Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Executive Summary

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Executive Summary

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Acronyms and Abbreviations

CCA	Compliance Certification Application
CCDF	complementary cumulative distribution functions
CFR	Code of Federal Regulations
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEPs	features, events, and processes
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
MgO	magnesium oxide
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
T fields	transmissivity fields
TRU	transuranic
RH	Remote-Handled
WIPP	Waste Isolation Pilot Plant

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EXECUTIVE SUMMARY

EXECSUM-1.0 Overview

The Waste Isolation Pilot Plant (WIPP), located near Carlsbad, New Mexico, is a deep geologic repository for the disposal of transuranic (TRU) wastes generated by U.S. defense activities. The WIPP Land Withdrawal Act (LWA) (Pub. L. 102-579, 106 stat. 4777, as amended by Pub. L. 104-201, 110 stat. 2422) requires the U.S. Environmental Protection Agency (EPA) to certify the WIPP's compliance with the long-term disposal regulations of 40 CFR Part 191 Subparts B and C prior to the commencement of disposal operations. To comply with this requirement, the U.S. Department of Energy (DOE) submitted the Compliance Certification Application (CCA) in October 1996 demonstrating compliance with the disposal standards and the criteria for compliance established at 40 CFR Part 194. The CCA demonstrated how the geological, hydrological, physical, chemical, and environmental characteristics of the site, along with engineered features of the facility, would safely contain radioactive waste for the 10,000-year regulatory time period. After a thorough review of the CCA, the EPA certified WIPP's compliance with these regulations in May 1998, paving the way for waste disposal operations which began on March 26, 1999.

The WIPP LWA also requires the DOE to submit documentation of WIPP's continued compliance with the disposal regulations to the EPA not later than five years after initial receipt of TRU waste for disposal at the repository, and every five years thereafter until the decommissioning of the facility is completed. This periodic documentation of continued compliance is referred to as "recertification." The DOE has completed one recertification cycle. The first Compliance Recertification Application (CRA-2004) was submitted to the EPA on March 26, 2004. After a thorough review of the CRA-2004, the EPA recertified the WIPP's compliance on March 29, 2006. The second five-year recertification cycle ends on March 26, 2009. As with the CRA-2004, the CRA-2009 is being submitted to the EPA in accordance with the provisions of the LWA and demonstrates that the WIPP continues to be in compliance with the applicable radioactive waste disposal standards.

According to the WIPP Certification Criteria at 40 CFR § 194.15, recertification applications must include any information that is new or different from information contained in the most recent compliance application. Therefore, the DOE must review any new information that relates to the WIPP's certification basis and include the new information in each CRA. The central message of this CRA-2009 is that no significant changes have taken place since the CRA-2004 was submitted in March 2004. While there are minor changes documented and analyzed in the following recertification application, none compromise compliance with the radioactive waste disposal standards. The second five-year recertification cycle ends on March 26, 2009. As with the CRA-2004, the CRA-2009 is being submitted to the EPA in accordance with the provisions of the LWA and demonstrates that the WIPP continues to be in compliance with the applicable radioactive waste disposal standards. Continuing scientific studies and analyses have led to the conclusion that the WIPP repository is operating and performing as expected. This conclusion is underpinned by the fact that the results and analyses based on well-established probabilistic modeling tools show that the repository will not adversely impact public health and the environment during the required regulatory period.

EXECSUM-1.1 Contents of the CRA-2009

The CRA-2009 has been developed in accordance with the EPA's Certification Criteria found at Part 194. The Criteria allow unchanged information contained in previous applications to be referenced, rather than repeated in recertification applications. Topics addressed in the CRA-2009 include, but are not limited to, the following:

- Natural and engineered features of the disposal system, including geology, geophysics, and hydrogeology of the repository and its environs, as well as the geochemistry of interactions between the disposal system and the wastes placed in it
- Information concerning the inventory of TRU waste emplaced in the repository, stored at DOE sites, and the waste expected to be generated at those sites and shipped to the WIPP in the future
- Updated WIPP-relevant features, events, and processes (FEPs) based on data and information acquired since the most recent CRA. FEPs are screened using specific criteria to determine what phenomena and components of the disposal system can and should be dealt with in PA calculations.
- Assessments of the disposal system's long-term performance, including the input parameters and models used in those assessments
- Individual and groundwater protection standards and the DOE's analyses demonstrating that the WIPP meets or exceeds those standards and will continue to do so
- Assurance requirements, including active and passive institutional controls, monitoring, and the effects of natural resource extraction.

EXECSUM-1.2 Changes Since the CRA-2004

This application incorporates information about, and assessments of, changes proposed by the DOE and approved by the EPA or requested by the EPA since the CRA-2004. In addition, some changes were driven by the availability of new data. These changes may involve different aspects of the physical repository and its components, as well as changes to the predictive tools used to demonstrate compliance. These changes include

- Inventory: The inventory included in the CRA-2004 was updated during the CRA-2004 Performance Assessment Baseline Calculation (PABC) in response to comments from the EPA. The inventory used in the CRA-2009 PA is the same as the PABC inventory, which is slightly different from that used in the CRA-2004. Section 24 of this application contains details on the inventory.
- Remote-Handled (RH) TRU Waste: WIPP began accepting RH-TRU waste in January 2007. The impact to the performance of the repository for this waste is assessed in the current performance assessment (PA) as was done in all previous PAs. Information related to the RH-TRU certification process is found in Sections 8 and 21.

- CRA-2004 PABC Parameters: Changes to the CRA-2004 PA were made during the recertification process as part of the CRA-2004 PABC. The CRA-2004 PABC included changes in gas generation modeling, PA parameter changes, new Culebra transmissivity fields (T fields), and revisions to the calculations of spallings releases during drilling.

- CRA-2009 PA Updates: Changes to PA since the CRA-2004 PABC include parameter updates, code improvements, and corrections. Upgrades were also made to the computational platform used to execute the CRA-2009 PA. These changes are described in detail in Appendix PA-2009, Section PA-2.1.1.

- Engineered Barrier: The DOE obtained approval from the EPA to reduce the excess factor for the WIPP's engineered barrier (magnesium oxide – MgO chemical buffer) from 1.67 to 1.2. Additionally, the supplier for the engineered barrier has changed from that used during the CRA-2004. See Section 44 of this application for additional information. These changes are detailed in Appendix MgO-2009.

- Peer Review: Documentation of WIPP peer reviews pertaining to RH-TRU waste visual examination data verification and sealed sources at Los Alamos National Laboratory (LANL) are presented in the CRA-2009. These peer reviews are detailed in Section 27.

EXECSUM-1.3 Results

Past PA results included in the previous certification applications (and two previous EPA-requested PAs) have all demonstrated compliance with the release limits of 40 CFR Part 191. Based on these PA results and other information contained in the compliance applications, the EPA has continued to certify the WIPP's compliance with the long-term disposal regulations. Similar to the CRA-2004, the CRA-2009 assesses the combined effect of any new changes on the performance of the disposal system. As with the results of past PAs, the combined effects of changes analyzed in this CRA do not adversely impact performance or compliance; the predicted releases from the repository remain well below the limits specified in Part 191 Subpart B. Continued compliance with the assurance requirements of the standards and the criteria is also demonstrated by CRA-2009.

The results of the CRA-2009 PA demonstrate that the repository continues to comply with the disposal standards. The results demonstrate a greater-than-95% level of statistical confidence that the overall mean of the population of complementary cumulative distribution functions (CCDFs) is in compliance with the containment requirements of 40 CFR § 191.13. The overall mean CCDFs of the CCA, CRA-2004, and CRA-2009 are shown in Figure EXECSUM-1 and illustrate the wide margin of compliance of the predicted releases with respect to the release limits.

Similarly, compliance analyses performed on the undisturbed repository result in a single postulated release whose value is significantly smaller than even the very small release estimated by the same analyses in the CCA. Taken together, the CCA, the CRA-2004, and the CRA-2009 compliance analyses demonstrate that the WIPP continues to comply with the individual and groundwater protection standards in Part 191 Subparts B and C.

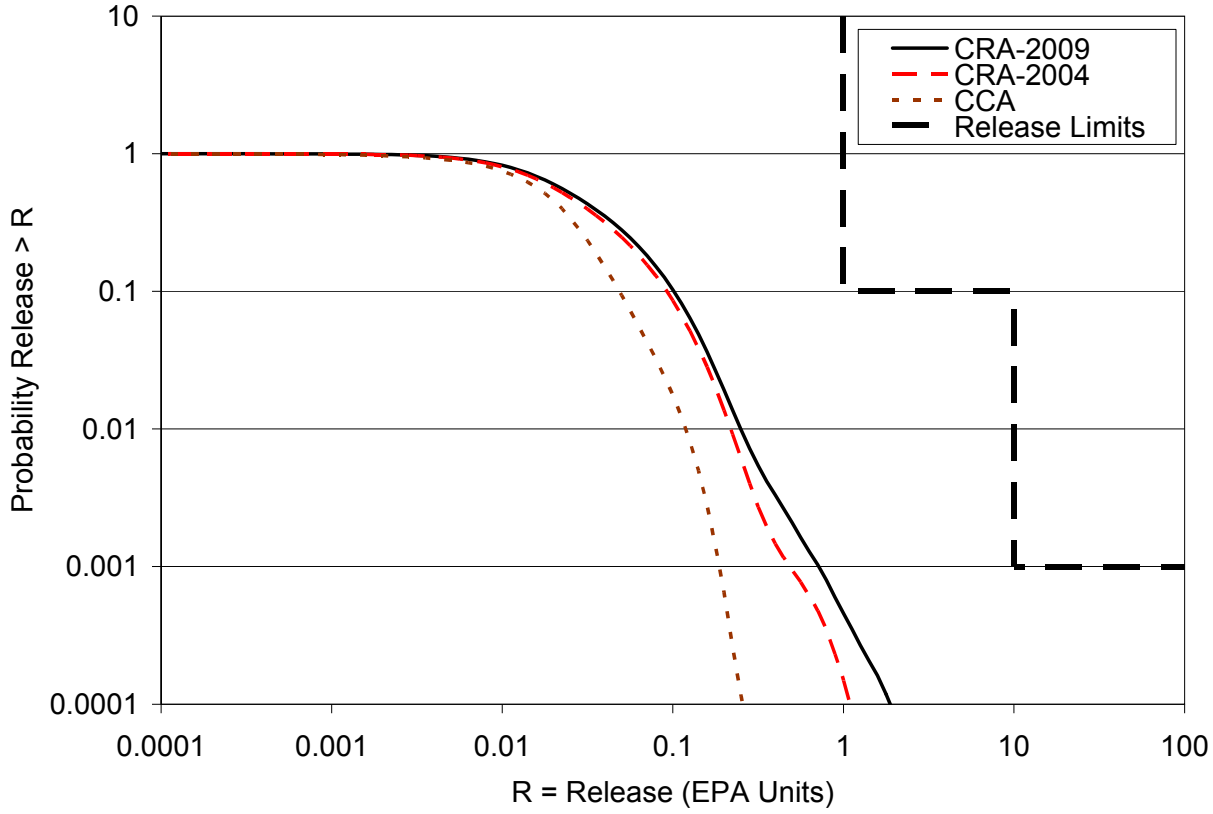

Figure EXECSUM-1. Overall Mean Total Releases for the CCA, CRA-2004, and CRA-2009

Title 40 CFR Part 191
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Approval Process for Waste Shipment From Waste Generator Sites for Disposal at the WIPP
(40 CFR § 194.8)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Approval Process for Waste Shipment From Waste Generator Sites for Disposal at the WIPP
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Acronyms and Abbreviations

ANL	Argonne National Laboratory
CARD	Compliance Application Review Document
CCP	Central Characterization Project
CH-TRU	contact-handled transuranic
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
NTS	Nevada Test Site
ORNL	Oak Ridge National Laboratory
QA	quality assurance
RFETS	Rocky Flats Environmental Technology Site
RH-TRU	remote-handled transuranic
RL	Hanford-Richland
SRS	Savannah River Site
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

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8.0 Approval Process for Waste Shipment From Waste Generator Sites for Disposal at the WIPP (40 CFR § 194.8)

8.1 Requirements

§ 194.8 Approval Process for Waste Shipment From Waste Generator Sites for Disposal at the WIPP

(a) *Quality Assurance Programs at Waste Generator Sites.* The Agency will determine compliance with requirements for site-specific quality assurance programs as set forth below:

(1) Upon submission by the Department of a site-specific quality assurance program plan the Agency will evaluate the plan to determine whether it establishes the applicable Nuclear Quality Assurance (NQA) requirements of § 194.22(a)(1) for the items and activities of §§ 194.22(a)(2)(i), 194.24(c)(3) and 194.24(c)(5). The program plan and other documentation submitted by the Department will be placed in the dockets described in § 194.67.

(2) The Agency will conduct a quality assurance audit or an inspection of a Department quality assurance audit at the relevant site for the purpose of verifying proper execution of the site specific quality assurance program plan. The Agency will publish a notice in the FEDERAL REGISTER announcing a scheduled inspection or audit. In that or another notice, the Agency will also solicit public comment on the quality assurance program plan and appropriate Department documentation described in paragraph (a)(1) of this section. A public comment period of at least 30 days will be allowed.

(3) The Agency's written decision regarding compliance with the requisite quality assurance requirements at a waste generator site will be conveyed in a letter from the Administrator's authorized representative to the Department. No such compliance determination shall be granted until after the end of the public comment period described in paragraph (a)(2) of this section. A copy of the Agency's compliance determination letter will be placed in the public dockets in accordance with § 194.67. The results of any inspections or audits conducted by the Agency to evaluate the quality assurance programs described in paragraph (a)(1) of this section will also be placed in the dockets described in § 194.67.

(4) Subsequent to any positive determination of compliance as described in paragraph (a)(3) of this section, the Agency intends to conduct inspections, in accordance with §§194.21 and 194.22(e), to confirm the continued compliance of the programs approved under paragraphs (a)(2) and (a)(3) of this section. The results of such inspections will be made available to the public through the Agency's public dockets, as described in § 194.67.

(b) *Waste characterization programs at transuranic waste sites.* The Agency will establish compliance with Condition 3 of the certification using the following process:

(1) DOE will implement waste characterization programs and processes in accordance with § 194.24(c)(4) to confirm that the total amount of each waste component that will be emplaced in the disposal system will not exceed the upper limiting value or fall below the lower limiting value described in the introductory text of § 194.24(c). Waste characterization processes will include the collection and use of acceptable knowledge; destructive and/or nondestructive techniques for identifying and measuring waste components; and the validation, control, and transmittal to the WIPP Waste Information System database of waste characterization data, in accordance with § 194.24(c)(4).

(2) The Agency will verify the compliance of waste characterization programs and processes identified in paragraph (b)(1) of this section at sites without EPA approval prior to October 14, 2004, using the following process:

(i) DOE will notify EPA by letter that a transuranic waste site is prepared to ship waste to the WIPP and has established adequate waste characterization processes and programs. DOE also will provide the relevant waste characterization program plans and documentation. EPA may request additional information from DOE.

(ii) EPA will conduct a baseline compliance inspection at the site to verify that adequate waste characterization program plans and technical procedures have been established, and that those plans and procedures are effectively implemented. The inspection will include a demonstration or test by the site of the waste characterization processes identified in paragraph (b)(1) of this section. If an inspection does not lead to approval, we will send an inspection report to DOE identifying deficiencies and place the report in the public docket described in § 194.67. More than one inspection may be necessary to resolve compliance issues.

(iii) The Agency will announce in the FEDERAL REGISTER a proposed Baseline Compliance Decision to accept the site's compliance with § 194.24(c)(4). We will place the inspection report(s) and any supporting documentation in the public docket described in § 194.67. The site inspection report supporting the proposal will describe any limitations on approved waste streams or waste characterization processes. It will also identify (through tier

designations in accordance with paragraph (b)(4) of this section) what changes to the approved waste characterization processes must be reported to and approved by EPA before they can be implemented. In the notice, we will solicit public comment (for a minimum of 45 days) on the proposed Baseline Compliance Decision, including any limitations and the tier designations for future changes or expansions to the site's waste characterization program.

(iv) Our written decision regarding compliance with the requirements for waste characterization programs and processes described in paragraph (b)(1) of this section will be conveyed in a letter from the Administrator's authorized representative to DOE. EPA will not issue a compliance decision until after the end of the public comment period described in paragraph (b)(2)(iii) of this section. EPA's compliance decision will respond to significant and timely-received comments. A copy of our compliance decision will be placed in the public docket described in § 194.67. DOE will comply with any requirements identified in the compliance decision and the accompanying inspection report.

(3) Subsequent to any positive determination of compliance as described in paragraph (b)(2)(iv) of this section, the Agency intends to conduct inspections, in accordance with § 194.24(h), to confirm the continued compliance of approved waste characterization programs and processes at transuranic waste sites. EPA will make the results of these inspections available to the public in the dockets described in § 194.67.

(4) Subsequent to any positive determination of compliance as described in paragraph (b)(2)(iv) of this section, the Department must report changes or expansions to the approved waste characterization program at a site in accordance with the tier designations established in the Baseline Compliance Decision.

(i) For changes or expansions to the waste characterization program designated as ''Tier 1,'' the Department shall provide written notification to the Agency. The Department shall not ship for disposal at WIPP any waste that has been characterized using the new or revised processes, equipment, or waste streams until EPA has provided written approval of such new or revised systems.

(ii) For changes or expansions to the waste characterization program designated as ''Tier 2,'' the Department shall provide written notification to the Agency. Waste characterized using the new or revised processes, equipment, or waste streams may be disposed at WIPP without written EPA approval.

(iii) EPA may conduct inspections in accordance with § 194.24(h) to evaluate the implementation of Tier 1 and Tier 2 changes or expansions to the waste characterization program at a site.

(iv) Waste characterization program changes or expansions that are not identified as either ''Tier 1'' or ''Tier 2'' will not require written notification by the Department to the Agency before implementation or before shipping waste for disposal at WIPP.

(5) Subsequent to any positive determination of compliance as described in paragraph (b)(2)(iii) of this section, EPA may revise the tier designations for approving changes or expansions to the waste characterization program at a site using the following process:

(i) The Agency shall announce the proposed tier changes in a letter to the Department. The letter will describe the Agency's reasons for the proposed change in tier designation(s). The letter and any supporting inspection report(s) or other documentation will be placed in the dockets described in § 194.67.

(ii) If the revised designation entails more stringent notification and approval requirements (*e.g.*, from Tier 2 to Tier 1, or from undesignated to Tier 2), the change shall become effective immediately and the site shall operate under the more stringent requirements without delay.

(iii) If the revised designated entails less stringent notification and approval requirements, (*e.g.*, from Tier 1 to Tier 2, or from Tier 2 to undesignated), EPA will solicit comments from the public for a minimum of 30 days. The site will continue to operate under the more stringent approval requirements until the public comment period is closed and EPA notifies DOE in writing of the Agency's final decision.

(6) A waste generator site that EPA approved for characterizing and disposing transuranic waste at the WIPP under this section prior to October 14, 2004, may continue characterizing and disposing such waste at the WIPP under paragraph (c) of this section until EPA has conducted a baseline compliance inspection and provided a Baseline Compliance Decision under paragraph (b)(2) of this section.

(i) Until EPA provides a Baseline Compliance Decision for such a site, EPA may approve additional transuranic waste streams for disposal at WIPP under the provisions of paragraph (c) of this section. Prior to the effective date of EPA's Baseline Compliance Decision for such a site, EPA will continue to conduct inspections of the site in accordance with § 194.24(c).

(ii) EPA shall conduct a baseline compliance inspection and issue a Baseline Compliance Decision for such previously approved sites in accordance with the provisions of paragraph (b) of this section, except that the site shall not be required to provide written notification of readiness as described in paragraph (b)(2)(i) of this section.

