it was determined that Pu and U were slightly less soluble under similar chemical conditions. The analogy of Np to Th in the +4 state was not discussed. The use of Th solubility values is still probably conservative and may raise the total +4 concentration by an order of magnitude.

The last major uncertainty concerns the chemical conditions in the repository of the Salado. The most important parameters are pH, fCO_2, brine major ion concentrations, waste material reducing capability, and organic ligand concentrations. The first two parameters (pH and fCO_2) are well controlled by the addition of MgO backfill. Such a buffering effect allows this uncertainty to be negated. Major ion concentration ranges are well constrained for Salado and Castile brines. They are not so well defined for intrusion of Culebra brine into the repository. DOE believes that the Culebra composition, after mixing with halite or anhydrite, is bounded by the Salado or Castile brines. For two of the four oxidation states, Culebra brines would be within an order of magnitude of other end-member solubilities. The uncertainties for the +4 and +6 oxidation state solubilities is larger than an order of magnitude but undefined. Reduction capabilities of waste are taken care of in a conservative sense by assigning a 50% probability to both the lower and higher oxidation states. The uncertainty concerning organic ligands is resolved by assigning an inventory value that is twice that calculated in the BIR, then incorporating the increased solubility effect of organic ligands on actinides.

In conclusion, the only outstanding large uncertainty (other than assumption validity) is that of the Culebra +4 and +6 oxidation state solubilites.

3.23.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The outstanding issues that must be dealt with are the six unvalidated assumptions stated in Section 3.23.2.2 and the one uncertainty still unresolved in Section 3.23.2.4. When one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items are not overwhelming. A further nagging problem is that two major appendices of the CCA, NUTS and SOTERM, are not available. If the discussions entailed in the appendices are reasonable and logical, the assumptions are found to be valid, and the uncertainty is resolved properly, then the conceptual model would be wholly adequate.

3.23.2.6. Adequacy of Application

The issue here is whether the individual conceptual model is applied in an acceptable overall performance modeling element. As mentioned above, this is a very complex model with many variables. There is a well-documented data base for thermodynamic modeling of high concentration brines. Such data have served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, ligand availability, and oxidation state potentials, all of which allow a very robust model to be adequately applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.23.2.7. Accuracy of Results

Preliminary results of the lookup tables have been provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the oxidation state analogy holds true, that the brine stays buffered at a pH of 9 to 10, and that the other assumptions mentioned are valid, then the results of the conceptual model are sufficiently accurate. The only qualification to this opinion is that the results may be too conservative. The solubilities calculated (and determined from experiments) are quite well defined. To allow an order of magnitude variation on either side of the solubility parameter mean value is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.23.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Dissolved Actinide Source Term conceptual model in the modeling framework are valid. This decision is made more difficult by the fact that the appropriate tables and appendices of the CCA have not been supplied as of this date. If the information not yet available is reasonable and adequate in content, then it is reasonable to state that the conclusions of this model, as they apply to the full system, are valid.

3.23.2.9. Adequacy for Implementation

This model has turned out to be a very strong representation of how actinides would dissolve in the two major brines (Salado and Castile) of the repository and is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model discussed in Section 3.22, and to the successful use of MgO to buffer pH conditions in the repository.

For the sake of completeness and accuracy, the remaining concerns listed in Sections 3.23.2.2 and 3.23.2.4 have not been thoroughly documented. These concerns are summarized below:

- What impact does the initial (approximately 100-year) oxygen-rich domain of the repository have on corrosion?
- What were the metastable phases in the laboratory experiments, and what stable phases did they transform to?
- Can a phase equilibria stability determination be performed for this chemical system (same as described in Section 3.22)?
- Is the oxidation state analogy valid for the +4 and +6 oxidation states?
- Did the AST 1-liter liquids reach equilibrium with the solids? If not, were the solubility results still used?
- Does the Culebra brine chemistry affect actinide solubility?

3.23.2.10. Dissenting Views

There were no dissenting views for this model.

3.24. Colloidal Actinide Source Term

3.24.1. Model Description

The Colloidal Actinide Source Term conceptual model describes the concentration of actinides sorbed to or contained in mobile colloidal particles in the disposal rooms and also describes the stable colloids that must be quantified for transport in the Culebra. The actinides addressed with this model are thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm). Presently, transport of colloids in the Culebra have not been rigorously modeled because of the complexities of coupling hydrogeology, geochemistry, and colloid chemistry. Because of the chemical complexities of the integrated system and high ionic strength brines present, an attempt has been made to characterize the major colloid types believed to be present in the repository.

The four types described are "hard sphere" carrier colloids (mineral fragments), microbes, soft sphere carrier colloids or hydrophilic colloids (humic and fulvic acids) , and intrinsic colloids (true colloids). These particles develop from a variety of processes in the repository, including waste degradation, microbial activity, rock decomposition, and chemical condensation. Intrinsic colloids form by condensation of dissolved actinides in the disposal rooms. Mineral fragments and humic substances provide surfaces that dissolved actinides may sorb to. Microbes actively bioaccumulate actinides intracellularly and also act as substrates for surficially extracellular sorption (Francis 1985).

Four major decisions have been made that greatly simplify this conceptual model. First, DOE has elected to disregard the effects of competition associated with the equilibrium between dissolved actinides and actinides associated with colloidal particles. Therefore, the two source terms are not inexorably linked, resulting in an overestimation of the total concentration of mobile actinides that may leave the repository. Second, in the event that the sum of the concentrations of the dissolved actinide and colloidal actinide source terms for a particular element exceed the inventory limited concentration of that element, then a partitioning scheme is utilized. Instead of basing the partitioning on an equilibrium approach, DOE has decided to use an approach based on conservatism. The concentration of a particular actinide in the inventory is first made available to the most efficient transport mode. If the inventory is not used up, then the next most efficient transport mechanism is filled. This rationale is continued until the inventory is exhausted by assignment to the five groups of transport vehicles (four colloidal and dissolved actinide source terms). Third, thermodynamic equilibrium is achieved by actinide intrinsic and humic colloids. And fourth, DOE has assumed that microbes and mineral fragments are present in constant quantities in the aqueous phase. This allows a steady state quantity on which the actinides can sorb.