(c) *Waste characterization programs at waste generator sites with prior approval.* For a waste generator site

that EPA approved for characterizing and disposing transuranic waste at the WIPP under this section prior to October 14, 2004, the Agency will determine compliance with the requirements for use of process knowledge and a system of controls at waste generator sites as set in this paragraph (c). Approvals for a site to characterize and dispose of transuranic waste at WIPP will proceed according to this section only until EPA has conducted a baseline compliance inspection and provided a Baseline Compliance Decision for a site under paragraph (b)(2) of this section.

(1) For each waste stream or group of waste streams at a site, the Department must:

(i) Provide information on how process knowledge will be used for waste characterization of the waste stream(s) proposed for disposal at the WIPP; and

(ii) Implement a system of controls at the site, in accordance with § 194.24(c)(4), to confirm that the total amount of each waste component that will be emplaced in the disposal system will not exceed the upper limiting value or fall below the lower limiting value described in the introductory text of § 194.24(c). The implementation of such a system of controls shall include a demonstration that the site has procedures in place for adding data to the WIPP Waste Information System (''WWIS''), and that such information can be transmitted from that site to the WWIS database; and a demonstration that measurement techniques and control methods can be implemented in accordance with § 194.24(c)(4) for the waste stream(s) proposed for disposal at the WIPP.

(2) The Agency will conduct an audit or an inspection of a Department audit for the purpose of evaluating the use of process knowledge and the implementation of a system of controls for each waste stream or group of waste streams at a waste generator site. The Agency will announce a scheduled inspection or audit by the Agency with a notice in the FEDERAL REGISTER. In that or another notice, the Agency will also solicit public comment on the relevant waste characterization program plans and Department documentation, which will be placed in the dockets described in § 194.67. A public comment period of at least 30 days will be allowed.

(3) The Agency's written decision regarding compliance with the requirements for waste characterization programs described in paragraph (b)(1) of this section for one or more waste streams from a waste generator site will be conveyed in a letter from the Administrator's authorized representative to the Department. No such compliance determination shall be granted until after the end of the public comment period described in paragraph (b)(2) of this section. A copy of the Agency's compliance determination letter will be placed in the public dockets in accordance with § 194.67. The results of any inspections or audits conducted by the Agency to evaluate the plans described in paragraph (b)(1) of this section will also be placed in the dockets described in § 194.67.

(4) Subsequent to any positive determination of compliance as described in paragraph (b)(3) of this section, the Agency intends to conduct inspections, in accordance with §§194.21 and 194.24(h), to confirm the continued compliance of the programs approved under paragraphs (b)(2) and (b)(3) of this section. The results of such inspections will be made available to the public through the Agency's public dockets, as described in § 194.67.

[63 FR 27404, May 18, 1998, as amended at 69 FR 42581, July 16, 2004]

8.2 Background

The requirements of 40 CFR § 194.8 (U.S. Environmental Protection Agency 2004a) apply to the process used by the U.S. Environmental Protection Agency (EPA) to approve the disposal of transuranic (TRU) waste from U.S. Department of Energy (DOE) waste generator sites to the Waste Isolation Pilot Plant (WIPP).

The requirements were established at the time of the EPA's 1998 Certification Decision to address compliance of site-specific quality assurance (QA) programs and a system of waste characterization and controls at waste generation sites.[1]

[1] The dose rate of transuranic waste to be shipped to WIPP is measured at the generator sites to determine if the waste is remote-handled transuranic (RH-TRU) waste or contact-handled transuranic (CH-TRU) waste and the waste is certified in accordance with these measurements. Radionuclide dose rates of waste assemblies (i.e., drum seven packs, ten drum over pack) are measured at the WIPP site for worker health and safety issues only.

8.3 1998 Certification Decision

In order to clarify the EPA's original intent for the compliance criteria regarding approval of site-specific activities, the EPA amended the compliance criteria at 40 CFR Part 194 to include the site-specific approval process (U.S. Environmental Protection Agency 1998, pp. 27404–406). Appendix A of the EPA's Certification Decision contains the requirements for the approval process and four certification-related conditions. Two of the four conditions included in this appendix are related to QA and waste characterization. Condition 2 specifies that no waste generator site other than the Los Alamos National Laboratory (LANL) shall be allowed to ship waste for disposal at the WIPP until the EPA determines that the site has established and executed a QA program in accordance with 40 CFR §§ 194.22(a)(2)(i) (U.S. Environmental Protection Agency 1996), 194.14(c)(3) (U.S. Environmental Protection Agency 1996), and 194.24(c)(5) (U.S. Environmental Protection Agency 2004a) for waste characterization activities and assumptions. Condition 3 specifies that no waste from any additional LANL waste streams (other than the ones already certified) or from any waste generator site other than LANL shall be shipped for disposal at the WIPP until the EPA has approved the process for characterizing those waste streams for shipment using the process set forth in section 194.8. The approval process includes an opportunity for public comment and an inspection (of a DOE audit) or audit of the waste generator site by the EPA. The procedures for demonstrating compliance with Conditions 2 and 3 of the EPA's 1998 Certification Decision were incorporated in the final rule as a new section to section 194.8, "Approval Process for Waste Shipment from Waste Generator Sites for Disposal at the WIPP."

For both QA and waste characterization programs, the approval process includes placement in the docket of site-specific documentation submitted by the DOE, publication of a *Federal Register* notice by the EPA announcing a scheduled inspection or audit, a period of at least 30 days for the public to comment on information placed in the docket, and the EPA's written decision regarding the approval of these programs in the form of a letter from the EPA to the DOE. The EPA proposed to approve QA programs on a site-wide basis and to approve waste characterization measures and controls on the basis of waste streams or, where multiple waste streams may be characterized by the same waste characterization processes and techniques, groups of waste streams.

8.4 Changes in the CRA-2004

A discussion of the requirements for section 194.8 was added to the Compliance Recertification Application of 2004 (CRA-2004) (U.S. Department of Energy 2004, Chapter 4.0). The CRA-2004 notes, "based on EPA acceptance of the site-specific TRU waste characterization and QA program, the Carlsbad Field Office Manager is responsible for granting and revoking the program certification that allows the TRU waste site to characterize and to ship waste to WIPP" but also adds, "consistent with the provisions of section 194.8, EPA also has a role in the approval process. The EPA determines compliance with requirements for site-specific QA programs." In addition to determining QA compliance, the EPA also approves the waste characterization programs at generator sites to ensure that the system of controls required to track important components is technically adequate.

The CRA-2004 notes that according to the WIPP Waste Information System (WWIS), as of September 30, 2002, the following five sites had approved QA and waste characterization programs under section 194.8 requirements: Hanford-Richland (RL), the Idaho National Engineering and Environmental Laboratory (now called the Idaho National Laboratory [INL]), LANL, the Rocky Flats Environmental Technology Site (RFETS), and the Savannah River Site (SRS). Additionally, the DOE's Central Characterization Project (CCP) had been approved to characterize and ship waste from SRS, Argonne National Laboratory (ANL), and the Nevada Test Site (NTS).

8.5 EPA's Evaluation of Compliance for the 2004 Recertification

The CRA-2004 did not identify instances where waste had been shipped to the WIPP from a generator site prior to approval of its waste characterization programs by the EPA before the CRA-2004 cutoff date of September 22, 2002. However, instances have occurred where waste was shipped before approval of instrumentation or techniques used to characterize that waste by the EPA Compliance Application Review Document (CARD) 8 (U.S. Environmental Protection Agency 2006a). In these cases, the DOE discontinued shipment of the waste under investigation until the EPA completed its inspection and approval. The EPA received no public comments on the DOE's continued compliance with the approval process for waste shipment from waste generator sites for disposal at the WIPP.

Based on its review and evaluation of the CRA-2004, supplemental information provided by the DOE, and the EPA inspections and audits, the EPA determined that the DOE continued to comply at that time with the requirements for section 194.8 (U.S. Environmental Protection Agency 2006b).

8.6 Changes or New Information Since the 2004 Recertification

The TRU waste sites approved by the EPA to ship contact-handled (CH) transuranic (TRU) (CH-TRU) waste to the WIPP in accordance with the requirements of section 194.8 are as follows: RL, INL/CCP, Advanced Mixed Waste Treatment Project, SRS/CCP, Oak Ridge National Laboratory (ORNL)/CCP (EPA-ORNL-CCP-CH-11.07-8) (U.S. Environmental Protection Agency 2008a), and LANL/CCP. The TRU waste sites identified in the CRA-2004 that have shipped CH-TRU waste to the WIPP but are not currently active are Lawrence Livermore National Laboratory (LLNL), NTS, ANL, and RFETS. RFETS has completed shipping its TRU waste. LLNL was certified after the CRA-2004 was submitted (EPA-LANL-CCP-5.04-8) (U.S. Environmental Protection Agency 2004b).

Since the CRA-2004, TRU waste characterization at LANL, SRS, and INL that was previously performed using site resources is now being performed by CCP resources. An inspection was performed by the EPA in April 2004 at LANL/CCP (EPA-LANL-CCP-4.04-08) (U.S. Environmental Protection Agency 2004c). Approval was granted in August 2004 for the CCP to characterize and ship CH-TRU waste from LANL. The EPA conducted a baseline inspection and QA audit of INL/CCP in May 2005. Approval was granted by the EPA on November 1, 2005, for the CCP to characterize and ship CH-TRU waste from the INL.

On March 26, 2004, the EPA announced its final decision (Marcinowski 2004) to approve the DOE's *Remote-Handled TRU Waste Characterization Program Implementation Plan* (U.S. Department of Energy 2003a and 2003b). The EPA stated that on-site inspections and approval of site-specific, remote-handled (RH) transuranic (TRU) (RH-TRU) waste characterization programs will be conducted under the authority at section 194.8 or 40 CFR § 194.24, as appropriate. Since then, four sites have been approved for RH-TRU waste characterization and shipment to the WIPP. The EPA conducted a baseline inspection at INL/CCP in June and August 2006 (U.S. Environmental Protection Agency 2007a) and approved the characterization program on January 12, 2007 (U.S. Environmental Protection Agency 2007a). The baseline approval designated the initiation of the WWIS for RH-TRU waste as a Tier 1 change (as defined in section 194.8). The EPA approved a Tier 1 change request in January 2008 to add K-Cell waste to the RH-TRU Waste Certification for INL/CCP (U.S. Environmental Protection Agency 2008b). The EPA also conducted a QA program inspection and baseline inspection (Inspection Number EPA-ANL-CCP-RH-09.06-08) at ANL/CCP in September 2006 (U.S. Environmental Protection Agency 2007b). The QA program was approved on December 20, 2006 (Reyes 2006), and the characterization program was approved on January 16, 2007 (U.S. Environmental Protection Agency 2007b). As with INL/CCP, the baseline approval designated the initiation of the WWIS for RH-TRU waste as a Tier 1 change. A review of WWIS data entry and waste component tracking was conducted by the EPA on November 21, 2006. The WWIS system was determined to be adequate for RH-TRU waste characterized by INL/CCP and ANL/CCP, as described by EPA correspondence dated January 17, 2007 (Reyes 2007). The EPA approved a Tier 1 change request in July 2008 to add newly-packaged waste to the RH-TRU Waste Certification for ANL/CCP (U.S. Environmental Protection Agency 2008c). In February 2008, the EPA approved the baseline for RH-TRU Waste Characterization for LANL/CCP (Inspection Number EPA-LANL-CCP-RH-05.07-8) (U.S. Environmental Protection Agency 2008d). In August 2008, the EPA approved the baseline for RH-TRU Waste Characterization for SRS-BCL/CCP (Inspection Number EPA-SRS-CCP-RH-07.07-8) (U.S. Environmental Protection Agency 2008e). The EPA conducted a baseline inspection (July 2008) of the RH-TRU Waste Characterization process at ORNL/CCP. Approval of the inspection has not been received at this time. The DOE continues to comply with the requirements of section 194.8 and there are no outstanding issues with the EPA related to section 194.8.

8.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Content of Compliance
Recertification Application(s)
(40 CFR § 194.15)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Content of Compliance Recertification Application(s) (40 CFR § 194.15)

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Acronyms and Abbreviations

ACR	Annual Change Report
ASER	Annual Site Environmental Report
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
COMP	compliance monitoring parameter
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRZ	Disturbed Rock Zone
EPA	U.S. Environmental Protection Agency
EXO	enriched xenon observatory
ft	foot/feet
GAR	Geotechnical Analysis Report
high-T	high-transmissivity
in	inch
km	kilometer
LANL	Los Alamos National Laboratory
LWA	Land Withdrawal Act
MEGA	multiple element germanium array
mi	mile
mm	millimeters
NE	northeast
NMIMT	New Mexico Institute of Mining and Technology
PA	performance assessment
PABC	performance assessment baseline calculation
RH-TRU	remote-handled transuranic
SEGA	segmented enriched germanium assembly
SNL	Sandia National Laboratories
SPDV	Site and Preliminary Design Validation

SSW	shallow subsurface water
SW	southwest
TDS	total dissolved solids
TRU	transuranic
WIPP	Waste Isolation Pilot Plant

Elements and Chemical Compounds

Am	americium
MgO	magnesium oxide
Nd	neodymium
Pu	plutonium
U	uranium

15.0 Content of Compliance Recertification Application(s) (40 CFR § 194.15)

15.1 Requirements

§ 194.15 Content of Compliance Recertification Application(s)

(a) In submitting documentation of continued compliance pursuant to section 8(f) of the WIPP LWA, the previous compliance application shall be updated to provide sufficient information for the Administrator to determine whether or not the WIPP continues to be in compliance with the disposal regulations. Updated documentation shall include:

(1) All additional geologic, geophysical, geochemical, hydrologic, and meteorological information;

(2) All additional monitoring data, analyses and results;

(3) All additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program;

(4) An identification of any activities or assumptions that deviate from the most recent compliance application;

(5) A description of all waste emplaced in the disposal systems since the most recent compliance certification or re-certification application. Such description shall consist of a description of the waste characteristics and waste components identified in § 194.24(b)(1) and § 194.24(b)(2);

(6) Any significant information not previously included in a compliance certification or re-certification application related to whether the disposal system continues to be in compliance with the disposal regulations; and

(7) Any additional information requested by the Administrator or the Administrator's authorized representative.

(b) To the extent that information required for a re-certification of compliance remains valid and has been submitted in previous certification or re-certification applications(s), such information need not be duplicated in subsequent applications; such information may be summarized and referenced.

15.2 Background

Information documented in the 2009 Compliance Recertification Application (CRA-2009) is prescribed in 40 CFR § 194.15 (U.S. Environmental Protection Agency 1996). These documentation requirements parallel the requirements of 40 CFR § 194.14 (U.S. Environmental Protection Agency 1996), which apply primarily to the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the original application. The focus of section 194.15 is to ensure that CRAs include documentation regarding any changes to the disposal system that may have occurred since the previous certification or recertification. Updated information regarding relevant aspects of the waste and the disposal system is documented. However, in cases where information and assumptions have not changed, no new information need be documented; the CRA-2009 may reference or summarize such unchanged information.

The CRA-2009 must identify relevant systems and program changes implemented during the preceding five-year period. Any activity or assumption that deviates from what was described in the most recent compliance certification or recertification application would be considered a change. The CRA-2009 also documents changes reviewed and approved by the U.S. Environmental Protection Agency (EPA) in the preceding five-year period (through modification of the certification or other processes). The CRA-2009 documents instances where new baseline program elements were established as a result of changes.

15.3 1998 Certification Decision

The CCA, Chapters 2.0 and 3.0 and Appendices GCR, HYDRO, and MASS, include general information about the Waste Isolation Pilot Plant (WIPP) site and disposal system design. Other site characteristics, design, location, and construction information is primarily provided in the CCA, Chapter 7.0 and Appendices BACK, DEL, PCS, and SEAL. After its review, the EPA concluded that the U.S. Department of Energy (DOE) adequately addressed the geology, geophysics, hydrogeology, hydrology, meteorology, climatology, and effects of waste and geochemistry of the disposal system and its vicinity, and how these conditions are expected to change and interact over the regulatory time frame (Compliance Application Review Document [CARD] 14, U.S. Environmental Protection Agency 1998a). The EPA reviewed the DOE's CCA and additional information submitted by the DOE and determined that the DOE complied with each of the criteria of section 194.14. A complete description of the EPA's 1998 Certification Decision for section 194.14 can be found in U.S. Environmental Protection Agency 1998b, as well as CARD 14 (U.S. Environmental Protection Agency 1998a).

15.4 Changes in the CRA-2004

Baseline documentation for section 194.14 was established at the time of the original EPA certification. Information on changes to section 194.14 topics that occurred since the original certification is required to be documented by section 194.15. Changes that occurred during the five-year period following the original certification are documented in the CRA-2004 (U.S. Department of Energy 2004a), which was submitted by the DOE and reviewed by the EPA under the requirements of section 194.15.

During public review of the CRA-2004, the EPA received comments regarding karst features, vertical fracturing, and transport through the Magenta. The EPA assessed these comments and concluded that DOE has demonstrated continued compliance. The EPA responses to comments on the CRA-2004 are documented in CARD 14/15, Appendix 15-A (U.S. Environmental Protection Agency 2006a).

15.5 EPA's Evaluation of Compliance for the 2004 Recertification

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE (available for review in EPA Docket A-98-49), the EPA determined that the DOE continued to comply with the disposal standards (U.S. Environmental Protection Agency 2006b).

15.6 Changes or New Information Since the 2004 Recertification

To document that the WIPP continues to comply with the disposal standards in each five-year recertification cycle, changes and new information since the previous recertification must be described. Changes and new information since the CRA-2004 related to section 194.15 are either described below, or references are provided to other sections or appendices of the CRA-2009 that provide the necessary material.

Much of the information provided in this section was obtained from routinely published reports. Table 15-1 lists these reports and summarizes the type of information contained in each.

Table 15-1. Routine Reports

Description	Summary	Frequency	Reference[a]
Annual Site Environmental Report (ASER)	Describes compliance status with applicable federal regulations and environmental monitoring performed during the year at the WIPP. Highlights any significant monitoring results or findings.	Annual	U.S. Department of Energy 2007a
Geotechnical Analysis Report (GAR)	Reports data related to the geotechnical performance of the various underground facility components, including the shafts, shaft stations, access drifts, and waste disposal areas. Volume 1 describes the overall program; Volume 2 provides a compilation of the collected data.	Annual	U.S. Department of Energy 2008a
Annual Change Report (ACR) (194.4(b)(4)[b] Report)	Provides information each year on any change in conditions or activities related to the disposal system, as required by 40 CFR § 194.4(b)(4). The majority of the items reported are inspections, reports, and modifications to written plans and procedures. In addition, the ACR provides updates on waste volumes of several parameters and radionuclides upon which the EPA imposes limits.	Annual	U.S. Department of Energy 2007b
Delaware Basin Drilling Surveillance Report	Lists changes in drilling including rates for shallow and deep drilling; pipeline activity; borehole plugging; injection wells; potash, sulfur, and solution mining; and any other new activity related primarily to human intrusion.	Annual	U.S. Department of Energy 2007c
Compliance Monitoring Parameters (COMPs) Report	The DOE uses PA to simulate the expected long-term performance of the WIPP. COMPs are used to indicate conditions that are not within expected PA data ranges or conceptual model assumptions, and to alert the project to unexpected conditions. Examples of COMPs include waste activity, changes in groundwater conditions, and creep closure rate.	Annual	Sandia National Laboratories (SNL) 2008
Subsidence Monument Leveling Survey	Survey includes determination of the elevation of each of the existing subsidence monuments and the WIPP baseline survey, and of the National Geodetic Survey's vertical control points.	Annual	U.S. Department of Energy 2007d
Biennial Environmental Compliance Report	As required by the WIPP Land Withdrawal Act (LWA), this document reports the status of the project's compliance with a variety of environmental protection laws and regulations.	Biennial	U.S. Department of Energy 2006a

[a]The entry in this column is the most recent report available.
[b]U.S. Environmental Protection Agency 1996.