Because of the effect of high ionic strength brines on mineral fragment colloids, which collapses the electric double layer surrounding the colloid, Van der Waals forces can cause agglomeration and settling of such colloids. Laboratory experiments using WIPP brines indicate that this settling effect largely negates mineral fragments as an effective transport mechanism. Thus, DOE has conservatively assigned a mineral fragment concentration for each actinide to be 10^{-9} m/L, one order of magnitude higher than the detection limit of the experiments.

Microbes have a large study base at WIPP, primarily to provide data for the gas generation program. This information has also been helpful in the Colloidal Actinide Source Term model. The source term concentrations associated with microbes are based on actinide uptake experimentally determined from experiments with relevant bacteria cultures. Source term values range from 10^{-5} to 10^{-11} m/L.

Humic and fulvic acids are of particular concern because of their well known capability to complex metal cations, including actinides. These soft sphere carrier colloids are not affected by high ionic strength brines, so they may be important in the transport of actinides at WIPP. To determine humic substance concentrations, actinide complexation constants from WIPP experiments or from literature are coupled with site binding densities and solubilities of humic substances in WIPP brines. Source term values range from 10^{-5} to 10^{-9} m/L.

Intrinsic colloids are well represented by the Pu(IV) polymer. The mechanism of formation of this polymer has not yet been identified; however, it is known to be stable in high concentrations in highly acidic environments. There is some evidence that the polymerization is strongly linked to hydrolysis, and that it produces an amorphous macromolecule that becomes crystalline with time. This polymer is typically on the order of nanometer size range. Hence, it is assumed to act like a hard sphere carrier colloid. Experiments were conducted by over- and undersaturation at a range of pH values to determine concentrations of Pu intrinsic colloids. The source term value of this polymer is 10^{-9} m/L. Other actinide intrinsic colloids (especially Am) were found to have negligible importance.

The computer code that will describe the transport of the Actinide Source Term model is called NUTS. NUTS is dependent on BRAGFLO (chemical conditions in waste rooms) to provide brine volumes and a lookup table to provide actinide concentrations. The actinides that will be tracked in Salado and Culebra Brines by this table are thorium (Th), uranium (U), plutonium (Pu), neptunium (Np), and americium (Am). Other chemical factors originally believed to impact colloidal source terms were pH, pCO_2, major brine constituents, ionic strength, oxidation speciation and organic ligand concentrations. Fixing the brine compositions and the addition of MgO backfill has significantly reduced the number of variables in the lookup table.

3.24.2. Review of Criteria

3.24.2.1. Information Used to Develop the Conceptual Model

The main sources of information used are journal articles, experimental programs, and classical thermodynamics. The conceptual model has made liberal use of research published in the journals. Items transferred to the Colloidal Actinide Source Term conceptual model from the journal articles are voluminous and are the basis of the experimental test program. Experimental work on actinide solubility was performed at a number of laboratories, including Sandia, Los Alamos, Lawrence Livermore, and Brookhaven National Laboratories, and Florida State University. The discipline of thermodynamics as a portion the chemical sciences is well founded. A major assumption of this science is one of equilibrium conditions.

No FEPs were included in the development of this conceptual model. In fact, colloids were not considered as a conceptual model until after the 1992 performance assessment was completed. The study of Ibaraki and Sudicky (1995) is very similar to the conceptual model developed here.

3.24.2.2. Validity of Model Assumptions

The majority of the assumptions used in the colloidal actinide source term are valid, in that they are either accurate scientific extrapolations or based on conservative measures. Four major assumptions made by DOE and discussed in the model description above are most probably valid in the context of this model. To assume that Dissolved and Colloidal Actinides Source Term models do not compete for actinides is certainly conservative and will overestimate the total actinide source term. The partitioning scheme used when the inventory is exceeded is reasonable and again conservative. The assumption that thermodynamic equilibrium is attained for intrinsic colloids and humic colloids is valid. The assumption that there is a steady state source of mineral fragments and microbes allows for conservatism, in that it provides an abundance of sorbing material.

Two other assumptions in the conceptual model concern the use of bounding calculations. Concentrations of actinides in both intrinsic colloids (Pu+4) and mineral fragments were below the detection limits of the experiments. Therefore, the actual detection limit was used as the bounding value for the intrinsic colloid, and an order of magnitude higher bounding value than the detection limit for mineral fragments. These are probably adequate, possibly overly conservative estimates for concentrations in both cases and can be considered adequate.

3.24.2.3. Evaluation of Alternatives

The Colloidal Actinide Source Term conceptual model describes the quantity of actinides that would be mobilized as colloid species in WIPP brine, and would migrate with the brines away from the repository. At one time or another over the last four years, six alternative models were proposed for the Actinide Source term. The model names are as follows: (1) Expert Panel, (2) Inventory Limits, (3) Inventory Limits with realistically conservative Maximum Concentrations, (4) Fresh Water Estimates, (5) Chemical Model for Mobile Actinide Concentrations, and (6) Inventory Limits with Sorption. Of the six models, numbers 1, 4, and 6 were not defensible. As of December 1994, the Expert Panel model was questioned as to its credibility and technical suitability, and the Fresh Water Estimate model was essentially undeveloped. Sorptive values for the Inventory with Sorption model were unavailable. Of the remaining three models presented, the Inventory model was complete and defensible but highly conservative. The model that, until recently, was used as the baseline was the Inventory Limits with Realistically Conservative Maximum Concentrations model. Essentially, this was a combination of the Inventory Limits and Expert Panel models and was intended to be more judiciously conservative than the Inventory Limits model. The Chemical equilibrium model is based on thermodynamics and is robust but was only recently fully developed. The final model for the performance assessment (Chemical Equilibrium model) will contain submodels that investigate the source terms for both dissolved and colloidal actinide species.