15.6.1 40 CFR § 194.15(a)(1)

40 CFR § 194.15(a)(1) requires the submittal of "all additional geologic, geophysical, geochemical, hydrologic, and meteorological information." Information responding to this requirement is provided in the following sections.

15.6.1.1 Geologic Information

New geologic information has been developed since the preparation of the CRA-2004, and is provided in Appendix HYDRO-2009. Geologic studies between 2003 and 2007 focused on Rustler Formation halite margins and karst. The map of Rustler halite margins delineated by Powers (2002) for the CRA-2004 was revised by Powers (2007) to incorporate data from recent drilling near the WIPP site. Lorenz (2006a and 2006b) reviews historical data and arguments on karst at the WIPP. Lorenz (2006b, p. 243) concludes that most of the geological evidence offered for the presence of karst in the subsurface at the WIPP site "has been used uncritically and out of context, and does not form a mutually supporting, scientifically defensible framework. . . . The remaining evidence is more readily interpreted as primary sedimentary features." Powers et al. (2006) provide new details on the gypsum karst present in the Rustler of Nash Draw. Powers (2006a) studies some of the natural brine lakes in Nash Draw, finding some of them to be fed by a shallow gypsum karst system with enough storage to sustain year-round flow, while others were fed by the potash-processing effluent discharged by Mosaic Potash Carlsbad into Laguna Uno. Powers (2006b) also maps closed catchment basins in the SW arm of Nash Draw that drain internally to karst features.

15.6.1.2 Geophysical Information

Regional seismic activity has been the focus of ongoing geophysical investigations since the development of the CRA-2004. Regional seismic activity is monitored to establish a basis for predicting ground motions that the WIPP repository may experience in both the near and distant future. Historic seismic monitoring data are divided into two categories: pre- and postinstrumentation. Prior to 1962, instrumented seismic monitoring stations did not exist in New Mexico; information about seismic activity was derived from qualitative sources, such as reports of effects on people, structures, and surface features. Since 1962, seismograph coverage for New Mexico has become sufficiently comprehensive to locate regional epicenters. As would be expected, after the installation of the monitoring network, the number of reported events increased. Recorded events include natural seismic events as well as those resulting from human activities.

In the early 1990s, to increase coverage in the vicinity of the WIPP, the New Mexico Institute of Mining and Technology (NMIMT) installed a network of seven seismograph stations in southeastern New Mexico. These instruments are sufficiently sensitive to detect events with magnitudes as low as 0.1 on the Richter scale. This further increased the number of seismic events recorded in the area.

Starting in January 1997, a large number of seismic events were concentrated in an area known as Dagger Draw, northwest of Carlsbad, New Mexico, and near the Dagger Draw gas field, suggesting that the events may be induced by natural gas production activity. In 2003, two more seismograph stations were located in the vicinity of Dagger Draw to allow the recording of smaller events that could not previously be detected. Although the number of recorded events increased dramatically in this area, peaking in 2004, almost all of the recorded events are of low magnitude.

Information regarding seismic events is generally recorded in catalogs, which are divided into categories based on the magnitude registered for each event. Most catalogs have a section detailing seismic events with a magnitude greater than 3.0 because this is the point at which seismic events can be felt.

The NMIMT has recently generated comprehensive catalogs incorporating new programs for locating the epicenter and defining the magnitude of seismic events. NMIMT then regenerated information from the old catalogs using the new programs. For some past events, both the recorded magnitude and epicenter changed, while in others, either the magnitude or the epicenter changed.

The WIPP Delaware Basin Drilling Surveillance Program (DBDSP) tracks seismic events occurring in the vicinity of the WIPP Site. In 2007, the DBDSP completed the update of its seismic database, incorporating the changes and adding events that were not previously considered in the area.

During the current CRA-2009 monitoring period (October 2002 through September 2007), there were 703 seismic events recorded within approximately 240 kilometers (km) (150 miles [mi]) of the WIPP site. Almost all (85%) of the recorded events occurred in the Dagger Draw area of Eddy County. Nearly all of these events were of a magnitude that would not be felt by humans.

Although the DBDSP collects information on areas outside of the Delaware Basin, such as Dagger Draw, the Delaware Basin is used as the defining area for data collection and input to PA. The number of recorded events that have occurred within the Delaware Basin between 1971 and September 2007 (the CRA-2009 cutoff date) are listed in Table 15-2, Seismic Events in the Delaware Basin.

A map showing the locations of 87 seismic events that have occurred within 240 km (150 mi) of the WIPP with a reported magnitude greater than 3.0 is provided in Appendix DATA-2009, Section DATA-2.2. Of these 87 events, only 4 occurred in the Delaware Basin. The one closest to the WIPP site occurred as a result of a roof fall in one of the local potash mines (U.S. Department of Energy 2007a).

Although an increased number of seismic events has been recorded, no significant or anomalous seismic events have occurred in the vicinity of the WIPP since the CRA-2004.

15.6.1.3 Geochemical Information

New hydrogeochemical information has been collected since the CRA-2004. This new information is described in detail in Domski and Beauheim (2008) and in Appendix HYDRO-2009. Extensive groundwater sampling has been performed in new wells and selected older wells. The last major geochemical evaluation of Culebra groundwater was performed by Siegel, Lambert, and Robinson (1991) based on samples from 22 wells. Samples are now available from 59 wells, allowing refinement of the conceptual understanding provided by Siegel, Lambert, and Robinson (1991). Whereas Siegel, Lambert, and Robinson (1991) identify only four hydrochemical facies (A, B, C, and D) based primarily on ionic strength and major

Table 15-2. Seismic Events in the Delaware Basin

County	No. of Events	Earliest Event	Latest Event	Smallest Magnitude	Largest Magnitude
Culberson	12	10/27/1992	12/20/2005	1.1	2.4
Eddy	15	11/28/1975	07/05/2007	0.5	3.7
Lea	1	06/23/1993	06/23/1993	2.1	2.1
Loving	4	02/04/1976	04/24/2003	1.1	2.0
Pecos	18	01/30/1975	12/22/1998	1.0	2.6
Reeves	18	02/19/1976	05/25/2002	1.0	3.1
Ward	47	09/03/1976	08/19/1978	0.3	2.8
Winkler	8	09/24/1971	09/15/1988	0.0	3.0

Key:
Magnitude
Less than 2 Very seldom felt
2.0 to 3.4 Barely felt
3.5 to 4.2 Felt as a rumble
4.3 to 4.9 Shakes furniture; can break dishes
5.0 to 5.9 Dislodges heavy objects; cracks walls
6.0 to 6.9 Considerable damage to buildings
7.0 to 7.3 Major damage to buildings; breaks underground pipes
7.4 to 7.9 Great damage; destroys masonry and frame buildings
Above 8.0 Complete destruction; ground moves in waves
Source: DBDSP, U.S. Department of Energy 2007c

constituents, two transitional facies (A/C and B/C) and one entirely new facies (E) can now be delineated (Domski and Beauheim 2008). The spatial distribution of these facies is consistent with the locations of the Rustler halite margins, the distribution of transmissivity in the Culebra, and the areas of known or suspected recharge to the Culebra.

15.6.1.4 Hydrologic Information

New piezometers have been installed, and new hydrological investigations have been undertaken since the CRA-2004. Related information is provided below and in Appendix HYDRO-2009.

15.6.1.4.1 New Piezometers

Shallow subsurface water (SSW) was first detected at the WIPP site in 1995 when a video inspection of the exhaust shaft showed seepage from about 50 to 80 feet (ft) below the ground surface. The SSW occurs in a perched water-bearing zone above the contact between the Santa Rosa Formation and the upper Dewey Lake Formation.

To evaluate if the Site and Preliminary Design Validation (SPDV) mined tailing pile was contributing to the anthropogenic SSW, piezometers PZ-13, PZ-14, and PZ-15 were drilled in August 2007. This pile has been decommissioned and is no longer used. An engineered cover has been placed on the pile.

Piezometers PZ-13, PZ-14, and PZ-15 indicated saturated sections in all three locations at different horizons, and, in one case, a different formation. Based on data from the piezometers, analysis of water levels, and geological analysis, it is concluded that the water levels identified in PZ-13 and PZ-14 are the result of the SPDV pile runoff or infiltration prior to the installation of the engineered cover. Water in PZ-15 is much more shallow and chemically different from that in the other two wells, indicating a different source, such as recharge and infiltration from a topographic depression east of the SPDV pile. A report on this investigation using the new piezometers is provided in U.S. Department of Energy 2008b.

15.6.1.4.2 Recent Hydrological Investigations

Since the September 2002 data-cutoff date for the CRA-2004, the DOE has collected a significant amount of new information on WIPP hydrogeology, both in response to requests from the EPA and as a result of ongoing monitoring programs. Appendix HYDRO-2009 describes the new information collected as of the end of 2007; a brief summary is provided below.

Hydrological investigations conducted from 2003 through 2007 provided a wealth of new information, some of it confirming long-held assumptions and others offering new insight into the hydrological system around the WIPP site. A Culebra monitoring-network optimization study was completed by McKenna (2004) to identify locations where new Culebra monitoring wells would be of greatest value and to identify wells that could be removed from the network with little loss of information. Eighteen new wells were completed, guided by the optimization study, geologic considerations, and/or unique opportunities. Seventeen wells were plugged and abandoned, and two others were transferred to the U.S. Bureau of Land Management.

The WIPP groundwater monitoring program has augmented monthly water-level measurements with continuous (nominally hourly) fluid-pressure measurements using downhole programmable TROLL® pressure gauges in all Culebra wells except for the Water Quality Sampling Program wells. The most significant new finding arising from the continuous measurements has been the observation of Culebra water-level responses to rainfall in Nash Draw. The Culebra has long been suspected of being unconfined in at least portions of Nash Draw because of dissolution of the upper Salado, subsidence and collapse of the overlying Rustler, and karst in Rustler gypsum units (Beauheim and Holt 1990). However, continuous monitoring with TROLL® gauges has provided the first direct evidence of Culebra water levels responding to rainfall. Furthermore, the rainfall-induced head changes originating in Nash Draw are now observed to propagate under Livingston Ridge and across the WIPP site over periods of days to months (Hillesheim, Hillesheim, and Toll 2007), explaining some of the changes in Culebra water levels. Other water-level changes that appear to occur quite suddenly can now be conclusively related to drilling of nearby oil and gas wells.

Extensive hydraulic testing has been performed in the new wells (Appendix HYDRO-2009). This testing has involved both single-well tests, which provide information on local transmissivity and heterogeneity, and long-term (19 to 32 days) pumping tests that have created observable responses in wells up to 9.5 km (5.9 mi) away. The transmissivity values inferred from the single-well tests (Roberts 2006 and 2007) support the correlation between geologic conditions and Culebra transmissivity developed by Holt and Yarbrough (2002) and elucidated by Holt, Beauheim, and Powers (2005). The types of heterogeneities indicated by the diagnostic

plots of the pumping-test data are consistent with the known spatial distribution of transmissivity in the Culebra. Mapping diffusivity values obtained from analysis of observation-well responses to pumping tests shows areas north, west, and south of the WIPP site connected by fractures, and also a wide area that includes a NE-to-SW swath across the middle part of the WIPP site where hydraulically significant fractures are absent (Beauheim 2007). This mapping, combined with the responses observed to the long-term SNL-14 pumping test, has confirmed the presence of a high-transmissivity (high-T) area extending from the SE quadrant of the WIPP site to at least 10 km (6 mi) to the south. Additional information related to this high-T area is discussed in Appendix HYDRO-2009, Section HYDRO-6.4.

Combining the Culebra monitoring data with catchment basin mapping in southwestern Nash Draw and groundwater geochemistry data provides insight into Culebra recharge. While some of the water entering gypsum karst in Nash Draw discharges into brine ponds such as Laguna Cinco, some portion of it must come into hydraulic communication with the Culebra, at least locally, because Culebra wells in Nash Draw show water-level responses to major rainfall events. However, these responses do not mean that the precipitation reached the Culebra. Rather, they indicate that the Culebra cannot be completely confined, but must be in hydraulic communication with a water table in a higher unit that does receive direct recharge from precipitation. Some of this water must eventually reach the Culebra, where it is recognized as the low ionic strength, $CaSO_4$-dominated hydrochemical facies B, but it must first have spent a considerable period in the Rustler gypsum beds to have as high a total dissolved solids (TDS) as it does. As a further indication of the recharge's indirect nature, the water from SNL-16 (which is located within a small catchment basin in Nash Draw) does not fall in the domain of facies B, but is instead in the higher ionic strength facies C, even though SNL-16 shows a clear pressure response to major rainfall events. This shows conclusively that rainfall is not rapidly flushing the Culebra in this area (Domski and Beauheim 2008).

Lowry and Beauheim (2004 and 2005) conclude from two modeling studies that leakage from units above the Culebra through poorly plugged and abandoned boreholes is a plausible explanation for the long-term rise in water levels observed at and near the WIPP site. The Intrepid East tailings pile may well be the primary source of leaking water north of the WIPP site, while natural recharge where the Culebra is unconfined southwest of the site could provide the leaking water ascribed to a southern borehole by Lowry and Beauheim (2005). The studies showed that a physically reasonable amount of leakage through unconfirmed but realistic pathways is consistent with the observed rising water levels. Greater detail is provided in Appendix HYDRO-2009.

15.6.1.5 Meteorological Information

The Meteorological Monitoring Program measures atmospheric data for the WIPP site. This section provides a brief description of the program and updated meteorological data covering the years 2002 through 2006. No anomalous weather events or changes in climatic conditions occurred during 2002–2006.

The primary WIPP meteorological station is located 600.5 m (1,970 ft) northeast of the Waste Handling Building. The main function of the station is to provide data for atmospheric modeling, measuring and recording wind speed, wind direction, and temperature at elevations of

2, 10, and 50 m (6.5, 33, and 165 ft) above ground level, as well as ground-level measurements of barometric pressure, relative humidity, precipitation, and solar radiation.

Information related to recent meteorological conditions is provided below. Data are from the WIPP environmental monitoring reports.

Temperatures are moderate throughout the year, although seasonal changes are distinct. The mean annual temperature in southeastern New Mexico is 17 ºC (63 ºF). In the winter (December through February), nighttime lows average near -5 ºC (23 ºF), and highs average in the 50s (°F). The lowest recorded temperature at the nearest Class A weather station in Roswell was -34 ºC (-29 ºF) in February 1905. In the summer (June through August), the daytime high temperature exceeds 32 ºC (90 ºF) approximately 75% of the time. The National Weather Service documented 50 ºC (122 ºF) at the WIPP site as the record high temperature for New Mexico on June 27, 1994.

The annual average, maximum, and minimum temperatures from 1990 through 2006 are listed in Table 15-3.

Table 15-3. Annual Average, Maximum, and Minimum Temperatures[a]

Year	Annual Average Temperature		Maximum Temperature		Minimum Temperature	
	(ºC)	(ºF)	(ºC)	(ºF)	(ºC)	(ºF)
1990	17.8	64.0	46.1	115.0	-13.9	7.0
1991	17.2	63.0	42.8	109.0	-7.8	18.0
1992	17.2	63.0	42.8	109.0	-10.0	14.0
1993	17.8	64.0	42.8	109.0	-18.9	-2.0
1994	17.8	64.0	50.0	122.0	-14.4	6.0
1995	17.0	63.0	42.0	107.0	-7.0	19.0
1996	17.0	63.0	41.0	106.0	-7.0	19.0
1997	16.3	61.4	38.6	101.5	-11.4	11.4
1998	18.3	64.9	41.6	106.9	-10.8	12.6
1999	18.1	64.6	40.9	105.6	-7.9	17.8
2000	17.4	63.3	40.2	104.4	-6.8	19.7
2001	17.5	63.5	39.5	103.2	-7.8	18.0
2002	17.2	62.3	40.82	105.5	-10.4	13.3
2003	18.1	64.6	39.2	102.7	-9.1	15.6
2004	16.8	62.2	38.6	101.5	-12.0	10.4
2005	16.8	62.2	39.8	103.6	-13.0	8.6
2006	18.3	65.0	39.6	103.3	-6.0	21.1
Average	17.4	63.4	41.5	106.8	-10.2	13.5

[a] Source: WIPP annual Site Environmental Reports for calendar years 2002 through 2006 (U.S. Department of Energy 2003, 2004b, 2005a, 2006b, and 2007a).

Precipitation is light and unevenly distributed throughout the year, averaging 400 millimeters (mm) (15.7 inches [in.]) per year from 1990 through 2006. Winter is the season of least precipitation, averaging less than 15 mm (0.6 in.) of rainfall per month. Snow averages about 137 mm (5 in.) per year at the site and seldom remains on the ground for more than a day. Approximately half the annual precipitation comes from thunderstorms in June through September. Rains are usually brief, but occasionally intense, when moisture from the Gulf of Mexico spreads over the region. Monthly average, maximum, and minimum precipitations recorded at the WIPP site from 1990 through 2006 are shown in Figure 15-1.

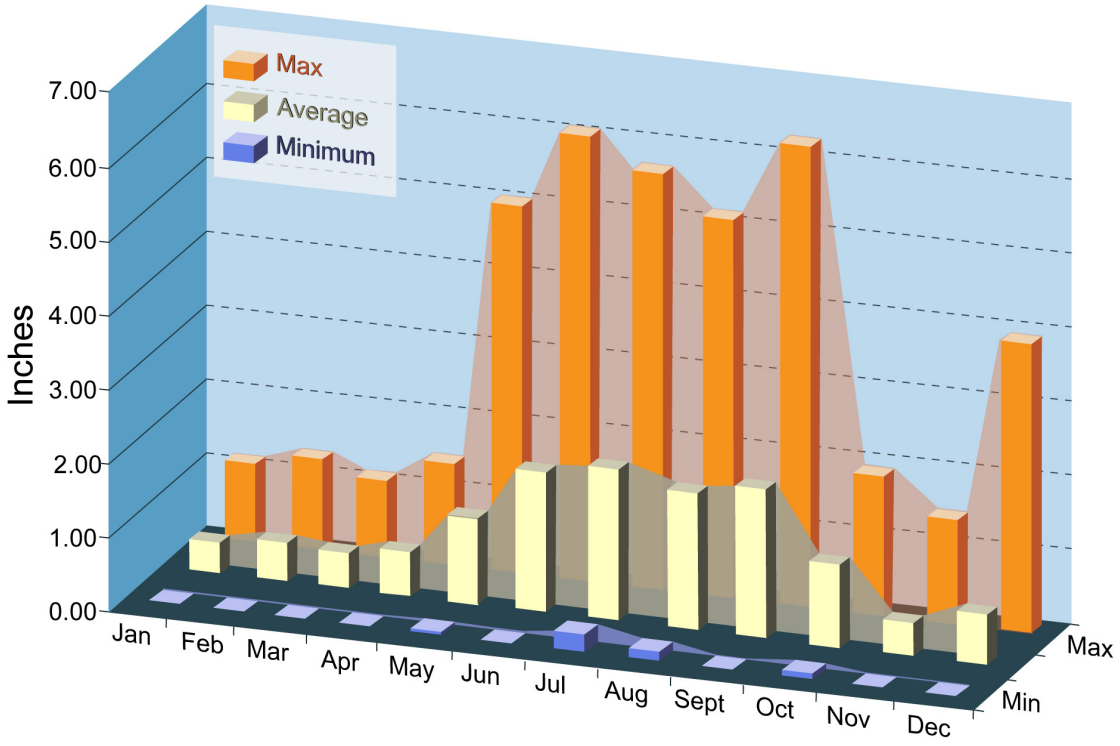

Figure 15-1. Monthly Precipitation for the WIPP Site, 1990–2006

Recent wind roses indicating the frequencies of wind speeds and directions at the WIPP are provided as Figure 15-2, Figure 15-3, Figure 15-4, and Figure 15-5.

15.6.2 40 CFR § 194.15(a)(2)

40 CFR § 194.15(a)(2) requires the submittal of "all additional monitoring data, analyses, and results." Information responding to this requirement is provided below.

The DOE has implemented and/or continued several experimental activities designed to address specific issues and needs of the WIPP repository. In addition, other investigations were initiated to examine the impacts of planned changes. The general areas covered under these investigations include the following:

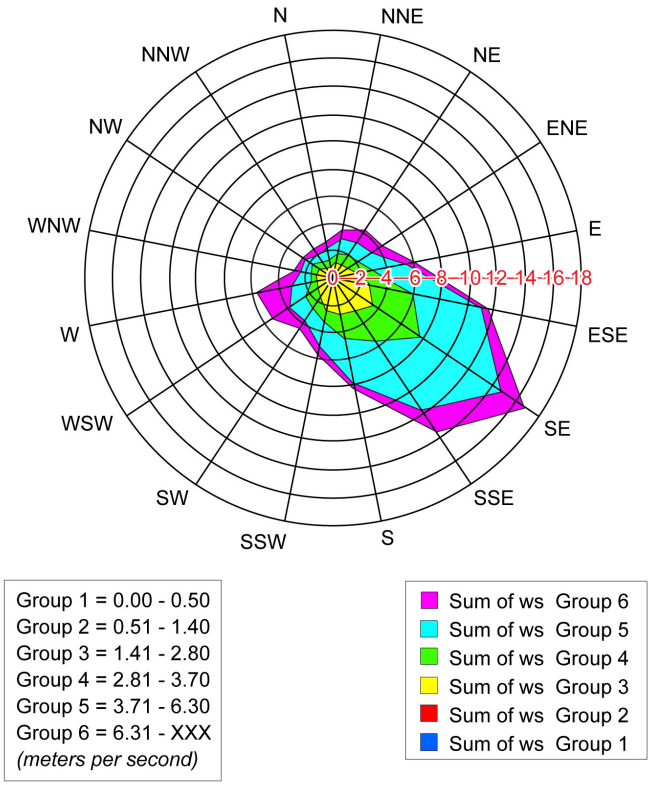

Figure 15-2. 2003 Annual Wind Rose at 10-m (33-ft) Height at the WIPP Site

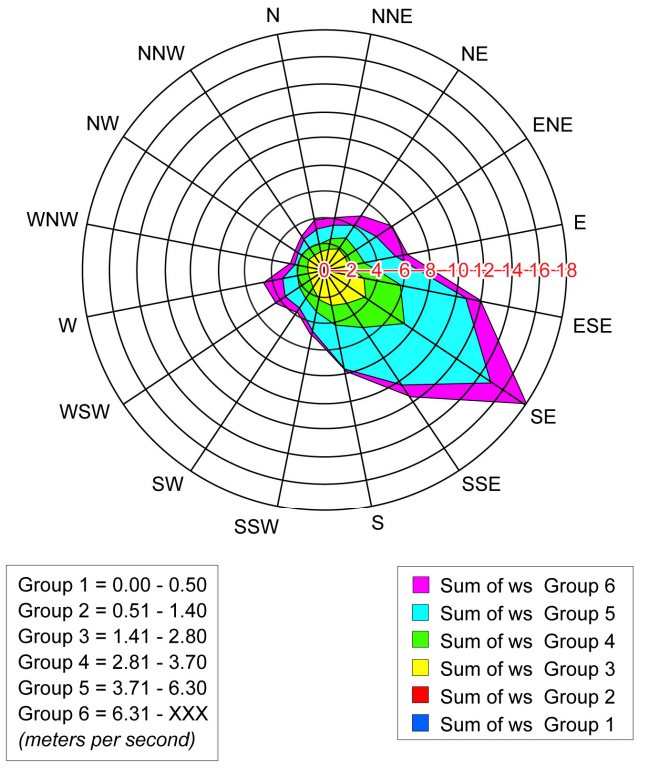

Figure 15-3. 2004 Annual Wind Rose at 10-m (33-ft) Height at the WIPP Site

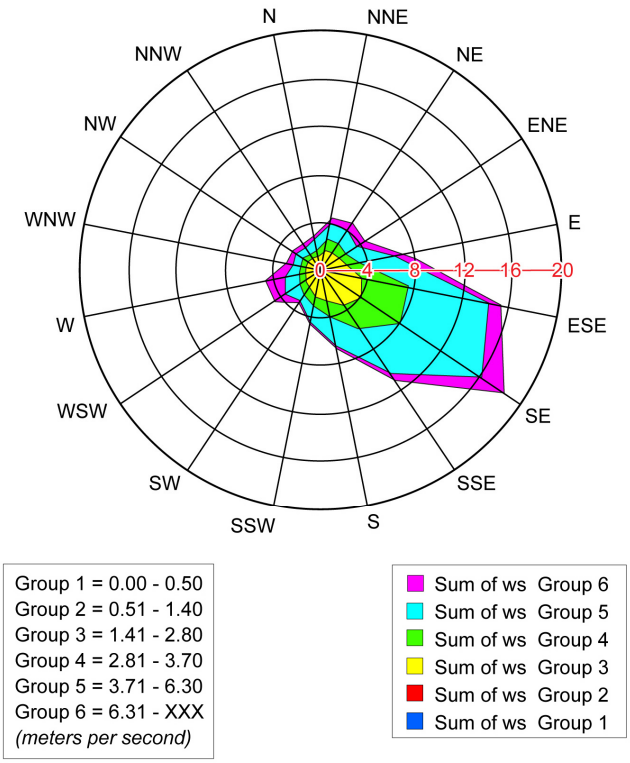

Figure 15-4. 2005 Annual Wind Rose at 10-m (33-ft) Height at the WIPP Site

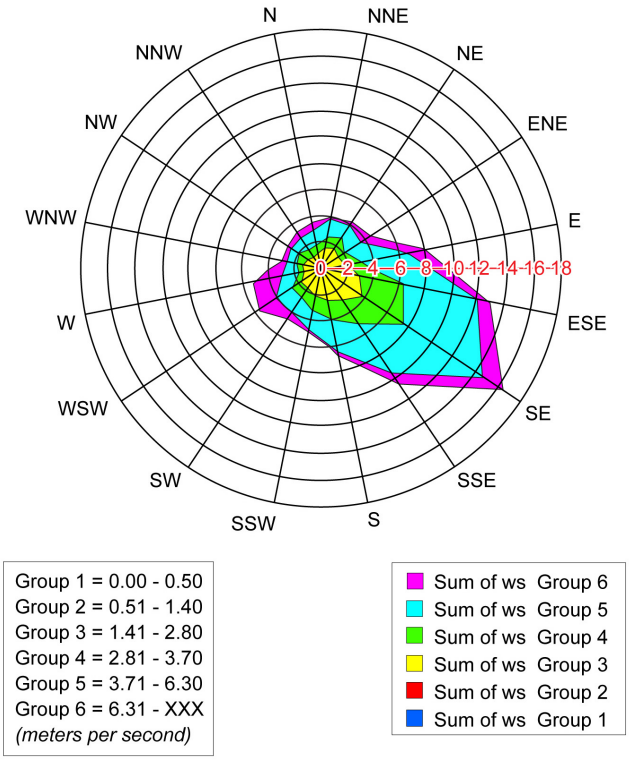

Figure 15-5. 2006 Annual Wind Rose at 10-m (33-ft) Height at the WIPP Site

- Geochemistry
- Engineered barriers
- Rock mechanics

Environmental monitoring programs and references to relevant reports are included in Appendix MON-2009 and Appendix DATA-2009. Data on parameters required for preclosure and postclosure monitoring, including programs for geotechnical and geoscience monitoring, are described in Appendix MON-2009, which focuses on parameters that may be relevant to the long-term performance of the repository. Appendix DATA-2009, Sections DATA-2.0 through DATA-5.0, describes the data collection procedures and references the reports related to parameters such as human activities in the Delaware Basin, including drilling rates, oil and gas production activities, and subsidence monitoring. Appendix DATA-2009, Attachment A, WIPP Borehole Update, provides an updated borehole list for the WIPP vicinity.

15.6.3 40 CFR § 194.15(a)(3)

40 CFR § 194.15(a)(3) requires the submittal of "all additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program." Experimental work conducted since the CRA-2004 in the areas of WIPP repository conditions and parameters, magnesium oxide (MgO) characterization and chemistry, and actinide studies is described in the following sections.

15.6.3.1 WIPP Repository Conditions, Chemistry, and Processes

There were no significant changes in the WIPP repository conditions, chemistry assumptions, or subsurface processes used in PA to establish compliance since the CRA-2004. Appendix DATA-2009, Section DATA-9.0, describes the disturbed rock zone (DRZ) experiments and waste shear strength experiments that occurred after the CRA-2004. A detailed description of the current conditions and assumptions used in PA is given in Appendix SOTERM-2009, Section SOTERM-2.0 and Appendix PA-2009.

15.6.3.2 MgO Studies and Characterization

Experimental investigations of MgO have continued since the CRA-2004. This experimental work has centered on two key aspects of MgO performance: (1) the characterization and qualification of vendor-provided MgO to insure that DOE requirements were being met and (2) MgO hydration studies to further establish the reaction pathways of this engineered barrier under repository-relevant conditions. A detailed description of these experimental results is provided in Appendix MgO-2009 and Appendix DATA-2009, Section DATA-9.0. The impact of MgO chemistry on actinide chemistry and solubility is described in Appendix SOTERM-2009, Section SOTERM-2.3.3.

15.6.3.3 Actinide Investigations

Experimental investigations to establish the speciation and solubility of actinides under WIPP-related conditions were reinitiated after the CRA-2004. These investigations focused on three

areas: (1) the solubility of neodymium (Nd) (III), as an analogue for the plutonium (Pu) (III) and americium (Am) (III) oxidation states, in simulated WIPP brine, (2) the reduction of higher valent Pu(V/VI) by iron to form low-solubility Pu(III/IV) phases, and (3) the solubility of uranium (U) (VI) in carbonate-free WIPP brine. The details of these experimental studies are given in Appendix SOTERM-2009, Section SOTERM-3.0. All results reported in these studies support the CRA-2004 PA position and did not lead to changes in the CRA-2009 PA.

15.6.4 40 CFR § 194.15(a)(4)

40 CFR § 194.15(a)(4) requires that the DOE "identify any activities or assumptions that deviate from the most recent compliance application." Information related to this requirement is provided in the following sections.

15.6.4.1 Status of Underground Excavation

The progress of mining the WIPP underground repository is shown in Figure 15-6. As shown on the figure, as of October 1, 2007, Panels 1 through 4 had been mined completely; Panels 1, 2, and 3 were filled with waste; waste was being emplaced in Panel 4; and mining of Panel 5 was in progress.

Geotechnical analysis reports from 2003 through 2007 show that no major ground control problems or events occurred since the CRA-2004 (U.S. Department of Energy 2004c, 2005b, 2006c, 2007e, and 2008a). As expected, slow deterioration of ground conditions has occurred in the WIPP underground repository as a result of aging, but this has been mitigated by routine maintenance and the implementation of engineered systems, as needed. One incident of minor damage occurred to a catch basin installed in the exhaust shaft to intercept water and prevent it from flowing laterally into the waste shaft sump. The catch basin was originally installed in March 1996; it was damaged by falling debris. A new catch basin was installed in December 2004. This basin was damaged in August 2005, again by debris. The catch basin was replaced by an interception well system between November 2005 and March 2006. The interception well system consists of 4, 30-ft deep, small-diameter holes located in the floor of the drift between the exhaust shaft and the waste shaft. The quantity and quality of fluid entering the system continues to be measured and analyzed. The fluid is routinely removed to prevent drainage into the waste shaft sump.

15.6.4.2 Remote-Handled Transuranic Waste Emplacement

The original plans for waste emplacement included the placement of remote-handled (RH) transuranic (TRU) (RH-TRU) waste in horizontal boreholes in the walls of waste-emplacement rooms, followed by the emplacement of contact-handled (CH) transuranic (TRU) (CH-TRU) waste in containers in each room. This configuration was planned to be used in all panels in the underground repository. Because CH-TRU waste disposal was approved about six years before RH-TRU waste approval, no RH-TRU waste was emplaced in Panels 1, 2, and 3. RH-TRU waste was emplaced beginning with Panel 4.

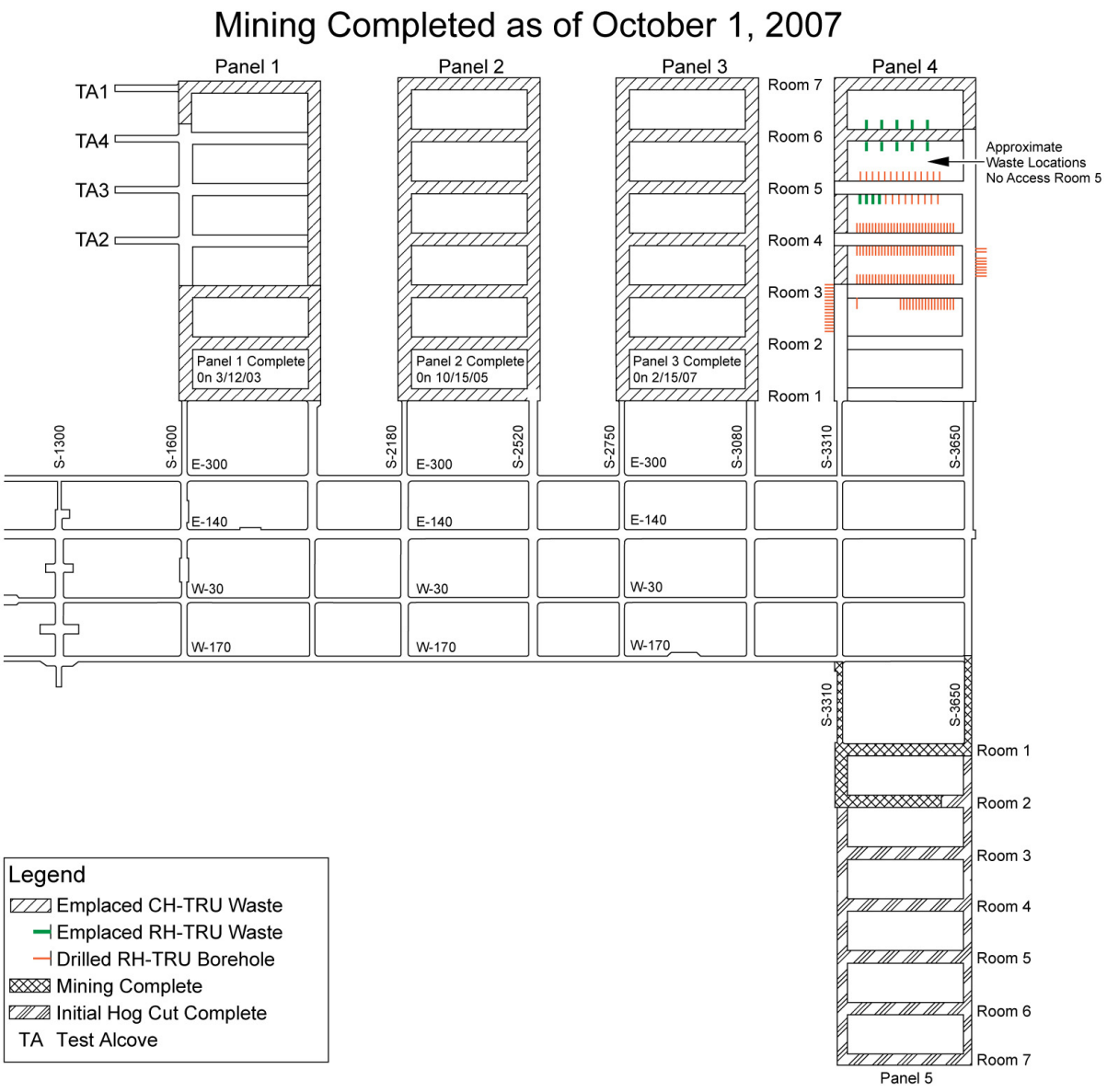

Figure 15-6. Status of Mining and Waste Emplacement as of October 1, 2007

15.6.4.3 Proposed RH-TRU Waste Container Modifications

On November 15, 2007, the DOE submitted a planned change request to the EPA to use shielded RH-TRU waste containers (Moody 2007) for a portion of RH-TRU waste shipped to the WIPP. The proposed shielded containers, approximately the size of a 55-gallon drum, have 1-in.-thick lead shielding placed between a double-walled steel shell. The external wall is 1/8 in. thick, and the internal wall is 3/16 in. thick. The lid and the bottom of the containers are made of carbon steel and are 3 in. thick. The containers are designed to hold a 30-gallon container, and would be

shipped to the WIPP in HalfPACT transportation containers. The surface dose rate would be no higher than 200 millirem/hour.

Use of the shielded containers is proposed to increase efficiency of transportation and operations at the WIPP, as well as at generator sites, because the shielded containers could be managed in the same manner as CH-TRU waste. Record-keeping for RH-TRU waste would not change; containers and waste streams would continue to be designated as RH-TRU waste in the WIPP Waste Information System, and would count against the limit of 5,100,000 curies for RH-TRU waste as specified in the WIPP LWA, as well as the limit of 250,000 ft^3 defined by the Consultation and Cooperation Agreement between the DOE and the State of New Mexico.

It is estimated that approximately 27% (Crawford and Taggart 2007) of the RH-TRU waste inventory would be suitable for management in the shielded containers. Higher-activity RH-TRU waste would continue to be managed and emplaced using the current practice.

An analysis of the disposal system performance implications of using the shielded container was performed. The analysis shows that use of shielded containers for candidate waste streams would have an insignificant impact on long-term performance of the disposal system (Dunagan et al. 2007).

15.6.4.4 Neutrino Experiments in the WIPP Underground Repository

Several new research projects have been initiated at the WIPP. Although these projects are not related to the expected performance of the repository, they are described here because they are being performed in the WIPP underground facility. The WIPP underground repository is a desirable location for the experiments because it provides an environment shielded from cosmic radiation that would otherwise interfere with the experiments. Equipment used during these experiments will be removed before closure of the repository.

The Segmented Enriched Germanium Assembly (SEGA) project and the Multiple Element Germanium Array (MEGA) projects are being performed to investigate double-beta decay, a rare type of nuclear decay that provides information on the mass of the neutrino. A modular building for housing the experiments was assembled in the Room Q alcove of the WIPP underground facility in 2003 and 2004. Experiments began in 2005, and preparations began in 2007 for additional studies and experiments in electroforming copper fabricated underground to purify the metal of its natural radioactive contaminants. The SEGA and MEGA projects are being performed by a collaboration of several universities, with Stanford University serving as the lead.

In addition, Los Alamos National Laboratory (LANL) is leading the Enriched Xenon Observatory (EXO) project, also in the WIPP underground repository. This project is investigating neutrinoless double-beta decay. In 2007, several pallets of materials for the experiment were received at WIPP after assembly in California. Setup of the experiments is planned for 2008. The experiments will be performed in the former E-300 shop space between drifts N-1100 and N-1400.

For all of these experiments, the role of the WIPP operator, Washington TRU Solutions, LLC, is to provide support in transporting project materials to the underground facility, health and safety oversight, infrastructure to operate and maintain the experiments, and operational coordination with project researchers.

15.6.5 40 CFR § 194.15(a)(5)

40 CFR § 194.15(a)(5) requires that the CRA-2009 include "a description of all waste emplaced in the disposal system since the most recent compliance certification or recertification application. Such description shall consist of a description of the waste characteristics and waste components identified in § 194.24(b)(1) and § 194.24(b)(2)." Information responsive to these requirements is provided in the following sections.