The actinide inventory is originally determined by projections in the Baseline Inventory Report (BIR). A series of chemical reactions that will have a major impact on the colloidal actinide source terms are as follows:

1. Actinide dissolution reactions.
2. Reactions between brines and organic waste.
3. Reactions between brines and backfill materials.
4. Reactions between actinides and dissolved ligands (organic and inorganic).
5. Reactions that produce carrier colloids.
6. Reactions among actinides to produce actinide-intrinsic colloids.
7. Reactions between actinides and carrier colloids to produce radioactive mobile substrates.
8. Actinide sorption onto immobile substrates.

Of the eight reactions listed above, the first seven have been used in developing the current model. DOE has discarded reaction number 8. This decision is thought to be conservative and allows the possibility of more actinides being transported by colloids.

3.24.2.4. Uncertainties

The only uncertainty listed by DOE for this model involves the inventory limited concentration of the actinides. If the sum of the dissolved and colloidal actinides exceeds the inventory total, the actinide concentrations will then be proportioned between the two actinide groups (dissolved and colloidal). This philosophy appears reasonable.

Three lesser uncertainties that would add clarity to the model have not been resolved. First, it has been theorized that the Pu intrinsic colloid would act as a mineral fragment with time. Studies have not proved this theory. The mechanistic operation of this intrinsic colloid has not been determined. A second uncertainty concerns site densities available on microbes for actinides. This parameter has not been determined. Third, it is assumed that humic colloids behave like dissolved actinides. This assumption has not been adequately supported.

3.24.2.5. Adequacy of the Conceptual Model

The present section addresses whether the conceptual model is adequate based on the four criteria above. The conservative bounding values for intrinsic and mineral fragment concentrations should (in a perfect world) be discarded and real measurements taken to obtain scientifically valid results. However, when one considers the magnitude and complexity of this conceptual model, and the fact that so many issues are well addressed, these items appear almost insignificant.

The outstanding issues that must be dealt with are the three unresolved uncertainties in Section 3.24.2.4. A further nagging problem exists in that two major appendices of the CCA are not available (MASS and PAR). If the discussions entailed in the appendices are reasonable and logical, and the uncertainties are qualified, then the conceptual model would be wholly adequate and much more accurate from a scientific viewpoint.

3.24.2.6. Adequacy of Application

This section assesses whether the colloidal actinide source term conceptual model is applied into an acceptable overall performance modeling element. As discussed previously, this complex model has many variables concerning the four colloid types that are merged in. There is a well-documented data base for colloids both from the laboratory experiments specific to WIPP and journal articles. Such a series of articles has served well as a foundation for the model. As an input to the mathematical code NUTS, this conceptual model would present its results in a lookup table. The table takes into account brine compositions, proportionality constants, and oxidation state potentials, all of which allow a very robust model to be applied to the performance assessment modeling elements. The true unknowns are to be found in the assumptions that the chemistry rapidly approaches equilibrium, that the microbe culture is well known, and that the waste has uniform characteristics and inventory. These fundamental assumptions are a basis of the conceptual model and are most probably adequate and reasonable.

3.24.2.7. Accuracy of Results

Draft portions of the lookup tables were provided to the Panel by a Principal Investigator for the conceptual model. If one assumes that the dissolved actinide concentration values are accurate, that the brine stays buffered at a pH of 9-10 due to the addition of MgO, and that the other assumptions mentioned are valid, then the results of the colloidal actinide conceptual model are felt to be reasonably accurate.

The only qualification to this opinion is that the results may be too conservative. To assume concentrations no greater than detection limits of analytical equipment is deemed reasonable by regulatory agencies. However, this method may easily produce inflated values (as applied to intrinsic colloids and mineral fragments). To allow an order of magnitude increase greater than the experimental detection limit for mineral fragments is probably extreme and not truly representative of the chemical system involved.

The one remaining piece of information needed to thoroughly qualify the accuracy of the results would be a series of sensitivity analyses. These results are not currently available.

3.24.2.8. Validity of Conclusions

This section judges whether the key conclusions that have been drawn on the results of the Colloidal Actinide Source Term conceptual model in the modeling framework are valid. Since this model is inexorably linked to the solubility concentrations of the dissolved actinide source term, one may conclude that this model is valid contingent on the validity of the other model (which was determined to be valid, with minor caveats). The overall decision of outcome validity is made slightly more difficult by the fact that the final complete table (6-10) and appendices (PAR and MASS) of the CCA have not been supplied as of this date. If those pieces of information not yet available are reasonable and adequate in their content, then it is sufficient to determine that the conclusions of this model as they apply to the full system, are valid.

3.24.2.9. Adequacy for Implementation

The Colloidal Actinide Source Term model is a reasonable, if somewhat overly conservative representation of how actinides would sorb onto colloids in the two major brines (Salado and Castile) available for the repository. This conceptual model is adequate to support performance assessment. However, this model is closely linked to the Chemical Conditions model (see discussion in Section 3.22 on MgO backfill).

For the sake of completeness and accuracy, the uncertainties listed in Section 3.24.2.4 that would benefit from more supporting evidence are:

- Pu intrinsic colloids are presumed to act like mineral fragments with time, but this assumption is not adequately supported.
- Colloid site densities on microbes have not been thoroughly characterized.
- Humic acid colloids are presumed to behave like dissolved actinides, but this assumption is not adequately documented.

3.24.2.10. Dissenting Views

There were no dissenting views for this model.