15.6.5.1 Status of Waste Emplacement

The status of waste emplacement in the WIPP underground repository is indicated in Figure 15-6. Additional detail is provided in Section 24, "Waste Characterization."

15.6.5.2 Waste Characteristics and Components Important to Demonstration of Compliance

Section 24 provides an updated waste inventory of both waste anticipated to be emplaced in the WIPP and waste that has already been emplaced since the CRA-2004. Section 24 also reports an analysis of waste inventory impacts on the performance of the WIPP disposal system. Information about the limits imposed by the DOE on significant components or characteristics of the waste to ensure that they are consistent with assumptions made for the PA is also provided in Section 24.

The inventory for the CRA-2009 PA is the same inventory used for the CRA-2004 PABC. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008c) was published and provides updated inventory information. The DOE anticipates this inventory update will have only a small impact on normalized releases relative to the CRA-2009 PA, and will not be significant for compliance. Therefore, the DOE is in compliance with section 194.24(a) (U.S. Environmental Protection Agency 2004).

15.6.6 40 CFR § 194.15(a)(6)

40 CFR § 194.15(a)(6) requires the submittal of "any significant information not previously included in a compliance certification or recertification application related to whether the disposal system continues to be in compliance with the disposal regulations." Information related to this requirement is provided below.

15.6.6.1 Status of Compliance

The remainder of this CRA provides the information required by this section of the certification criteria. The DOE believes that this information demonstrates that the WIPP continues to comply with the disposal regulations.

15.6.7 40 CFR § 194.15(a)(7)

40 CFR § 194.15(a)(7) requires the submittal of "any additional information requested by the Administrator or the Administrator's authorized representative." Information related to this requirement is provided below.

15.6.7.1 Status of Compliance

There currently are no outstanding requests from the EPA for additional information. As such, the DOE is in compliance with this certification criterion.

15.6.8 40 CFR § 194.15(b)

40 CFR § 194.15(b) states, "To the extent that information required for a re-certification of compliance remains valid and has been submitted in previous certification or re-certification applications(s), such information need not be duplicated in subsequent applications; such information may be summarized and referenced." Information related to this requirement is provided below.

15.6.8.1 Status of Compliance

The DOE has followed this direction in the preparation of this recertification application. To the extent appropriate, information from the CCA and the CRA-2004 that remains valid and unchanged is not repeated in this recertification application; instead, it is summarized and incorporated by reference.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Inspections
(40 CFR § 194.21)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Inspections
(40 CFR § 194.21)

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Acronyms and Abbreviations

AMWTF	Advanced Mixed Waste Treatment Facility
CARD	Compliance Application Review Document
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
QA	quality assurance
RH-TRU	remote-handled transuranic
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

Elements and Chemical Compounds

MgO	magnesium oxide

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21.0 Inspections (40 CFR § 194.21)

21.1 Requirements

§ 194.21 Inspections

(a) The Administrator or the Administrator's authorized representative(s) shall, at any time:

(1) Be afforded unfettered and unannounced access to inspect any area of the WIPP, and any locations performing activities that provide information relevant to compliance application(s), to which the Department has rights of access. Such access shall be equivalent to access afforded Department employees upon presentation of credentials and other required documents.

(2) Be allowed to obtain samples, including split samples, and to monitor and measure aspects of the disposal system and the waste proposed for disposal in the disposal system.

(b) Records (including data and other information in any form) kept by the Department pertaining to the WIPP shall be made available to the Administrator or the Administrator's authorized representative upon request. If requested records are not immediately available, they shall be delivered within 30 calendar days of the request.

(c) The Department shall, upon request by the Administrator or the Administrator's authorized representative, provide permanent, private office space that is accessible to the disposal system. The office space shall be for the exclusive use of the Administrator or the Administrator's authorized representative(s).

(d) The Administrator or the Administrator's authorized representative(s) shall comply with applicable access control measures for security, radiological protection, and personal safety when conducting activities pursuant to this section.

21.2 Background

40 CFR § 194.21 (2004) provides the U.S. Environmental Protection Agency (EPA) with the authority to inspect all activities at the Waste Isolation Pilot Plant (WIPP) and all activities located off-site that provide information relevant to any compliance applications.

21.3 1998 Certification Decision

The EPA conducted no inspection under the authority of section 194.21 prior to the 1998 Certification Decision. With the issuance of its 1998 Certification Decision (U.S. Environmental Protection Agency 1998), the EPA identified inspections that may be performed under the authority at section 194.21. These include the following:

- The inspection of the panel closure system on waste panels that have been filled and are being sealed to confirm compliance with Condition 1 of the EPA's 1998 Certification Decision (U.S. Environmental Protection Agency 1998)

- The verification that specific actions identified by the U.S. Department of Energy (DOE) in the Certification and supplementary information (and in any additional documentation submitted in accordance with Condition 4) are being taken to test and implement passive institutional controls

- Announced and unannounced inspections of activities at the WIPP and at all off-site facilities that provide information included in certification applications

- The inspection of the DOE's implementation of the monitoring plans that the DOE has set forth to demonstrate compliance with 40 CFR § 194.42

- The inspection of any records relevant to the Certification kept by the DOE, including those records required to be generated in accordance with the compliance criteria

- The inspections of approved quality assurance (QA) programs at the WIPP and at waste generator sites to ensure the programs are being adequately maintained and documented

After the 1998 Certification Decision, the EPA began using the authority given by section 194.21 to conduct inspections at the WIPP. Inspections include magnesium oxide (MgO) backfill, waste emplacement, the monitoring programs established to collect data for each of the Monitored Parameters identified in Table 21-1, and the examination of documentation (records) to verify compliance at the WIPP.

Table 21-1. Monitored Parameters

Monitored Parameters	
Geomechanical Parameters • Creep closure • Extent of deformation • Initiation of brittle deformation • Displacement of deformation features Hydrological Parameters • Culebra groundwater composition • Change in Culebra groundwater flow direction	Waste Activity Parameter • Waste activity subsidence parameter • Subsidence measurements Drilling-Related Parameters • Drilling rate • The probability of encountering a Castile brine reservoir

The monitoring inspection activities included an examination of monitoring and sampling equipment both on- and off-site and underground. The EPA also reviewed sampling procedures and measurement techniques and verified implementation of an effective QA program for monitoring activities.

This provision of the EPA's Compliance Criteria was not applied prior to the 1998 Certification Decision. After 1998, the EPA used the authority given by section 194.21 to inspect the WIPP monitoring programs, MgO backfill, and waste emplacement requirements.

21.4 Changes in the CRA-2004

The 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004) did not address the EPA's inspection activities under section 194.21. However, the EPA inspection activities were addressed in Compliance Application Review Document (CARD) 21 (U.S. Environmental Protection Agency 2006a). CARD 21 identified monitoring inspections and waste emplacement inspections that were conducted from March 23, 1999, through July 12, 2005. This information is duplicated in Table 21-2.

Table 21-2. CRA-2004 Monitoring and Waste Emplacement Inspection Results (1999–2005)

Date of Inspection	Inspection Type	Inspection Results	Reference
March 24–25, 1999	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (1999a)
September 8, 1999	Waste Emplacement	The EPA did not have any findings. The EPA had one minor concern that two procedures did not specify the form that records must take. This concern did not require a response from the DOE.	U.S. Environmental Protection Agency (1999b)
June 21–22, 2000	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2000a)
June 20–22, 2000	Waste Emplacement	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2000b)
June 20–21, 2001	Monitoring	The EPA had one finding and no concerns. The finding noted that the subsidence monitoring program at the WIPP did not have an adequate written procedure to implement an effective QA program. In response to the EPA's finding, the DOE developed a new subsidence procedure. The EPA evaluated the procedure and found it to be adequate.	U.S. Environmental Protection Agency (2001a)
June 21, 2001	Waste Emplacement	The EPA did not have any findings, but they identified one concern. The EPA found that the DOE did not appear to have a procedure that required proper documentation of off-normal events. This concern did not require a response from the DOE because the DOE provided all documentation requested.	U.S. Environmental Protection Agency (2001b)
June 26–28, 2002	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2002a)
June 24–27, 2002	Waste Emplacement	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2002b)
June 18–19, 2003	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2003a)
June 17–19, 2003	Waste Emplacement	The EPA had one finding and no concerns during this inspection. The EPA was unable to determine that waste was being emplaced in a random manner. This finding was resolved in the CRA-2004.	U.S. Environmental Protection Agency (2003b)

Table 21-2. CRA-2004 Monitoring and Waste Emplacement Inspection Results (1999–2005) (continued)

Date of Inspection	Inspection Type	Inspection Results	Reference
June 28 through July 1, 2004	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2004a)
June 28 through July 1, 2004	Waste Emplacement	The EPA did not have any findings but did have one concern. The EPA found that the DOE did not appear to have a real-time system to track and calculate the actual MgO placed with waste at disposal. This concern was resolved by using the WIPP Waste Information System (WWIS) to track the quantities of MgO.	U.S. Environmental Protection Agency (2004b)
July 12–15, 2005	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2005a)
May 17–19, 2005	Waste Emplacement	The EPA did not have any findings, but did have one concern during this inspection. The EPA found that the DOE needed to develop a formal procedure that guides the MgO emplacement decision-making process rather than using training materials, and that the WWIS needs to be back-populated with the quantity of emplaced MgO. In response to this concern, the WWIS was back-populated.	U.S. Environmental Protection Agency (2005b)

21.5 EPA's Evaluation of Compliance for the 2004 Recertification

During each of the inspections listed in Table 21-3, the DOE provided the EPA with unfettered access to facilities, lists of records, access to these records as requested, and access to private office space. Additionally, the DOE actively supported the EPA's inspection activities. Based on the EPA's review and evaluation of the CRA-2004, the EPA determined that the DOE continued to comply with the requirements for section 194.21 (U.S. Environmental Protection Agency 2006a).

21.6 Changes or New Information Since the 2004 Recertification

Table 21-3 lists the seven new inspections conducted by the EPA under the authority of section 194.21 since the ones reported in CARD 21 (U.S. Environmental Protection Agency 2006a).

During each of the inspections listed in Table 21-3, the DOE met all the requirements of section 194.21, providing the EPA with unfettered access to facilities, lists of records, access to the records requested, and access to private office space. Additionally, the DOE actively supported the EPA's inspection activities as required by section 194.21.

Table 21-3. Post-CRA-2004 Monitoring and Waste Emplacement Inspection Results (2006–2007)

Date of Inspection	Inspection Type	Inspection Results	Reference
June 20–22, 2006	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2006b)
June 20–22, 2006	Waste Emplacement	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2006c)
July 10–12, 2007	Monitoring	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2007a)
July 10-12, 2007	Waste Emplacement	The EPA did not have any findings or concerns during this inspection.	U.S. Environmental Protection Agency (2007b)
January 9–11, 2007	Remote-Handled (RH) transuranic (TRU) (RH-TRU) Emplacement Plan	The EPA did not have any findings or concerns during this inspection. The EPA verified that RH-TRU waste could be emplaced in the WIPP repository according to the RH-TRU Emplacement Plan.	U.S. Environmental Protection Agency (2007c)
October 7, 2007	Unannounced inspection at the Advanced Mixed Waste Treatment Facility (AMWTF) and the Accelerated Retrieval Project at the Idaho National Laboratory	The EPA did not have any findings or concerns during the inspection of the AMWTF. However, the EPA requested information on the process used for regrouping four pre-1970 buried waste streams. EPA also requested information for estimating TRU, mixed TRU, and low-level waste volumes. On December 28, 2007, the DOE provided the EPA with the requested information. The DOE is awaiting the EPA's response as of November 1, 2008.	U.S. Environmental Protection Agency (2007d)
November 21-28, 2007	DOE document development and review process	Five process improvement recommendations were made.	Reyes (2008)

21.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Quality Assurance
(40 CFR § 194.22)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Quality Assurance
(40 CFR § 194.22)

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Acronyms and Abbreviations

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CCP	Central Characterization Project
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
MP	Management Procedure
NQA	Nuclear Quality Assurance
ORNL	Oak Ridge National Laboratory
QA	quality assurance
QAPD	Quality Assurance Program Document
RH-TRU	remote-handled transuranic
SNL	Sandia National Laboratories
SRS	Savannah River Site
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions

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22.0 Quality Assurance (40 CFR § 194.22)

22.1 Requirements

§ 194.22 Quality Assurance

(a)(1) As soon as practicable after April 9, 1996, the Department shall adhere to a quality assurance program that implements the requirements of ASME NQA–1–1989 edition, ASME NQA– 2a-1990 addenda, part 2.7, to ASME NQA–2–1989 edition, and ASME NQA–3– 1989 edition (excluding Section 2.1 (b) and (c), and Section 17.1). (Incorporation by reference as specified in § 194.5.)

(2) Any compliance application shall include information which demonstrates that the quality assurance program required pursuant to paragraph (a)(1) of this section has been established and executed for:

(i) Waste characterization activities and assumptions;

(ii) Environmental monitoring, monitoring of the performance of the disposal system, and sampling and analysis activities;

(iii) Field measurements of geologic factors, ground water, meteorologic, and topographic characteristics;

(iv) Computations, computer codes, models and methods used to demonstrate compliance with the disposal regulations in accordance with the provisions of this part;

(v) Procedures for implementation of expert judgment elicitation used to support applications for certification or re-certification of compliance;

(vi) Design of the disposal system and actions taken to ensure compliance with design specifications;

(vii) The collection of data and information used to support compliance application(s); and

(viii) Other systems, structures, components, and activities important to the containment of waste in the disposal system.

(b) Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a)(1) of this section have been qualified in accordance with an alternate methodology, approved by the Administrator or the Administrator's authorized representative, that employs one or more of the following methods: Peer review, conducted in a manner that is compatible with NUREG–1297, ''Peer Review for High-Level Nuclear Waste Repositories,'' published February 1988 (incorporation by reference as specified in § 194.5); corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to ASME NQA–1–1989 edition, ASME NQA– 2a–1990 addenda, part 2.7, to ASME NQA–2–1989 edition, and ASME NQA–3– 1989 edition (excluding Section 2.1 (b) and (c) and Section 17.1). (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall provide, to the extent practicable, information which describes how all data used to support the compliance application have been assessed for their quality characteristics, including:

(1) Data accuracy, i.e., the degree to which data agree with an accepted reference or true value;

(2) Data precision, i.e., a measure of the mutual agreement between comparable data gathered or developed under similar conditions expressed in terms of a standard deviation;

(3) Data representativeness, i.e., the degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions;

(4) Data completeness, i.e., a measure of the amount of valid data obtained compared to the amount that was expected; and

(5) Data comparability, i.e., a measure of the confidence with which one data set can be compared to another.

(d) Any compliance application shall provide information which demonstrates how all data are qualified for use in the demonstration of compliance.

(e) The Administrator will verify appropriate execution of quality assurance programs through inspections, record reviews and record keeping requirements, which may include, but may not be limited to, surveillance, audits and management systems reviews.

22.2 Background

40 CFR § 194.22 (2004) establishes quality assurance (QA) requirements for the Waste Isolation Pilot Plant (WIPP). QA is a process for enhancing the reliability of technical data and analyses

used for the U.S. Department of Energy's (DOE) Compliance Certification Application (CCA) (U.S. Department of Energy 1996) and 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004) that demonstrate compliance with the U.S. Environmental Protection Agency's (EPA's) disposal standards. Section 194.22 requires the DOE to (1) establish and execute a QA program for all items and activities important to the containment of waste in the disposal system, (2) qualify data that are collected prior to implementation of the required QA program, (3) assess data for their quality characteristics, to the extent practicable, (4) demonstrate how data are qualified for their use, and (5) allow verification of the above measures through the EPA inspections and audits. The DOE's QA program is required to adhere to specific Nuclear Quality Assurance (NQA) standards issued by the American Society of Mechanical Engineers (ASME) (NQA-1-1989, NQA-2a-1990 addenda part 2.7, and NQA-3-1989).

22.3 1998 Certification Decision

The EPA's Certification Decision was provided in *Federal Register* vol 63 (1998), pp. 27353–406, as "40 CFR Part 194 Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision; Final Rule." A complete description of the EPA's 1998 Certification Decision for section 194.22 is contained in the U.S. Environmental Protection Agency 1998 (Docket A-93-02, Items V-A-1 and V-B-2).

The EPA performed three types of assessments during review of the CCA to determine compliance with section 194.22:

1. Determine if the DOE correctly established and implemented QA programs for items and activities important to the long-term isolation of transuranic (TRU) waste in the disposal system (40 CFR § 194.22(a))
2. Determine if the DOE qualified all data, including existing data collected prior to the implementation of QA programs (40 CFR §§ 194.22(b) and (d))
3. Determine if the DOE assessed the CCA data for their quality characteristics (40 CFR § 194.22(c)).

The EPA took two general steps to perform each of the three assessments mentioned above. First, the EPA reviewed the CCA and associated references to determine if the DOE provided a satisfactory description of compliance with the QA requirements. During this stage, the EPA requested and reviewed additional information.

In the second step, the EPA conducted formal audits at WIPP-related facilities to verify compliance with the requirements of section 194.22. These audits were conducted under the authority of 40 CFR § 194.22(e) and were essential to verifying implementation of the QA requirements. Each WIPP-related facility generated much activity and documentation, and it was not practical to witness proper implementation of QA programs away from each facility based solely on documents provided by the DOE. Therefore, the EPA auditors went to four DOE facilities to witness the proper implementation of the QA requirements of section 194.22. As a result of the audits, the EPA approved the WIPP's QA programs at the DOE Carlsbad Field Office (CBFO), the WIPP site (managed by Washington TRU Solutions [WTS]), Sandia

National Laboratories (SNL), and Los Alamos National Laboratory (LANL). These four WIPP-related facilities are all located in New Mexico.

At that time (1996–1998), other WIPP-related facilities located outside of New Mexico were not approved by the EPA. 40 CFR § 194.22(a)(2)(i) requires the DOE to apply QA programs for waste characterization activities prior to certification. The criteria in 40 CFR § 194.24(c)(3) and 40 CFR § 194.24(c)(5) cross-reference the QA requirements set forth in section 194.22(a)(2)(i). The CCA indicates that waste generator sites outside New Mexico would not begin waste characterization until after 1997 and that it was not reasonable to implement QA programs at that time for future waste characterization. The EPA applied a condition to the approval of the CCA that sites without approved QA programs could not dispose of TRU waste at the WIPP. Each unapproved site would have to be audited after the approval of the CCA to verify compliance prior to shipment of waste from each unapproved site.

The EPA examined the application of QA for waste characterization at one waste generator site as part of the CCA review. After DOE informed the EPA that LANL was ready for an audit, the EPA auditors reviewed the LANL QA Plan to verify establishment of QA requirements, and later verified the proper implementation of the QA Plan at LANL. Based on the audit samples taken, the EPA determined that LANL had properly established and implemented a QA program for its waste characterization. The other waste generator sites required EPA audits of their individual QA programs before the EPA could allow them to send waste to the WIPP.

After the EPA approved the CCA, the agency conducted periodic audits at the four approved facilities to verify continued compliance. The EPA also began to audit other facilities that had not been ready to perform work at the time of the CCA.

22.4 Changes in the CRA-2004

The CRA-2004, Chapter 5.0, like the CCA, Chapter 5.0, discusses the QA programs for the WIPP. The DOE extensively revised the CRA-2004, Chapter 5.0 to make it clearly match the structure of the NQA standards and to update information. Changes to the QA portions of the CRA-2004 reflected a maturing and expansion of the WIPP QA program since the CCA. The QA programs that were new at the time of the CCA had increased their effectiveness over time. Between 1998 and 2004, new waste generator sites were added, thus adding more QA programs.