4.0 INTEGRATION OF CONCEPTUAL MODELS IN PERFORMANCE ASSESSMENT

For the 24 conceptual models evaluated in Section 3.0 to be collectively useful, they must be integrated into a performance assessment model that adequately represents repository performance. The following paragraphs present a structure (reminiscent of the CCA, performance assessment code sequence) within which conceptual model integration can be illustrated and discussed. The discussion addresses criteria used for the individual conceptual model evaluations in Section 3.0. Since conceptual models are not directly used in the performance assessment, the integration of these models is, in itself, a concept equal in significance to the 24 conceptual component models.

Conceptual models provide the definition of the scope and limits of the issue addressed, define processes, enumerate variables, and provide a framework for consideration of sensitivities within an integrated system definition. The conceptual model specifies the analytical formulations to be used in numerical modeling and their relationships. Process linkages and parameter sensitivities provide a basis for data base planning and data sufficiency assessment. The conceptual model supports judgments used in generalizing data distributions for populating numerical models and supports qualitative judgments like those in the FEP process. A well established and clearly validated conceptual model for each issue is a strong element in the global integration of the overall performance assessment of a site and facility. A robust set of conceptual models for an integrated set of valid issues is the best possible control of site characterization work scope and costs.

The degree of development of conceptual models and their integration within the investigation of issues varied strongly among the models reviewed. In some cases the conceptual model and estimates based on theoretical constructs suggested by the model provided most of the information on which the review was based (for example, the Salado flow model). In some cases no conceptual model relating processes and properties to test results at a useful scale could be propounded. Robust numerical models, based on well developed testing data bases and geostatistical treatments, were successfully substituted for conceptually constrained investigations in some cases (for example, Culebra flow model). The degree to which an unquestionably valid, accurate, and precise modeling result is necessary depends on the consequence of uncertainty in any model system. Some elements of the performance model system could be adequately dealt with by assigning an unquestionably conservative result or by sampling between wide limits, based on credible analytical assessment (for example, the model). Generally, the assessment of consequences and the choice of assigned alternatives depend on strong conceptual model formulations. Where conceptual models failed or were not acceptably replaced, the formulation of a clearly defined and systematic assessment of the relationship between the issue, processes, and data seemed to be missing. The result was sometimes the overanalysis of inadequate or low quality data or the omission of the consideration of key processes, events, or features.

4.1. Model Integration

Figure 4-1 is an illustration of where the various conceptual models represent their system or subsystem within the CCA performance assessment code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes all conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF. The diamond-shaped element illustrated in the figure that receives input from NUTS and directs that input to SECO TP or CCDFGF is a decision point. If a release into the Salado has occurred, the input is directly to the CCDFGF. If the release involves transport to the Culebra, the input is directed to SECO TP. It is possible for a release scenario where NUTS output is directed to both the CCDFGF and SECO TP.

Figure 4-1 illustrates the primary associations among the conceptual models and the key WIPP performance assessment codes. One conceptual model, Chemical Conditions, is shown twice because it provides primary support to both the BRAGFLO and NUTS codes. As shown in the figure, the conceptual models do not all represent their system or subsystem in the same place in the code sequence. The figure illustrates that the conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in one direction. For example, while SANTOS is illustrated as related to BRAGFLO and receiving system representation from the conceptual model for Creep Closure, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS.

The integration of the conceptual models, therefore, identifies the overall performance assessment model as a complex structure that represents the 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

4.2. Review of Criteria

Applying evaluation criteria to the integration of conceptual models as a concept in itself, focuses the discussion on summations of the 24 individual conceptual model evaluations. For example,