The QA Plan that establishes the NQA standards for the WIPP is the "Quality Assurance Program Document" (QAPD). The CRA-2004, Appendix QAPD, as in the CCA, contained the current QAPD at the time. The DOE revised the QAPD between the CCA and the CRA-2004 to more clearly establish each of the applicable NQA elements and to update the DOE organizational structure. The CRA-2004, Appendices PEER-2004 and AUD-2004 were also updated to include peer reviews and audits performed since the CCA.

22.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA's Recertification Decision was published in *Federal Register* vol. 71 (2006), pp. 18010–021, (U.S. Environmental Protection Agency 2006a) as "40 CFR Part 194 [EPA–HQ–OAR–2004–0025; FRL–8055–1] Criteria for the Certification and Recertification of the Waste

Isolation Pilot Plant's Compliance with the Disposal Regulations: Recertification Decision." Detailed technical evaluation of the CRA-2004, Chapter 5.0, Quality Assurance, was provided in Compliance Application Review Document (CARD) 22 (U.S. Environmental Protection Agency 2006b). The following is a summary of the EPA's evaluation of compliance with section 194.22 (CRA 2004, Chapter 5.0 and Appendices PEER-2004 and AUD-2004), as contained in the EPA documents mentioned above.

22.5.1 NQA Standards

The CRA-2004 provides information on the DOE's implementation of the NQA standards. ASME NQA-1-1989 requirements are addressed in the CRA-2004, Chapter 5.0, Sections 5.3.1 through 5.3.19. ASME NQA-2a-1990 addenda part 2.7 is addressed in the CRA-2004, Chapter 5.0, Section 5.3.20. ASME NQA-3-1989 is addressed in the CRA-2004, Chapter 5.0, Sections 5.3.21, 5.3.22, and 5.3.23 (Docket A-93-02 Items V-A-1 and V-B-2).

The DOE QA Plan that implements the NQA standards, the QAPD, is provided in the CRA-2004 as Appendix QAPD. Since the CCA, the EPA periodically audited the QAPD to verify the continued proper establishment of the NQA standards.

The EPA found that the CBFO QA Plan (the CRA-2004, Appendix QAPD) properly established the applicable elements of the NQA standards invoked under section 194.22 for items and activities important to the long-term isolation of TRU waste.

22.5.2 Audits of QA Plan Implementation

The CRA-2004 provides information on internal and external auditing of the implementation of the CBFO QAPD in the CRA-2004, Chapter 5.0, Sections 5.3.19 and 5.7. The CRA-2004, Chapter 5.0, Section 5.7 describes the CBFO audit process that covers internal and external audits, audit schedules, and audit team leader requirements. The CRA-2004, Appendix AUD-2004, Table AUD-10 provides a summary of audits conducted on the CBFO QA Plan. The EPA determined that the CRA-2004 provided references to general and auditable information regarding internal and external audits to verify proper implementation of the CBFO QA Plan. Further, the EPA conducted periodic audits since the CCA to verify the proper implementation of the CBFO QA Plan.

22.5.3 Audits of QA Programs at Lower-Tier Organizations

The CRA-2004, Chapter 5.0, Section 5.3.19 addresses internal and external auditing of the CBFO QA Plan as a requirement of NQA-1-1989, and the CRA-2004, Chapter 5.0, Section 5.7 describes the CBFO audit process that covers internal and external audits, audit schedules, and audit team leader requirements. An audit history of assessments of TRU waste generator sites and suppliers performing quality-affecting work between 1999 and 2003 is located in CRA-2004, Appendix AUD-2004, Tables AUD-1 through AUD-11. All audits are assigned an audit number, which allows traceability.

Audited suppliers included CBFO Technical Assistance Contractor, Argonne National Laboratory (ANL) – East, Battelle Columbus Lab, Mobile Characterization Services, LLC, and Carlsbad Environmental Monitoring and Research Center.

The EPA found that the CRA-2004 contained general and auditable information describing an active auditing program by the CBFO of lower-tier and supplier organizations. Further, the EPA conducted periodic audits since the CCA to verify the proper execution of QA programs at the lower-tier organizations.

22.5.4 NUREG-1297 for Peer Reviews

NUREG-1297 (U.S. Nuclear Regulatory Commission 1988) provides guidance on the definitions of peer reviews, the area for which peer review is appropriate, the acceptability of peers, and the conduct and documentation of peer reviews. The CBFO peer review process is outlined in the CRA-2004, Chapter 9.0, Section 9.2, which is broken into Sections 9.2.1 through 9.2.8 that generally mirror the topics in NUREG-1297. The remainder of the CRA-2004, Chapter 9.0 discusses the results of peer reviews conducted prior to 2004.

CBFO Management Procedure (MP) 10.5 defines the requirements of NUREG-1297. The EPA evaluated MP 10.5 and its description in the CRA-2004, Chapter 9.0, Sections 9.2.1 through 9.2.8 and found it to be acceptable.

22.5.5 Assessments of Data Quality Characteristics

The CRA-2004 provides information that describes how all data used to support the compliance application have been assessed for accuracy, precision, representativeness, completeness, and comparability.

The DOE applies the data quality characteristics to tasks involving the quantification of specific constituents in an environmental medium through sampling and analysis, and applies these data quality characteristics to activities such as the determination of the presence or absence of constituents within TRU waste streams. In these cases, the performance measurement is the concentration of the constituent of interest. Data quality measures are found in the CRA-2004, Chapter 5.0, Section 5.3.22.

The EPA found that the CRA-2004 provides information that describes how all data used to support the compliance application have been assessed for their quality characteristics.

22.5.6 Data Qualifications

The CRA-2004, Chapter 5.0, Section 5.3.23 provides information on how all data are qualified for use in the demonstration of compliance. This section provides information on how all data used are qualified by using one or more of five methods. Audits were conducted to verify that data not qualified by one of these methods were not used for demonstrating compliance. The EPA found that the CRA-2004 provides information describing how all data used to support the compliance application have been qualified.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.22.

22.6 Changes or New Information Since the 2004 Recertification

Changes to the QAPD since the CRA-2004, additions and changes to the CBFO implementing procedures, and an updated list of waste generator sites certified under the QA program are described below.

22.6.1 Changes to QAPD

Revisions to the QAPD identified below are a summary of changes as noted in the revision history. The detailed changes are incorporated within the document.

In October 2004, Rev. 6 of the QAPD implemented the restructured CBFO organization.

In July 2005, changes implemented in Rev. 7 of the QAPD were the direct result of the DOE Headquarters (DOE EM 3-2) comments relative to compliance with the DOE Order (DOE O 414.1B).

The changes implemented in Rev. 8 of the QAPD, effective November 2006, were made to address 13 minor findings and 1 concern from an EPA inspection of the CBFO QA program. Document citations were added to include remote-handled (RH) transuranic (TRU) (RH-TRU) waste packaging. The exemption of National Environmental Policy Act–related software from the requirements of the QAPD was deleted. The applicability of software QA to safety software was clarified. Editorial changes related to the June 26, 2006, reorganization of the CBFO were also incorporated.

In December 2007, Rev. 9 of the QAPD clarified that reliance on administrative controls alone is not sufficient for differentiating between waste that is acceptable for shipment to the WIPP and waste that does not meet the WIPP waste acceptance criteria. The classification of conditions adverse to quality related to the Hazardous Waste Facility Permit was also clarified. The language regarding reporting nonconformances was revised to comply with the November 16, 2006, Permit Modification. The requirements for records disposition were revised to comply with the Class 1 Permit Modification that took effect on September 13, 2007.

22.6.2 Changes to CBFO/DOE Procedures

The following CBFO procedures have been added since the CRA-2004:

- MP 3.2, “Trend Identification and Reporting” (changed from a Team Procedure to an MP)
- MP 3.4, “CBFO Manager Actions upon Notification of Potential Noncompliant Waste Identified During the Waste Confirmation Process”
- TP 3.3, “Protocol for CBFO Observers at Baseline Inspections”

- MP 4.11, "Safety Basis Review Procedure"
- MP 4.12, "National Environmental Policy Act Compliance"
- MP 4.14, "Review of Acceptable Knowledge Sufficiency Determination Requests"
- MP 5.4, "Orders Compliance Program Implementation"

The following procedure has been inactivated:

- MP 2.1, "Personnel Qualification and Training"

22.6.3 Updated List of Waste Generator Sites Certified under the QA Program

The contact-handled TRU waste generator sites currently certified under the QA program include:

- LANL/Central Characterization Project (CCP)
- Hanford
- Idaho National Laboratory (INL)/Central Characterization Project
- Savannah River Site (SRS)/CCP
- Advanced Mixed Waste Treatment Project
- Oak Ridge National Laboratory (ORNL)/Central Characterization Project

Since the CRA-2004, two RH-TRU waste generator sites, INL/CCP and ANL/CCP, have been certified (see Section 8, Approval Process of Waste Shipment from Waste Generator Sites for Disposal at the WIPP). There have also been three peer reviews since the CRA-2004 (see Section 27, Peer Review). A listing of audits and surveillances performed by CBFO can be found in Appendix AUD-2009.

The following CBFO procedures were revised since the CRA-2004:

- MP 1.2, "Selection of Quality Levels"
- MP 3.1, "Corrective Action Reports"
- MP 4.1, "Preparation and Maintenance of CBFO Procedures"
- MP 4.2, "Document Review"
- MP 4.4, "Document Preparation and Control"

- MP 4.10, "Processing of TRU Waste Site Documents"
- MP 5.2, "TRU Waste Site Certification/Recertification"
- MP 7.1, "QA Requirements for Procurement of Services"
- MP 9.1, "Management Assessments"
- TP 10.1, "Qualification of Audit Personnel and Certification of Lead Auditors"
- MP 10.2, "Surveillances"
- MP 10.3, "Audits"
- MP 10.5, "Peer Review"
- TP 10.7, "Operational Assessments"

The changes identified to the QAPD and its implementing procedures since the CRA-2004 represent normal evolution and improvement in the DOE QA program. The current WIPP QA program is effectively managed and maintained as demonstrated by the CBFO audit and surveillance program (see Appendix AUD-2009), and meets the provisions of section 194.22.

22.7 References

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U.S. Environmental Protection Agency (EPA). 1998. "40 CFR Part 194: Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision; Final Rule." *Federal Register*, vol. 63 (May 18, 1998): 27353–406.

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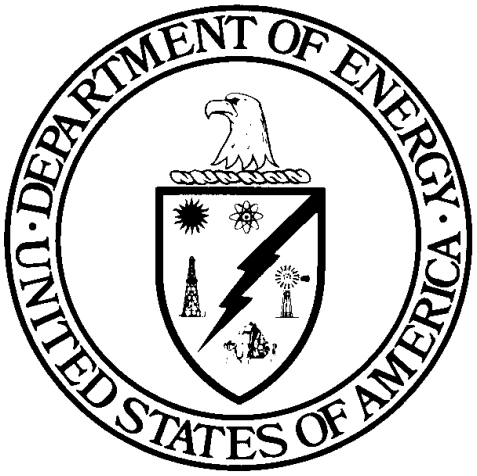
Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Models and Computer Codes
(40 CFR § 194.23)



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Models and Computer Codes
(40 CFR § 194.23)

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Acronyms and Abbreviations

AP	Analysis Packages
ASME	American Society of Mechanical Engineers
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DD	Design Document
DOE	U.S. Department of Energy
DRP	Data Records Packages
DRZ	Disturbed Rock Zone
EPA	U.S. Environmental Protection Agency
FEP	features, events, and process
IB	Inside Boundary
ID	Implementation Document
LHS	Latin Hypercube Sampling
NQA	Nuclear Quality Assurance
NRC	U.S. Nuclear Regulatory Commission
OB	Outside Boundary
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PEF	Parameter Entry Form
PIRP	Principal Investigator Records Package
QA	quality assurance
QAP	Quality Assurance Procedure
QAPD	Quality Assurance Program Document
RD	Requirements Document
SNL	Sandia National Laboratories
UM	User's Manual
VD	Validation Document
VVP	Verification and Validation Plan
WIPP	Waste Isolation Pilot Plant

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23.0 Models and Computer Codes (40 CFR § 194.23)

23.1 Requirements

§ 194.23 Models and Computer Codes

(a) Any compliance application shall include:

(1) A description of the conceptual models and scenario construction used to support any compliance application.

(2) A description of plausible, alternative conceptual model(s) seriously considered but not used to support such application, and an explanation of the reason(s) why such model(s) was not deemed to accurately portray performance of the disposal system.

(3) Documentation that:

(i) Conceptual models and scenarios reasonably represent possible future states of the disposal system.

(ii) Mathematical models incorporate equations and boundary conditions which reasonably represent the mathematical formulation of the conceptual models.

(iii) Numerical models provide numerical schemes which enable the mathematical models to obtain stable solutions.

(iv) Computer models accurately implement the numerical models; i.e., computer codes are free of coding errors and produce stable solutions.

(v) Conceptual models have undergone peer review according to §194.27.

(b) Computer codes used to support any compliance application shall be documented in a manner that complies with the requirements of ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition.

(c) Documentation of all models and computer codes included as part of a compliance application performance assessment calculation shall be provided. Such documentation shall include, but shall not be limited to:

(1) Descriptions of the theoretical backgrounds of each model and the method of analysis or assessment.

(2) General descriptions of the models; discussions of the limits of applicability of each model; detailed instructions for executing the computer codes, including hardware and software requirements, input and output formats with explanations of each input and output variable and parameter (e.g., parameter name and units); listing of input and output files from a sample computer run; and reports on code verification, bench marking, validation, and quality assurance procedures.

(3) Detailed descriptions of the structure of the computer codes and complete listings of the source codes.

(4) Detailed descriptions of data collection procedures, data reduction and analysis, and code input parameter development.

(5) Any necessary licenses;

(6) An explanation of the manner in which models and computer codes incorporate the effects of parameter correlation.

(d) The Administrator or the Administrator's authorized representative may verify the results of computer simulations used to support any compliance application by performing independent simulations. Data files, source codes, executable versions of computer software for each model, other material or information needed to permit the Administrator or the Administrator's authorized representative to perform independent simulations, and to access necessary hardware to perform such simulations, shall be provided within 30 calendar days of a request by the Administrator or the Administrator's authorized representative.

23.2 40 CFR § 194.23(a)(1)

23.2.1 Background

The criteria in 40 CFR § 194.23(a)(1) (U.S. Environmental Protection Agency 1996) requires descriptions of the conceptual models and scenario construction used to demonstrate compliance.

23.2.2 1998 Certification Decision

To meet the requirements for section 194.23(a)(1), the U.S. Environmental Protection Agency (EPA) expected the U.S. Department of Energy (DOE) to include a complete, clear, and logical description of each conceptual model used to demonstrate compliance in the application. Documentation of the conceptual models was expected to discuss site characteristics and processes active at the site (e.g., gas generation or creep closure of the Salado salt formation). The conceptual models were to consider both natural and engineered barriers. The DOE developed 24 conceptual models to describe the Waste Isolation Pilot Plant (WIPP) disposal system.

For the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the EPA reviewed each of the 24 conceptual models included in the CCA (Table 23-1), using

Table 23-1. WIPP Conceptual Models

Conceptual Model	Component
1 Disposal System Geometry[a]	**Salado F/T**
2 Culebra Hydrogeology	Non-Salado F/T
3 Repository Fluid Flow	**Salado F/T**
4 Salado	Salado F/T
5 Impure Halite	Salado F/T
6 Salado Interbeds	Salado F/T
7 DRZ	**Salado F/T**
8 Actinide Transport in the Salado	Salado F/T
9 Units Above the Salado	Non-Salado F/T
10 Transport of Dissolved Actinides in the Culebra	Non-Salado F/T
11 Transport of Colloidal Actinides in the Culebra	Non-Salado F/T
12 Exploration Boreholes	Human Intrusion
13 Cuttings and Cavings	Human Intrusion
14 Spallings	**Human Intrusion**
15 Direct Brine Release	Human Intrusion
16 Castile and Brine Reservoir	Human Intrusion
17 Multiple Intrusions	Human Intrusion
18 Climate Change	Non-Salado F/T
19 Creep Disposal	Salado F/T
20 Shafts and Shaft Seals	Salado F/T
21 Gas Generation	Salado F/T
22 Chemical Conditions	Salado F/T
23 Dissolved Actinide Source Term	Salado F/T
24 Colloidal Actinide Source Term	Salado F/T

[a] Entries in bold were modified and peer reviewed for the CRA-2004 PA.

information contained in the CCA, supplementary peer review panel reports, and supplementary information provided to the EPA by the DOE in response to specific EPA comments. Upon the conclusion of the conceptual model peer review, the panel states, "With the exception of the Spallings Model presented in the CCA, which the Panel continues to find inadequate, all remaining conceptual models have been determined to be adequate and all significant issues regarding their adequacy have been resolved" and "Although further refinement in understanding and predictive capability for spallings events would be desirable as part of a new conceptual model, the Panel has determined that the additional information presented by the DOE is sufficiently complete at this time to support a conclusion that the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that would be expected to be released by the spallings process at the WIPP" (Compliance Recertification Application of 2004 [CRA-2004] [U.S. Department of Energy 2004], Appendix PEER-2004, Section PEER-2004 1.1.5, Section 4.0). The EPA agreed with the peer review panel that all models, with the exception of spallings, were considered adequate to represent future states of the repository. In the case of the spallings model, the EPA considered the results adequate, because the DOE showed in its additional spallings modeling that the release of solid waste predicted by the PA spallings model overestimated releases by a factor of 10 or more (Sandia National Laboratories and Carlsbad Area Office Technical Assistance Contractor 1997).

The EPA determined that the CCA and supporting documentation contained a complete and accurate description of each conceptual model and the scenario construction methods used in performance assessment (PA). The scenario construction descriptions included sufficient detail to understand the basis for selecting some scenarios and rejecting others, and were adequate for use in the CCA PA calculations. The EPA found the DOE to be in compliance with the requirements of section 194.23(a)(1) (Compliance Application Review Document [CARD] 23, Section 1.4 (U.S. Environmental Protection Agency 1998a).

A complete description of the EPA's 1998 Certification Decision for section 194.23(a)(1) can be obtained from CARD 23, Section 1.4 (U.S. Environmental Protection Agency 1998a).

23.2.3 Changes in the CRA-2004

For the CRA-2004, the DOE undertook an extensive screening process to determine which features, events, and processes (FEPs) were still applicable to the disposal system and which changes were appropriate for the CRA-2004. The DOE's scenario construction methods have not changed since the CCA. The DOE constructed two basic scenarios: undisturbed performance and disturbed performance, which include drilling and mining events. As part of this scenario development, the DOE selected FEPs that were relevant. FEPs judged to be significant were included in the 24 conceptual models of the CCA and the CRA-2004.

The CCA FEPs were reassessed to determine if the screening justifications remained valid in light of changes within the WIPP project. Although minor changes were made to the FEPs, the results of the reassessment did not impact the original conceptual models or scenarios (CRA-2004, Appendix PA, Attachment SCR and Chapter 6.0, Section 6.2.6). In the CRA-2004, Appendix PA, Attachment SCR-1.0, the DOE summarized the results of the CRA-2004 FEPs reevaluation. Of the original 237 CCA FEPs, 106 had not changed in the CRA-2004, and 120 FEPs required minor updates to their descriptions and/or screening arguments (CRA-2004,

Appendix PA, Attachment SCR, Table SCR-2). The screening decisions for seven of the original baseline FEPs were changed, four FEPs had been deleted or combined with other related FEPs, and two new FEPs had been added to the list (see Table 23-2 for a summary of these changes).