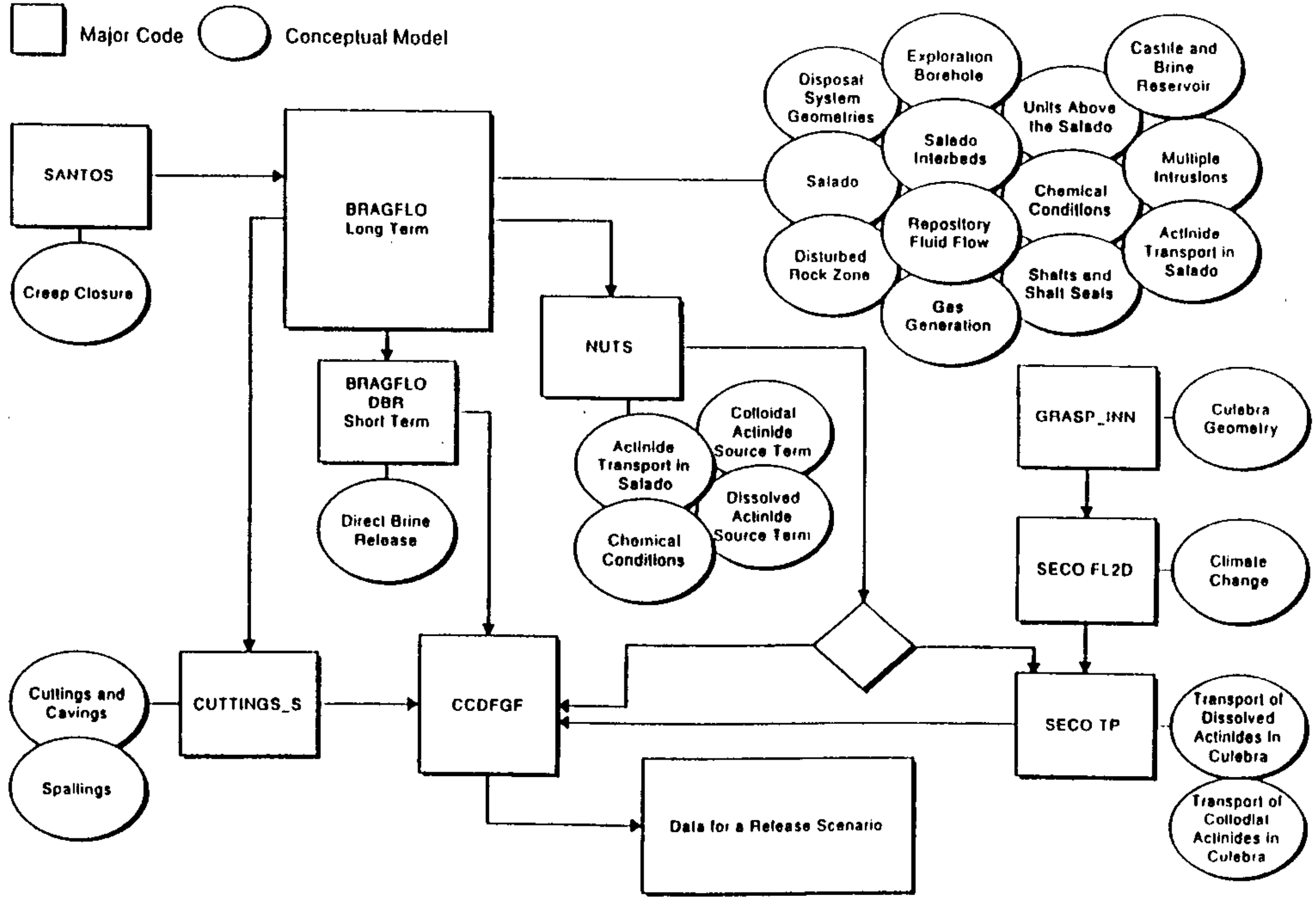


Figure 4.1. Illustration of Conceptual Model Integration

evaluations of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the individual conceptual models or the implementing mathematical representations or codes. The criteria have already been discussed in Section 3 for the conceptual models and without results of realizations, sensitivity analyses, and uncertainty analyses for the overall system or subsystem, conclusions cannot be made with respect to the implementing mathematics or codes.

Because the overall performance assessment modeling results were not available for Panel review, the overall adequacy for implementation of the integrated conceptual models (PA model) can only be judged at this time through the adequacy of the individual conceptual models. Some of the conceptual models are adequate but there is insufficient information (e.g., results, analysis) for the implementing structure (mathematical representations, codes, code sequence) to be judged adequate or inadequate.

5.0 SUMMARY OF EVALUATIONS

This section presents a summary of the evaluations of the WIPP Conceptual Models Peer Review Panel performed between April 2, 1996 and June 28, 1996. Over 20 years of scientific effort have been expended on the WIPP characterization project and it is beyond the scope of this report to summarize all of the positive factors and scientific evidence compiled. This section is not intended to be a reiteration of comments and discussions on the 24 individual conceptual models, but instead to provide an overview of conclusions from the evaluations. For those models found to be inadequate, the key concerns of the Panel are summarized. With the acceptable resolution of those concerns, the Panel may find most of the models to be adequate. The Culebra Hydrogeology and Units Above the Salado models are exceptions, as discussed below. The Panel's evaluations were made as a best effort over a short period of time when some models were in final development and supporting information was in flux, and therefore it is possible that some key information was available but overlooked.

Of the 24 models reviewed, 13 were found to be adequate for implementation in performance assessment for the WIPP. For most of the adequate models, minor Panel concerns remain and are identified in Section 3. These concerns primarily address issues of documentation gaps and issues with features, events, or processes that were not considered sufficiently important to find the model inadequate. The thirteen models found to be adequate are listed below.

1. Disposal System Geometry
2. Salado
3. Impure Halite
4. Disturbed Rock Zone
5. Actinide Transport in the Salado
6. Transport of Dissolved Actinides in the Culebra
7. Cuttings/Cavings
8. Multiple Intrusions
9. Climate Change
10. Creep Closure
11. Shafts and Shaft Seals
12. Dissolved Actinide Source Term
13. Colloidal Actinide Source Term

The 11 models found to be inadequate are presented in the following paragraphs with a brief discussion of the key concerns identified by the Panel. Comprehensive discussions of each of these models are presented in Section 3.

Culebra Hydrogeology

- No conceptual model was developed that explains the variability of hydrologic properties and processes in the Culebra at a scale that is useful in correlating those properties in the numerical hydrologic flow model.

- An extensive hydrologic testing data base and an apparently adequate numerical flow model were developed as a substitute for performance assessment purposes.

Although the Culebra Hydrogeology conceptual model was found to be inadequate to support numerical modeling, this inadequacy was inconsequential for performance assessment because an extensive hydrologic data base was developed and serves as an adequate substitute to support numerical modeling.

Repository Fluid Flow.

- The conceptual model and its two-dimensional numerical implementation may unrealistically restrict brine movement within the repository to the anhydrite interbeds because of the shallow depths of the borehole and shaft model cells. These restrictions could result in underestimating brine migration in the interbeds toward the accessible environment.

- The conceptual model and its two-dimensional numerical implementation do not include the presence of the unplugged ERDA-9 borehole within the wall of the operations area. This borehole could provide a pathway for gas and possibly brine to the ground surface, and no description of the plugging plan for this hole was seen in the documentation provided to the Panel.

- The sensitivity of model results to the selection of constant permeability values for the waste, panel seals, and repository DRZ has not been evaluated for the current performance assessment. Early time permeabilities may be significantly greater than the model parameter for each of these media, and could lead to underestimating radionuclide releases.

- The long-term performance of the panel closure seals has not been subjected to a detailed engineering evaluation of the type performed for the shaft seals. The role of the panel seals in restricting brine flow among the waste panels and into other parts of the repository is an important element of the conceptual model and its implementation in performance assessment.

Salado Interbeds.

- The conceptual model does not consider how the physical properties of the bounding clay seams affect model fracture propagation and permeability. Ignoring the characteristics of the clay seams may significantly overestimate the threshold pressure at which repository gases may be released.

Units Above the Salado.

- The conceptual models and the testing data base are inadequate to exclude the Dewey Lakes Redbeds and the Magenta Dolomites as potential transport pathways for radionuclides in the event of an intrusion.

- The analysis of brine flow in the intrusion scenarios limits the quantity of radionuclides reaching the region above the Culebra to such small amounts that transport in the Dewey Lakes and Magenta have negligible consequences.

The Units Above the Salado conceptual model was found to be inadequate to support the assumption that the Culebra is the only horizon above the Salado capable of significant radionuclide transport. This inadequacy was inconsequential for performance assessment because of modeling results indicating that long-term fluid flow in exploration boreholes above the Culebra was negligible because of relatively high permeability and low pressure in the Culebra.

Transport of Colloidal Actinides in the Culebra.

- The conceptual model does not adequately support the assumption that dissolved actinides will not interact with Culebra colloids. Ignoring this phenomenon could overestimate the travel time calculated for radionuclides to reach the accessible environment.

- The experimental K_ds determined for this model are not fully defensible. Such values may overestimate the retardation of actinides in the Culebra.

- Recent experimental work to support assumptions and data for this model has not yet been published and was not available for Panel review.

Exploration Boreholes.

- The potential for releases or changes in repository conditions from borehole penetrations in the operations and experimental areas of the repository does not appear to have been evaluated. Radionuclides that may have migrated into those areas through the panel closures by diffusion or other transport mechanisms could be released to the ground surface, and gas pressures could be relieved by such boreholes. Also, brine could migrate into those areas from a borehole and then into the waste panels.

- The assumption that shorter (40 m) borehole plugs beneath the repository horizon will not significantly degrade during the 10,000-year regulatory time frame has not been adequately supported. For the two- and three-plug configurations, degradation of these plugs could result in creation of a low permeability pathway for fluid migration between the Bell Canyon and the repository. For the three-plug configuration, degradation could result in increased fluid migration from a Castile brine reservoir to the repository.

- The possibility that an effect on the repository could result from Castile brine encountered in an E1 borehole that is assigned a three-plug configuration does not appear to have been considered in the conceptual model. Castile brine could enter the repository during drilling before the borehole is cased and result in increased rates of corrosion, waste degradation, and gas production.

- The sensitivity of the performance assessment to the simplified approach taken to determine reference conditions for BRAGFLO output does not appear to have been evaluated for the current model configuration. If reference conditions are not provided at sufficiently frequent time intervals, the modeling results may be erroneous.

Spallings.

- The conceptual model for channel flow of gases toward an exploratory borehole appears to be valid but has not been adequately evaluated. Spallings is a potentially important mechanism for direct waste release to the ground surface.

- The conceptual model for waste erosion by flowing gases has not been adequately defined. The model describing the source(s) of waste erosion resistance and the parameter(s) characterizing that resistance have not been adequately evaluated. Errors in this conceptual model could lead to overestimating or underestimating the volume of waste released in the spallings process.

- The waste has not been adequately characterized and the understanding of its physical properties in its decayed state has not been adequately developed to support the Spallings model. An adequate understanding of waste erosion processes requires an adequate understanding of the properties of the waste.

Direct Brine Release.

- The basis for the assumption that radionuclides do not accompany the direct discharge of Castile brine has not been adequately supported. This assumption could lead to underestimating radionuclide releases.

- Radionuclide transport through entrainment of brine and waste solids in rapid, two-phase liquid/gas releases during inadvertent borehole intrusions does not appear to have been evaluated. This transport mechanism may be an important component of the conceptual model.

- Releases resulting from flow into an exploration borehole intersecting a disturbed rock zone in the wall of a waste panel do not appear to have been evaluated. Large, open fractures in the walls could significantly increase the local halite permeability, allowing gas and brine to migrate through the borehole to the ground surface.

Castile and Brine Reservoir.

- The basis for excluding larger, potentially depressurized brine reservoirs from performance assessment has not been adequately supported. Larger reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The basis for the concept of reservoir depletion through previous borehole penetrations has not been adequately supported. Non-depleted reservoirs may have greater brine flow volumes and may result in greater radionuclide releases.

- The expected probability of encountering pressurized brine beneath the waste panels has not been adequately supported, nor has the basis for apparently ignoring the quantitative value of site-specific geophysical data been presented. Unrealistically low probabilities of encountering brine may result in underestimating radionuclide releases.

Gas Generation.

- The conceptual model does not consider aluminum in the waste, steel in the rock bolts and netting, radiolysis of water by undissolved alpha emitters, and radiolysis of plastics and cellulose as sources of additional hydrogen, oxygen, and other gases. Ignoring gases generated by these effects could result in underestimating the gas pressure in the repository.

- An adequate basis has not been presented for the assumption of complete and rapid carbon dioxide removal by magnesium oxide in the waste panels. The chemical conditions in the repository would significantly change if the magnesium oxide did not function as planned, and could result in higher radionuclide releases than the model would estimate.

- An adequate basis has not been presented for ignoring the effects of heat generation from corrosion and microbial action. Higher ambient repository temperatures could increase the rates of chemical reactions, fluid flow, and halite creep.

Chemical Conditions.

- The combined temperature increase (due to radioactive decay and exothermic reactions) and its effect on repository conditions has not been adequately addressed. Significantly higher repository temperatures could accelerate chemical reactions, fluid flow, and halite creep rates.

- Phase equilibria have not been critically assessed within the chemical parameters of the conceptual model. A major element stable phase that was overlooked could significantly alter the chemical conditions of the repository and vary the actinide source terms.

- The MgO backfill has not been demonstrated to be able to react completely with CO_2 generated by microbial action. If the MgO backfill did not react as planned, the pH-buffering capability of the repository would be significantly compromised, and could result in underestimating the actinide source terms.