Table 23-2. FEPs Change Summary in the CRA-2004[a]

EPA FEP I.D.	FEP Name	Summary of Change
FEPs Combined with other FEPs		
N17	Lateral Dissolution	Combined with N16, Shallow Dissolution. N17 removed from baseline.
N19	Solution Chimneys	Combined with N20, Breccia Pipes. N19 removed from baseline.
H33	Flow Through Undetected Boreholes	Combined with H31, Natural Borehole Fluid Flow. H33 removed from baseline.
W38	Investigation Boreholes	Addressed in H31, Natural Borehole Fluid Flow, and H33, Flow Through Undetected Boreholes. W38 removed from baseline.
FEPs with Changed Screening Decisions		
W50	Galvanic Coupling	Screened-out probability to screened-out consequence
W68	Organic Complexation	Screened-out consequence to undisturbed performance
W69	Organic Ligands	Screened-out consequence to undisturbed performance
H27	Liquid Waste Disposal	Screened-out regulatory to screened-out consequence
H28	Enhanced Oil and Gas Production	Screened-out regulatory to screened-out consequence
H29	Hydrocarbon Storage	Screened-out regulatory to screened-out consequence
H41	Surface Disruptions	Screened-out consequence to undisturbed performance
New FEPs for the CRA-2004		
H58	Solution Mining for Potash	Separated from H13, Potash Mining
H59	Solution Mining for Other Resources	Separated from H13, Potash Mining

[a] From the CRA-2004, Appendix PA, Attachment SCR, Table SCR-1.

The CRA-2004 maintained 24 conceptual models to describe the WIPP disposal systems. The DOE did, however, modify three conceptual models related to the Salado Formation modeling: Disposal System Geometry, Repository Fluid Flow, and the Disturbed Rock Zone (DRZ). Furthermore, the DOE developed a new spallings model for the CRA-2004. The 24 conceptual models included in the CCA and the CRA-2004 are listed in Table 23-1; the four changed models are noted in bold type. The components in this table refer to broad groupings of the conceptual models for those models related to human intrusion, flow and transport within the Salado Formation (Salado F/T), and flow and transport in hydrostratigraphic units other than the Salado (Non-Salado F/T).

23.2.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA's review of the CRA-2004 for compliance with section 194.23(a)(1) focused on changes to FEPs, conceptual models, scenarios, or models since the 1998 Certification Decision (U.S. Environmental Protection Agency 1998b). The CCA and CRA-2004 scenario construction process had not changed and was based on screening decisions using a comprehensive list of FEPs developed for the Swedish Nuclear Power Inspectorate (also known as SKI), and other WIPP-specific FEPs developed by the DOE (see the CRA-2004, Chapter 6.0, Section 6.2.1, and the CCA, Chapter 6.0). The DOE's methods for addressing conceptual model development and scenario construction had not changed since the CCA, and consisted primarily of identifying and screening processes and events and combining them into scenarios. The EPA reviewed each of the steps used in this process during its evaluation and review of changes since the CCA. The EPA reviewed the DOE's FEPs reevaluation and found the documentation to be adequate and the reasons for changes to the FEPs reasonable (see Section 4.0 in U.S. Environmental Protection Agency 2006a).

During the CRA-2004 evaluation, the EPA paid particular attention to any FEP changes concerning human intrusion scenarios related to mining and oil and gas drilling, such as fluid injection and air drilling. The review is documented in *Technical Support Document for Sections 194.32 and 33: Compliance Recertification Application Re-evaluation of Selected Human Intrusion Activities* (U.S. Environmental Protection Agency 2006b). As noted in this document, some parameters, such as drilling rate and other drilling-related values were updated since the CCA as a result of continued activities in the Delaware Basin. The parameter changes did not have a detrimental impact on the compliance determination, as exhibited by the results of the subsequent PA, the CRA-2004 Performance Assessment Baseline Calculation (PABC) (see U.S. Environmental Protection Agency 2006c, Section 11.3). Drilling practices, such as injection techniques and air drilling, and mining activities have not significantly changed since the CCA. Therefore, the EPA did not believe that the original conclusions during the CCA needed to be modified for the CRA-2004.

In the EPA's August 2002 Guidance Letter (Marcinowski 2002), the EPA instructed the DOE to develop a new spallings model for the CRA-2004 PA. The new spallings model (CRA-2004, Appendix PA, Attachment MASS-2004, Section 16.1.3) included three major elements: consideration of multiphase flow processes in the intrusion borehole, consideration of fluidization and transport of waste particulates from the intact waste mass to the intrusion borehole, and a numerical solution for the coupled mechanical and hydrological response of the waste as a porous medium. The new spallings model was peer reviewed in 2003 and found to be adequate (CRA-2004, Chapter 9.0, Section 9.3.1.3.5 and CRA-2004, Appendix PEER-2004, Section PEER-2004 3.0). The EPA found the spallings model peer review to be adequate (U.S. Environmental Protection Agency 2006d, Section 5.0) and the new spallings model to be appropriate for use in the WIPP PA (see U.S. Environmental Protection Agency 2006c, Section 10.3.1).

The DOE modified the Disposal System Geometry, Repository Fluid Flow, and DRZ conceptual models. These models were changed to reflect new information on the Salado and to incorporate the EPA-mandated Option D panel closure design requirements. The DOE modified the BRAGFLO computational grid and the computational grid for the direct brine release

calculations to include the Option D panel closure design requirements. The DOE also simplified the shaft in the BRAGFLO grid and refined the BRAGFLO grid. These modified conceptual models were peer reviewed during 2002 to 2003 and found to be adequate (CRA-2004, Chapter 9.0, Section 9.3.1.3.4 and CRA-2004, Appendix PEER-2004, Section PEER-2004 2.0). The EPA found the Salado flow peer review to be adequate (see the U.S. Environmental Protection Agency 2006e, Section 5.0). The EPA determined that while these new models better reflected the knowledge of the disposal system, the changes had little impact on the results of the PA (U.S. Environmental Protection Agency 2006c, Section 12.0).

The EPA's review found that the CRA-2004 and supplementary information contained a complete and accurate description of each conceptual model that changed, and that documentation of all conceptual models continued to adequately discuss site characteristics and processes at the site. The EPA determined that the conceptual models continued to adequately represent those characteristics, processes, and attributes of the WIPP disposal system affecting its performance, and that the conceptual models considered both natural and engineered barriers. The EPA found that the DOE considered conceptual models that continued to adequately describe the future characteristics of the disposal system. The conceptual models continued to reasonably describe the expected performance of the disposal system and incorporate reasonable simplifying assumptions of the disposal system's behavior. The EPA found that the modifications to four of the conceptual models were reasonable and the related CRA-2004 documentation was complete (CARD 23, Section "Recertification Decision 194.23(a)(1);" U.S. Environmental Protection Agency 2006f).

The EPA concluded that the CRA-2004 continued to contain an adequate description of the scenario construction methods used, and that the scenario construction descriptions include sufficient detail to understand the basis for selecting some scenarios and rejecting others. Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.23(a)(1) (CARD 23, Section "Recertification Decision 194.23(a)(1)," U.S. Environmental Protection Agency 2006f).

23.2.5 Changes or New Information Since the 2004 Recertification

A FEPs reassessment was conducted for the CRA-2009 and the results are documented in Appendix SCR-2009. In Appendix SCR-2009, Section SCR-1.0, the results of the CRA-2009 FEPs reevaluation are summarized. Of the 235 FEPs considered for the CRA-2004, 188 have not been changed, 35 have been updated with new information, 10 FEPs have been split into 20 similar but more descriptive FEPs, one screening argument has been changed to correct errors discovered during review, and one FEP has had its screening decision changed (Appendix SCR, Table SCR-2). Table 23-3 summarizes the FEPs that have been added, separated or had a screening decision change since the CRA-2004.

No changes in the 24 conceptual models or scenario construction methodology resulted from the FEPs reevaluation. Thus, the DOE continues to demonstrate compliance with the provision of section 194.23(a)(1).

Table 23-3. FEPs Change Summary Since CRA-2004[a]

EPA FEP I.D.[b,c]	FEP Name	Summary of Change
FEPs Clarified to be Less Generic		
H27	Liquid Waste Disposal – Outside Boundary (OB)	Name changed to "Liquid Waste Disposal Boundary – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
H28	Enhanced Oil and Gas Production – OB	Name changed to "Enhanced Oil and Gas Production – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
H29	Hydrocarbon Storage – OB	Name changed to "Hydrocarbon Storage – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
W6	Shaft Seal Geometry	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W7	Shaft Seal Physical Properties	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W8	Shaft Seal Chemical Composition	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W17	Radiological Effects on Shaft Seals	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W36	Consolidation of Shaft Seals	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W37	Mechanical Degradation of Shaft Seals	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
W74	Chemical Degradation of Shaft Seals	Name changed to be specific to Shaft Seals, rather than generic "seals" which also included panel closures (seals).
FEPs With Changed Screening Decisions		
H41	Surface Disruptions	Screening changed from screened-out regulatory to screened-out consequence due to inconsistency with screening rationale.
New FEPs for CRA-2009		
H60	Liquid Waste Disposal – Inside Boundary (IB)	New FEP; separated from H27. The creation of this new FEP allows for more appropriate screening based on regulatory provisions pertaining to activities within the WIPP land withdrawal boundary.
H61	Enhanced Oil and Gas Production – IB	New FEP; separated from H28. The creation of this new FEP allows for more appropriate screening based on regulatory provisions that pertain to activities within the WIPP land withdrawal boundary.
H62	Hydrocarbon Storage – IB	New FEP; separated from H29. The creation of this new FEP allows for more appropriate screening based on regulatory provisions that pertain to activities within the WIPP land withdrawal boundary.
W109	Panel Closure Geometry	New FEP; separated from W6. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W110	Panel Closure Physical Properties	New FEP; separated from W7. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.

[a] From the Appendix SCR-2009, Table SCR-1.
[b] H = Human-induced FEP.
[c] W = Waste and Repository-Induced FEP.

Table 23-3. FEPs Change Summary Since CRA-2004[a] (Continued)

EPA FEP I.D.[b,c]	FEP Name	Summary of Change
W111	Panel Closure Chemical Composition	New FEP; separated from W8. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W112	Radiological Effects on Panel Closures	New FEP; separated from W17. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W113	Consolidation of Panel Closures	New FEP; separated from W36. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W114	Mechanical Degradation of Panel Closures	New FEP; separated from W37. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W115	Chemical Degradation of Panel Closures	New FEP; separated from W74. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.

[a] From the Appendix SCR-2009, Table SCR-1.
[b] H = Human-induced FEP.
[c] W = Waste and Repository-Induced FEP.

23.3 40 CFR § 194.23(a)(2)

23.3.1 Background

40 CFR § 194.23(a)(2) requires a description of those conceptual models that were identified or developed while preparing the compliance application, but were determined not to be appropriate for portraying disposal system performance. It also requires that the reasons for not using these models be explained.

23.3.2 1998 Certification Decision

To meet the requirements of section 194.23(a)(2), the CCA described the plausible alternative conceptual models considered but not used and explained why these models were not used. The description of the rejected alternative models did not need to be as detailed as the description of the models actually used in the CCA. In the CCA, the DOE describes plausible alternative conceptual models considered but not used for PA in the CCA and supplementary information (the CCA, Chapters 2.0, 9.0, and Appendix MASS). The DOE also explains why these alternative models are not used to describe the performance of the repository. The descriptions of the alternative models and justifications for the conceptual model selections are summarized in Dials (1997, Table 1). The EPA reviewed the material on alternative conceptual models and the comments made by the Conceptual Models Peer Review Panel on alternative models. The peer review panel identified no substantive issues regarding alternative models. The EPA found the DOE to be in compliance with the requirements of section 194.23(a)(2) (CARD 23, Section 2.4, U.S. Environmental Protection Agency 1998a).

A complete description of the EPA's 1998 Certification Decision for section 194.23(a)(2) can be obtained from CARD 23, Section 2.4 (U.S. Environmental Protection Agency 1998a).

23.3.3 Changes in the CRA-2004

As stated at the time of the CCA, the DOE's position is that the basic elements of the conceptual models used in the CCA have been developed over a number of years, as a result of continuing analysis of alternatives and elimination of those alternative conceptual models found to be unacceptable or inappropriate.

For the CRA-2004, the DOE describes the conceptual models used to evaluate the WIPP's performance in the CRA-2004, Chapter 2.0; Chapter 6.0, Section 6.4; and Chapter 9.0, Section 9.3.1. The DOE changed four conceptual models since the CCA. The DOE developed a new spallings model for the CRA-2004 and made minor changes to three other conceptual models: the Disposal System Geometry, Repository Fluid Flow, and DRZ models. These changes can be considered alternative models, as described by section 194.23(a)(2). All of these models were peer reviewed as required by 40 CFR § 194.27. The Conceptual Models Peer Review Panel's consideration of alternative conceptual models for the four changed conceptual models is described in the CRA-2004, Appendix PEER-2004, Sections PEER-2004 2.0 and PEER-2004 3.0.

23.3.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed the CRA-2004 documentation listed above and reevaluated the CCA documentation. The EPA reviewed all aspects of the DOE's work related to alternative conceptual models to confirm that the DOE continued to comply with the requirements of section 194.23(a)(2) (CARD 23, Section "Evaluation of Compliance for Recertification 194.23(a)(2)," U.S. Environmental Protection Agency 2006f).

As part of the EPA's alternative model review, the EPA examined the CRA-2004 documentation to determine if any other models had changed or if any new alternative models had been developed since the CCA. The EPA also reexamined the CCA for alternative conceptual models seriously considered in the CCA, as summarized by Dials (1997, Table 1), to determine if any of the DOE's original approach or justification had changed since the original certification. Based on this review, the EPA determined that all alternative models had been appropriately considered by the DOE and that the DOE continued to be in compliance with the requirements of section 194.23(a)(2) (CARD 23, Section "Recertification Decision 194.23(a)(2)," U.S. Environmental Protection Agency 2006f).

Members of the public suggested that karst formation and processes may be a possible alternative conceptual model for flow in the Rustler. Karst may be thought of as voids in near-surface or subsurface rock created by water flowing when rock is dissolved. Public comments stated that karst could develop interconnected "underground rivers" that may enhance the release of radioactive materials from the WIPP. Because of this comment, the EPA required the DOE to perform a thorough reexamination of all historical data, information, and reports, both those by the DOE and others, to determine if karst features or development had been missed during previous work done at the WIPP. The DOE's findings are summarized in Lorenz (2006). The

EPA also conducted a thorough reevaluation of karst and of the work done during the CCA (U.S. Environmental Protection Agency 2006g). The reevaluation of historical evidence and recent work by the DOE did not show even the remotest possibility of an "underground river" near WIPP, nor did it change the CCA conclusions. Therefore, the EPA believed karst was not a viable alternative model at the WIPP. For a more complete discussion of the reevaluation of karst, see CARD 14/15 (U.S. Environmental Protection Agency 2006h) and Lorenz (2006).

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements of section 194.23(a)(2) (CARD 23, Section "Recertification Decision 194.23(a)(2)," U.S. Environmental Protection Agency 2006f).

23.3.5 Changes or New Information Since the 2004 Recertification

The 24 conceptual models have not changed since the CRA-2004 decision in March 2006. As part of DOE's continuous evaluation of alternative conceptual models, the DOE proposed in 2007 modifications that would affect two of the existing conceptual models, cuttings and cavings and DRZ (Vugrin and Nemer 2007). It was determined that since these proposed modifications would impact the conceptual models, an independent technical peer review on the adequacy of the proposed changes to the approved conceptual models should be performed in accordance with the requirements of section 194.27. Before the peer review was completed, the DOE decided in October 2007 to postpone the consideration of the proposed modifications (see Section 27.7.3). The DOE continues to demonstrate compliance with the provision of section 194.23(a)(2).

23.4 40 CFR § 194.23(a)(3)

23.4.1 Background

40 CFR § 194.23(a)(3) includes provisions to ensure documentation of the basis for conceptual models used in compliance applications. Specific requirements are for documentation that

1. Conceptual models and scenarios reasonably represent possible future states of the disposal system.

2. The equations and boundary conditions in a model reasonably represent the mathematical basis of the conceptual model.

3. Numerical schemes enable the mathematical models to obtain stable solutions.

4. Computer models implement the numerical models, have no coding errors, and produce stable solutions.

5. Peer review has been conducted on the conceptual models.

23.4.2 1998 Certification Decision

For the CCA, the DOE convened a Conceptual Models Peer Review Panel to review the 24 conceptual models used in PA (see Section 23.2.2). The EPA concurred with the panel's findings and found the DOE in compliance with the requirements of 40 CFR §§ 194.23(a)(3)(i) and 194.23(a)(3)(v).

During the CCA, the EPA performed an independent review of the computer codes, focusing on (1) whether mathematical models incorporated equations and boundary conditions that reasonably represented the mathematical formulation of the conceptual models reviewed under section 194.23(a)(1); (2) whether the numerical models provided numerical schemes that enabled the mathematical models to obtain stable solutions; and (3) whether the computer codes were properly implemented.

The EPA independently reviewed the mathematical models and boundary conditions for the following codes: CUTTINGS_S, SECOFL2D, SECOTP2D, CCDFGF, PANEL, BRAGFLO, NUTS, FMT, SANTOS, and GRASP-INV. The codes that used numerical solvers included CUTTINGS_S, SECOFL2D, SECOTP2D, PANEL, BRAGFLO, NUTS, and SANTOS. The EPA concluded that the mathematical models incorporated equations that reasonably represented the conceptual models.

A complete description of the EPA's 1998 Certification Decision for section 194.23(a)(3) can be obtained from CARD 23, Sections 4.4, 5.4, 6.4, and 7.4 (U.S. Environmental Protection Agency 1998a).

23.4.3 Changes in the CRA-2004

23.4.3.1 Documentation

A description of the code documentation is given here for completeness and to aid in further discussion.

- User's Manual (UM)—describes the code's purpose and function, mathematical governing equations, model assumptions, the user's interaction with the code, and the models and methods employed by the code. The UM includes:
  - The numerical solution strategy and computational sequence, including program flowcharts and block diagrams.
  - The relationship between the numerical strategy and the mathematical strategy (e.g., how boundary or initial conditions are introduced).
  - A clear explanation of model derivation. The derivation starts from generally accepted principles and scientifically proven theories. The UM justifies each step in the derivation and notes the introduction of assumptions and limitations. For empirical and semi-empirical models, the documentation describes how experimental data are used to arrive

at the final form of the models. The UM clearly states the final mathematical form of the model and its application in the computer code.

- Descriptions of any numerical method used in the model that go beyond simple algebra (e.g., finite-difference, Simpson's rule, cubic splines, Newton-Raphson Methods, and Jacobian Methods). The UM explains the implementation of these methods in the computer code in sufficient detail that an independent reviewer can understand them.

- The derivation of the numerical procedure from the mathematical component model. The UM gives references for all numerical methods. It explains the final form of the numerical model and its algorithms. If the numerical model produces only an intermediate result, such as terms in a large set of linear equations that are later solved by another numerical model, then the UM explains how the model uses intermediate results. The documentation also indicates those variables that are input to and output from the component model.

- Analysis Packages (APs)—contain detailed information on how the computer codes were used in the PA, including code implementation approaches and justification of parameters used. The DOE required each code to supply the following information relevant to 40 CFR § 194.23(c)(1) in its APs:

  - Description of the overall nature and purpose of the general analysis performed by the model. The APs describe the specific aspects of the analysis for which the model is used. The documentation shows input and output parameters of the model. The APs discuss the input and output parameters for each model.

  - The modeling information describing the components (e.g., unsaturated vs. saturated) and their role in the overall modeling effort. The APs identify the contribution of each component model to the complete solution of the problem and the linkages between the component models. The documentation uses flowcharts and block diagrams to describe the mathematical solution strategy for the PA.

The DOE continued to use five additional documents as secondary references for the CRA-2004:

- Requirements Document (RD)—identifies the computational requirements of the code (e.g., MODFLOW must be able to simulate groundwater flow under steady-state conditions)

- Verification and Validation Plan (VVP)—identifies tests and associated acceptance criteria for the code and validation that all aspects of the code work properly together.