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APPENDIX A - PANEL MEMBER INFORMATION

John Gibbons, Panel Member, is an independent geosciences consultant residing in Albuquerque, New Mexico. Dr. Gibbons has a Ph.D. in Geology from Syracuse University and Bachelors and Masters Degrees in Geology from the University of Arkansas. Dr. Gibbons has over 25 years of experience consulting to the nuclear industry and regulators. He has been involved since 1965 in several research and field studies of the behavior and geology of bedded salt deposits. He presently is a principal consultant to the Illinois Department of Nuclear Safety in its effort to license a low level nuclear waste disposal facility. His duties include the review of and contribution to work by world class contractors, national laboratories, and state scientific surveys in all aspects of site selection, characterization, and performance assessment. Dr. Gibbons has been a principal investigator for hydrogeology in many low level nuclear waste and uranium mine and mill tailings projects in the southwestern United States since 1976.

Darrell D. Porter, Panel Member, is a Senior Scientist and Manager with Science Applications International Corporation (SAIC). He has a Ph.D. in Mineral Engineering with a specialty in rock mechanics from the University of Minnesota. His M.S. degree from the Colorado School of Mines focused on experimental work in dynamic aspects of rock mechanics. He has 34 years of experience. Much of Dr. Porter's work has been in the field of blasting with high explosives and analyzing effects from a rock mechanics perspective. He has held technical management positions with the Rio Blanco Oil Shale Company where significant testing results paved the way for an effective process development resulting in four patents for Dr. Porter. During the past 13 years, Dr. Porter has supported the U.S. Geological Survey in their site characterization program for the Yucca Mountain Project. The work there included technical reviews, preparation of technical procedures, geological mapping programs, oversight of numerous contributing scientists involved in geologic sampling, mapping, modeling, technical data management, and preparation and implementation of quality assurance programs. He has collaborated with scientists from many of the National Laboratories and Universities on rock fracture and fragmentation issues.

Florie Caporuscio, Panel Member, is a Senior Scientist for Informatics Corporation. He received his Ph.D. in Geology from the University of Colorado, a Masters degree in Geology from Arizona State University, and a Bachelors degree in Geology from the University of Massachusetts. Dr. Caporuscio has 10 years of experience as a geochemist working on issues relating to high level and transuranic waste disposal.

Eric B. Oswald, Panel Member, is a Senior Scientist/Hydrologist-Water Resources Planning Specialist with the Morrison-Maierle Environmental Corporation in Tucson, Arizona. Dr. Oswald has a Ph.D. in Hydrology and Water Resources Administration and a Bachelors degree in Agricultural Economics, both from the University of Arizona. Dr. Oswald has over 25 years of experience relating to mine permitting, hazardous material contamination, flood control and flood plain design, resource damage and conservation, power generation, salinity, solid waste management, and water management. Dr. Oswald has managed many environmental programs for federal and state agencies, and municipalities.

Charles R. Wilson, Panel Technical Coordinator, has 26 years of experience managing a broad range of projects involving hydrogeology and geotechnical engineering, water resources planning, and environmental contamination. Dr. Wilson is a private consultant residing in New Mexico. He has a Ph.D. in Civil Engineering-Groundwater and a Masters degree in Geotechnical Engineering from the University of California at Berkeley. He received his Bachelors degree in Engineering from the University of California at Los Angeles. Dr. Wilson's work has included designing and conducting large scale hydrologic tests in very low permeability, fractured rock; design and regulatory permitting of large mixed radioactive/hazardous waste landfills; development of a national water resources planning agency for the Republic of the Philippines; and design of a site-wide groundwater monitoring system for the U.S. Department of Energy's Idaho National Engineering Laboratory.

Glen Sjoblom, Panel Member, is an independent consultant in the areas of nuclear waste management and safety management, residing in Great Falls, Virginia. He has a Master of Science in Chemical Engineering from University of California, Berkeley, a Bachelors of Science in Chemical Engineering from University of Minnesota, a Certificate in Nuclear Engineering from Bettis Atomic Power School, Pittsburgh, and a Certificate from the Course for Senior Managers in Government, JFK School, Harvard University. His graduate thesis dealt with two phase flow for heat and mass transfer; his undergraduate research dealt with solid liquid state chemical reaction kinetics. He was an officer in the United States Navy. He has held senior technical management positions in four different Federal Agencies over a thirty-year period, in Washington, D.C. He was responsible for the environmental controls aspects of the Naval Nuclear Propulsion Program, while on active Naval Service, including radiation protection, waste management, and environmental monitoring. He was Director of the Office of Radiation Programs at the Environmental Protection Agency, and directed development and promulgation of environmental standards for high level and transuranic waste, uranium mill tailings, Presidential Guidance to Federal Agencies on Occupational Radiation, and improved emergency response capability. He directed improvements in safety regulation and enforcement over nuclear fuel cycle facilities, industrial and medical uses of radioactive materials, promoted improved cleanup of deactive nuclear facilities, and improved interagency coordination on chemical safety, while a Deputy Division Director at the Nuclear Regulatory Commission. He directed formation of an Environmental Management Advisory Board, and focused on improved public involvement and the use of risk assessment science in environmental restoration and waste management programs, while a Special Assistant Secretary for Environmental Management, Department of Energy. Throughout his career he has utilized risk assessment modeling and methods to promote sound decisions in the public interest.

DETERMINATIONS OF PEER REVIEW MEMBER INDEPENDENCE

C.R. Wilson

Determination of Peer Review Member Independence Form

____ Currently employed by DOE or DOE Contractor? Yes/No

__x__ Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983-1985 Hydrotechnique Inc, Berkeley CA - Performed consulting services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting services to Hanford, INEL, Los Alamos Sites

____ Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Charles R Wilson

Date: 3/29/96

Peer Review Manager Approval: John A. Thies   4/8/96 Date

Darrell Porter

Determination of Peer Review Member Independence Form

Yes Currently employed by DOE or DOE Contractor? Yes/No

yes Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SAIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP Programs.

No Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Darrell Porter

Date: March 29, 1996

Peer Review Manager Approval: John A. Thies 4/8/96
Date

E.B. Oswald

Determination of Peer Review Member Independence Form

No — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor <u>previously</u>? Yes/No

If yes, give dates, location, company, position type work performed.

April Through August 1995. Albuquerque NM. S.M. Stoller Corporation. Served as Independent Review Team member assisting WIPP WTAC in the review of data record packages.

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: ______________________

Date: 3/30/96

Peer Review Manager Approval: ______________________ 4/8/96

John A. Thies — Date

Florie Caporuscio

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

Yes — Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

4/96 Informatics, Albuquerque NM, Staff consultant
Peer Review of WIPP

8/93 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project Manager and Senior technical Lead, Environmental Restoration Project

No — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: 4/1/96

Peer Review Manager Approval: [signature] 4-1-96

John A. Thies — Date

Glen Sjoblom

Determination of Peer Review Member Independence Form

1. 2. See below — Currently employed by DOE or DOE Contractor? Yes/No
Employed by DOE/or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

1. I have a contract with Oak Ridge Institute for Science and Education, to provide an assessment of effectiveness of DOE office of Nuclear Energy Program of Assistance ~~of~~ nuclear reactor safety to Former Soviet Countries; this has no bearing on the proposed peer review at WIPP.
2. I was a special assistant to the Asst. Secy for Environmental Management but was not involved with Activities at WIPP.

NO — Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: Glen L. Sjoblom

Date: 3/29/96

Peer Review Manager Approval: John A. Thies — 4/8/96 Date

John Gibbons

Determination of Peer Review Member Independence Form

NO Currently employed by DOE or DOE Contractor? Yes/No

Yes Employed by DOE or DOE Contractor <u>previously</u>? Yes/No

If yes, give dates, location, company, position type work performed.

Battelle Alb., IRT reviewer of WIPP Data Packages 1994-1995

AFA & Alb. Site Characterization Technology Research 1992-1993

SNL Civil Systems Inc., High Level WIPP Experiment Planning 1977-1978

NO Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature] II

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies 4/8/96 Date

CERTIFICATIONS REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

C.R. Wilson

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No.__________ Date of Offer __________

Name of Offeror:__________ Signature Charles R Wilson

Date Signed: 3/29/96 Typed name CHARLES R. WILSON

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies: and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Darrell Porter

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No.____________________ Date of Offer 3/29/96

Name of Offeror: DARRELL PORTER Signature Darrell Porter

Date Signed: April 2, 1996 Typed name____________________

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

E.B. Oswald

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No.______________ Date of Offer 4/1/96

Name of Offeror:______________ Signature [signature]

Date Signed: ______________ Typed name Eric B.Oswald

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Florie Caporuscio

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No.__________ Date of Offer 3/25/96

Name of Offeror: Florie A Caporuscio Signature Florie A Caporuscio

Date Signed: 4/1/96 Typed name__________

3. SUPPLEMENTAL INFORMATION

(a) As *supplemental information to the organizational conflicts of interest* Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (X) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

Glen Sjoblom

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No ____________ Date of Offer 3/25/96

Name of Offeror: Glen L. Sjoblom Signature Glen L Sjoblom

Date Signed: 3/29/96 Typed name ____________

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (*oil drilling, railroads*) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (X) No

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(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (X) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (X) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (X) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

John Gibbons

CERTIFICATION REGARDING ORGANIZATIONAL CONFLICTS OF INTEREST

(Complete and return if there are no known interests relevant to possible organizational conflicts of interest)

I certify to my best knowledge and belief that no facts exist concerning any past, present, or currently planned interests (financial, contractual, organizational, or otherwise) relating to the work to be performed pursuant to this solicitation and bearing on a possible organizational conflict of interest.

Solicitation No. ________	Date of Offer ________
Name of Offeror: John Gibbons	Signature ________
Date Signed: Mar 29/96	Typed name ________

3. SUPPLEMENTAL INFORMATION

(a) As supplemental information to the organizational conflicts of interest Disclosure or Representation, the Offeror shall provide answers to the following questions (provide a complete explanation for each answer):

(i) Does the Offeror have any involvement with or interests in technologies which may be subjects of the subcontract or which are substitutable for such technologies? This involvement or interest could take any form, including interest in relevant proprietary processes or in patents; interests in energy consuming or producing industries (utilities) or ancillary industries (oil drilling, railroads) which could be affected by the technologies; and interests in energy resources (coal, timber, natural gas, geothermal sites). ( ) Yes (✓) No

(ii) Does the Offeror depend upon industries or firms, which could be affected by actions resulting from the subcontract, for a significant portion of its business, or have a relationship (financial, organizational, contractual or otherwise) with such industries or firms? ( ) Yes (✓) No

(iii) Where work in support of DOE's regulatory activities is contemplated, could any impact result from these regulatory activities directly to the Offeror, or to its business clients? ( ) Yes (✓) No ( ) N/A

(iv) Will Offeror perform any self evaluation or inspection of a service or product, or evaluation or inspection of another with whom a relation-ship exists, including evaluation or inspection of goods or services which compete commercially with the performer's goods or services? ( ) Yes (✓) No

(v) Will any of the Offeror's chief executives, directors, or entities which they own or represent, or any of the Offeror's affiliates be involved in the performance of the subcontract? ( ) Yes (✓) No

(If "yes" provide an adequate disclosure or representation statement from each such executive, director, entity or affiliate.)

(b) The Offeror shall also provide a description of its experience pertinent to the proposed effort, and resumes of key personnel, a current annual report, and a current 10K statement (if filed by the Offeror).

APPENDIX B - SIGNATURE PAGE

I acknowledge by my signature below that I concur with the findings and conclusions documented in this Conceptual Models Peer Review Report.

Florie Caporuscio

John Gibbons

Eric Oswald

Darrell Porter

Glen Sjoblom

Charles Wilson