- Design Document (DD)—describes the major features of the software design: the theoretical basis; the embodied mathematical model; control flow; control logic; data structures; functionalities and interfaces of objects; components, functions, and subroutines used in the software; and the allowed or prescribed ranges for data inputs and outputs in a manner that can be implemented.

- Implementation Document (ID)—provides the information necessary to recreate the code used in the PAs. Using this information, the computer user can reconstruct the code or install it on an identical platform to that used in the PAs. The document includes the source code listing, subroutine-call hierarchy, and code compilation information.

- Validation Document (VD)—summarizes the results of the testing activities prescribed in the RD/VVP documents for the individual codes and provides evaluations based on those results. The VD contains listings of sample input and output files from computer runs of each model. The VD also contains reports on code verification, bench marking, and validation, and documents the results of the quality assurance procedures (QAPs).

23.4.3.2 Conceptual Models

Analogous to the original certification, all modified conceptual models used in the WIPP PA were reviewed by conceptual model peer review panels. The peer review panels considered whether a conceptual model represents possible future states of the disposal system. For each of the four changed conceptual models in the CRA-2004 PA (see Section 23.2.3), the peer review panels approved the conceptual models considered (see CRA-2004, Appendix PEER-2004; Sections PEER-2004 2.0 and PEER-2004 3.0).

23.4.3.3 Mathematical Models

In the CRA-2004, the DOE consolidated computer code documentation of mathematical models and initial and boundary conditions, primarily in the CRA-2004, Appendix PA, Section PA-4.0. The DOE also discussed specific topics in CRA-2004, Appendix PA, and Attachments PORSURF, MASS, SOTERM, and TFIELD. The DOE documented each code's characteristics in the UM and the other documents listed in Section 23.4.3.1.

The mathematical models or initial or boundary conditions for the following codes did not change after the CCA: SANTOS, BRAGFLO, FMT, NUTS, PANEL, and SECOTP2D. The cuttings and cavings mathematical models in CUTTINGS_S were not changed, but the spallings mathematical models were replaced by the new DRSPALL code. Three new codes were included in the EPA's review for the CRA-2004: MODFLOW, PEST, and DRSPALL. See U.S. Environmental Protection Agency (2006i, 2006j) for more information on the code review conducted for the CRA-2004.

23.4.3.4 Numerical Models

Information used to evaluate the stability of the numerical schemes was provided in the VDs and APs that the DOE prepared for each of the CRA-2004 PA computer codes. The DOE's evaluation of numerical schemes to ensure the stability of the numerical solutions included an evaluation of the impact on previous analyses and any appropriate corrective actions to either the computer code or the earlier analyses. Errors that qualified as a condition adverse to quality, such as computer code stability problems, were controlled and resolved as described in the CRA-2004, Chapter 5.0, Section 5.3.20.

The DOE maintains a record of whether any of the codes experienced stability problems during the PA calculations. This record is documented in the output for each code and notes the convergence criteria and the number of numerical iterations required to reach convergence. Convergence criteria, and the maximum number of iterations allowed to achieve convergence, are set within various subroutines in the computer codes where appropriate. Although the DOE did not specify strict requirements for the convergence criteria, if the criteria are too lenient, the results will indicate potentially unstable solutions to the numerical model's numerical schemes. The code generates messages if the mathematical solution algorithm does not converge within the user-specified criteria (see the UM for each computer code). Problems are documented in each code's AP.

23.4.3.5 Computer Models

As in the CCA, to ensure that the DOE's computer codes accurately implement the numerical models and are free of coding errors, a number of QAPs were adopted (see the CRA-2004, Chapter 5.0). The QAPs specify quality assurance (QA) requirements for each step of the software development process (see CARD 22, U.S. Environmental Protection Agency 2006k, for a discussion of EPA's review of the DOE's QA program). This process involved four primary development phases: (1) requirements, (2) design, (3) implementation, and (4) verification and validation (CRA-2004, Chapter 5.0, Section 5.3.20 and Appendix QAPD, Section 6.0). The objective of each phase is discussed below.

The requirements phase consists of defining and documenting both the functional requirements that the software must meet and the verification and validation activities that must be performed to demonstrate that the computational requirements for the software are met. Two documents are produced during this phase: the RD and the VVP, which, when combined, are called RD/VVP. The RD contains the functional requirements that the proposed software must satisfy, with specific requirements relating to the aspects of the system to be simulated with a particular computer code. For example, groundwater flow through the Culebra Dolomite Member of the Rustler (hereafter referred to as Culebra) is assumed to be steady through time. Therefore, MODFLOW was required to demonstrate that the flow equation provided accurate solutions over time under steady-state conditions. The VVP identifies tests and associated acceptance criteria to ensure verification of each software development phase (i.e., that the portion of the code being tested matches known solutions) and validation of the entire software baseline the first time the computer code is placed under QA control (i.e., that all aspects of the code work together properly). The RD documents what the PA computer codes do by listing the functional requirements of each computer code. The VVP explains the various tests needed to show that the computer code properly performed the functional requirements listed in the RD.

The design phase consists of developing and documenting the overall structure of the software and the reduction of the overall software structure into descriptions of how the code works. During this phase, the software structural design may necessitate modifying the RD and VVP. The DD describes the theoretical model, the mathematical model, and the major components of the software.

The implementation phase consists of developing source code using a programming language (e.g., FORTRAN) or other form suitable for compilation or translation into executable computer

software. The design, as described in the DD, is used as the basis for the software development, and it may need to be modified to reflect changes identified in the implementation phase. Two documents are produced during this phase: the ID and the UM. The ID provides the source code listing and describes the process performed to generate executable software, and the UM provides information that assists the user in understanding and using the code.

The verification and validation phase consists of executing the functional test cases identified in the VVP to demonstrate that the developed software meets the requirements defined for it in the VVP. The tests demonstrate the capability of the software to produce valid results for problems encompassing the range of permitted usage as defined by the UM. One document, the VD, is produced during this phase. The VD documents the test case input and output files and evaluates the results against the acceptance criteria in the VVP.

In the CCA, the DOE used these procedures and documents to show that the PA computer codes calculated numerical models properly, were free of coding errors, and produced stable results. The DOE used the same process and requirements for the CRA-2004 PA computer codes.

23.4.3.6 Peer Review

The DOE performed two peer reviews to support the CRA-2004 PA calculations. These peer reviews evaluated the new spallings model and the minor changes made to the Disposal System Geometry, Repository Fluid Flow, and DRZ conceptual models.

The Spallings Model Peer Review was performed from July 2003 to October 2003; the final report was published in October 2003 (CRA-2004, Appendix PEER-2004, Section PEER-2004-3.1.2). The new spallings model includes three major elements: consideration of multiphase flow processes in the intrusion borehole, consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and a numerical solution for the coupled mechanical and hydrological response of the waste as a porous medium. The DOE developed a new numerical code, DRSPALL, to implement the new spallings conceptual model that calculates the volume of WIPP solid waste that may undergo material failure and be transported to the surface as a result of a drilling intrusion.

The Salado Flow Conceptual Model Peer Review was performed from April 2002 to March 2003; the final report was published in May 2003 (CRA-2004, Appendix PEER-2004, Section PEER-2004-2.1.3). This peer review evaluated changes made to three conceptual models (Disposal System Geometry, Repository Fluid Flow, and DRZ) as a result of (1) new information acquired after the original certification decision; or (2) changes to conceptual model assumptions mandated by the EPA in the final CCA decision, such as the Option D panel closure condition. The changes included: (1) modification of the computational grid to accommodate the new panel closure requirement, (2) shaft simplification, and (3) refinement to the BRAGFLO grid.

23.4.4 EPA's Evaluation of Compliance for the 2004 Recertification

23.4.4.1 Conceptual Models

As in the CCA, all conceptual models used in the CRA-2004 were approved (see Section 23.2.4 for more discussion of the results of the CCA conceptual model peer review) by conceptual model peer reviews that considered whether or not conceptual models represented possible futures of the disposal system. The EPA agreed with the peer review panels and therefore found that the DOE continued to be in compliance with section 194.23(a)(3)(i) (CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

23.4.4.2 Mathematical Models

In the evaluation for recertification, the EPA evaluated each of the mathematical models for the computer codes used in the CRA-2004 PA to determine if the governing equations (e.g., flow and transport governing equations), process-related equations (e.g., the anhydrite fracture model), and boundary conditions (e.g., no-flow boundary assumptions) included in each mathematical model provided a reasonable representation of each conceptual model used in the CRA-2004 PA. CRA-2004, Appendix PA, Section PA-4.0 and UMs and APs for each code were the primary sources of information on the mathematical models employed in PA. In general, mathematical formulations were adequately explained and reasonable. The DOE adequately documented and described simplifications of conceptual models in the CRA-2004 PA. The EPA found that the DOE provided an adequate technical basis to support the mathematical formulations (CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

The EPA also reevaluated the functional tests described in the VD for each computer code to ensure that the DOE's tests of the computer codes demonstrated that they performed as specified in the RD. The EPA reviewed the testing of each code to verify that the DOE adequately tested functional requirements listed for each computer code. This analysis and testing indicated that equations and boundary conditions were properly incorporated into the mathematical models and those boundary conditions were reasonable representations of how the conceptual models should be implemented. The EPA found that the DOE continued to comply with 40 CFR § 194.23(a)(3)(ii) (U.S. Environmental Protection Agency 2006c, Section 12.0; 2006j, Section 6.0; 2006i, Section 6.0; CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

23.4.4.3 Numerical Models

For the CRA-2004, the EPA reviewed all relevant documentation on numerical models solution schemes, which was primarily contained in the CRA-2004, Appendix PA; APs; and supplementary information (e.g., UMs, VDs). The EPA also reviewed each code's QA documentation package for completeness and technical adequacy.

For the CRA-2004, the EPA reviewed the testing used to qualify each code for use in the CRA-2004 PA. The EPA found that the DOE had adequately set the range of functional tests for each code to verify that the code would perform as expected and provide reasonable results (see each

code's VD for details of this testing). The EPA found that the DOE continued to comply with the requirements of 40 CFR § 194.23(a)(3)(iii) (U.S. Environmental Protection Agency 2006c, Section 12.0; 2006j, Section 6.0; 2006i, Section 6.0; CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

23.4.4.4 Computer Models

The EPA reviewed all of the relevant documentation (UM, DD, RD, VVP, and VD) pertaining to each of the major codes described above as well as the CRA-2004, Appendix PA and associated attachments. Since the CCA, the EPA also periodically performed an independent review of the DOE's testing of each code to verify that results appeared accurate and free of coding error (U.S. Environmental Protection Agency 2006c, 2006i, and 2006j). The EPA ultimately found that each PA computer code produced results that showed continued compliance with this requirement.

During its review, the EPA questioned whether SANTOS produced results that were an accurate implementation of the numerical models and were free of coding errors (Cotsworth 2004). Specifically, the EPA questioned whether SANTOS was properly tested for accuracy and whether the average stress of less than 5 megapascal that SANTOS predicted for waste was reasonable. In the DOE's response (Detwiler 2004a), the DOE showed that a full functionality test of SANTOS was performed as part of the code qualification and that the results of SANTOS calculations were compared to the results of another computer code called SPECTROM-32. These activities showed that SANTOS produces results adequate for the development of porosity surfaces used in the CRA-2004 PA and was accepted by the EPA (U.S. Environmental Protection Agency 2006l, Section 6.0).

The EPA was able to determine that the CRA-2004 PA computer codes continued to comply with 40 CFR § 194.23(a)(3)(iv) (CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

23.4.4.5 Peer Review

The DOE performed two peer reviews to support the CRA-2004 PA calculations. The DOE developed a new spallings model and made minor changes to the Disposal System Geometry, Repository Fluid Flow, and DRZ models.

The EPA examined the peer review plan and the final peer review report for the Spallings Model Peer Review and found that they adequately fulfilled the requirements of section 194.27 and NUREG-1297. The EPA also observed the actual performance of the peer review panel, the selection of the panel members, the interaction of the panel with the DOE, and the documents produced during and as a result of the peer review. The EPA found the process satisfied the requirements of section 194.27 and the guidance in NUREG-1297 (U.S. Environmental Protection Agency 2006d, Section 5.0).

The EPA examined the peer review plan and the final peer review report for the Salado Flow Conceptual Model Peer Review and found that they adequately fulfilled the requirements of section 194.27 and NUREG-1297. The EPA also observed the actual performance of the peer review panel members, the selection of the panel, the interaction of the peer review panel with

the DOE, and the documents produced during and as a result of the peer review. The EPA found the process compatible with the requirements of section 194.27 and the guidance in NUREG-1297 (U.S. Environmental Protection Agency 2006e, Section 5.0).

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.23(a)(3)(v) (CARD 23, Section "Recertification Decision 194.23(a)(3)," U.S. Environmental Protection Agency 2006f).

23.4.5 Changes or New Information Since the 2004 Recertification

23.4.5.1 Conceptual Models

All conceptual models used in the CRA-2009 PA were previously peer reviewed. No modifications have been made to the conceptual models since the 2006 recertification decision (see Section 23.3.5 for a discussion of modifications that were proposed, but not included in the CRA-2009). Thus, there is no new information to provide in the CRA-2009 and the DOE continues to demonstrate compliance with the provision of section 194.23(a)(3)(i).

23.4.5.2 Mathematical Models

No changes were made in the methodology used to document mathematical models and initial and boundary conditions from the CRA-2004. Discussion of the mathematical models and initial and boundary conditions are found in Appendices PA-2009, PORSURF-2009, SOTERM-2009, and TFIELD-2009. UMs and APs are also used to document mathematical models and the initial and boundary conditions for the CRA-2009. Table 23-4 lists the APs for the CRA-2009 PA.

Table 23-4. APs for the CRA-2009 PA

AP	Reference
Parameters	Kirchner 2008a; Fox 2008
Cuttings & Cavings	Ismail 2008
Spallings	Vugrin 2005; Ismail 2008
Direct Brine Release	Clayton 2008
Actinide Mobilization	Garner and Leigh 2005
Salado Flow	Nemer and Clayton 2008
Salado Transport	Ismail and Garner 2008
Culebra Flow	Lowry and Kanney 2005
Culebra Transport	Lowry and Kanney 2005
Normalized Release	Dunagan 2008
Sensitivity Study	Kirchner 2008b
Summary	Clayton et al. 2008

No new codes have been added to the WIPP PA since the CRA-2004 PABC. Two codes, BRAGFLO and NUTS, were modified for the CRA-2009 PA. BRAGFLO was modified from version 5.0 to version 6.0 to incorporate additional capabilities and flexibility (Nemer 2006). The UM (Nemer 2007a), RD/VVP (Nemer 2007b), ID (Nemer 2007c), and VD (Nemer 2007d) were generated for BRAGFLO version 6.0. NUTS version 2.05a had a time and date incompatibility with the upgraded operating system (Gilkey 2006), so it was modified to version 2.05c. The only difference between version 2.05a and 2.05c is the change made to correct the time and date incompatibility. As this was a minor code change, only the ID (Gilkey 2006) was updated and no changes were made to the UM, RD/VVP, or VD.

The DOE continues to provide documentation that mathematical models incorporate equations and boundary conditions that reasonably represent the mathematical formulation of the conceptual models, and thus continues to demonstrate compliance with the provision of section 194.23(a)(3)(ii).

23.4.5.3 Numerical Models

As in the CRA-2004, the information used to evaluate the stability of the numerical schemes was provided in the VDs and APs that the DOE prepared for each of the CRA-2009 PA computer codes. Therefore, the DOE continues to provide documentation that numerical models provide numerical schemes that enable the mathematical models to obtain stable solutions and thus continues to demonstrate compliance with the provisions of section 194.23(a)(3)(iii).

23.4.5.4 Computer Models

As in the CRA-2004, the information used to show that the PA computer codes calculated numerical models properly and that the computer codes were free of coding errors and produced stable results was provided in the RD/VVP and VD prepared for each of the CRA-2009 PA computer codes. Therefore, the DOE continues to provide documentation that computer models accurately implement the numerical models and thus, continues to demonstrate compliance with the provision of section 194.23(a)(3)(iv).

23.4.5.5 Peer Review

No additional peer review results since the 2006 recertification decision have been included in the CRA-2009 PA calculations (see Section 23.3.5 for a discussion of modifications that were proposed, but not included, in the CRA-2009). Thus, there is no new information to provide in the CRA-2009, and the DOE continues to demonstrate compliance with the provision of section 194.23(a)(3)(v).

23.5 40 CFR § 194.23(b)

23.5.1 Background

40 CFR § 194.23(b) requires that computer codes be documented in accordance with an appropriate quality assurance standard.

23.5.2 1998 Certification Decision

In the CCA, to meet the requirements of section 194.23(b), the DOE provided documentation of compliance with quality assurance requirements of American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA)-2a-1990 addenda, Part 2.7, to ASME NQA-2-1989 edition. This documentation included plans for QA software, software requirements documentation, software design and implementation documentation, software verification and validation documentation, and user documentation. Based on the EPA audits and the CCA review, the EPA found the DOE in compliance with the requirements of section 194.23(b).

A complete description of the EPA's 1998 Certification Decision for section 194.23(b) can be obtained from CARD 23, Section 8.4 (U.S. Environmental Protection Agency 1998a).

23.5.3 Changes in the CRA-2004

The CRA-2004, Chapter 5.0 describes the DOE's QA program. Software QA is described in the CRA-2004, Chapter 5.0, Section 5.3.20. The DOE's QA program, dated May 2003, is contained in the CRA-2004, Appendix QAPD. Section 6 of the DOE QAPD incorporated the requirements of ASME NQA-2a-1990 addenda, Part 2.7, to ASME NQA-2-1989 edition. See CARD 22, U.S. Environmental Protection Agency (2006k), for further discussion of the EPA's review of the DOE's approach to the QA requirements for computer codes and models.

23.5.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA verified compliance with the requirements of 40 CFR § 194.22(a)(2)(iv) by reviewing Section 6.0 of the Carlsbad Field Office QAPD and conducting periodic inspections of the Sandia National Laboratories (SNL) and Washington TRU Solutions QA programs since the CCA decision. The DOE's documentation included plan(s) for software QA, software requirements documentation, software design and implementation documentation, software verification and validation documentation, and user documentation. The EPA found that the DOE's QA requirements for computer codes used in the PA and compliance assessment continued to be in agreement with those specified in 40 CFR § 194.22, and that their code documentation was adequate. See CARD 22, Section "Evaluation of Compliance for Recertification" (U.S. Environmental Protection Agency 2006k), for further discussion of the EPA's review.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.23(b) (CARD 23, Section "Recertification Decision 194.23(b)," U.S. Environmental Protection Agency 2006f).

23.5.5 Changes or New Information Since the 2004 Recertification

The documentation standards of the computer codes have not changed since the CRA-2004 decision. Thus, there is no new information to provide in the CRA-2009, and the DOE continues to demonstrate compliance with the provision of section 194.23(b).

23.6 40 CFR § 194.23(c)(1)

23.6.1 Background

40 CFR § 194.23(c)(1) requires documentation of all models and computer codes, including descriptions of the theoretical backgrounds and the method of analysis for each model.

23.6.2 1998 Certification Decision

In the CCA, the DOE provided documentation of all models and computer codes, including descriptions of the theoretical backgrounds and the method of analysis for each model. The EPA's evaluation found that the CCA and supplementary information provided an adequate description of the theoretical backgrounds and method of analysis for each model used in the calculations. The DOE's documentation of conceptual models, alternative conceptual models, and the Conceptual Models Peer Review Panel is discussed in CARD 23 Sections 1.4, 2.4, and 7.4, respectively (U.S. Environmental Protection Agency 1998a).

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(1) can be obtained from CARD 23, Section 9.4 (U.S. Environmental Protection Agency 1998a).

23.6.3 Changes in the CRA-2004

Most of the major codes used for modeling the PA in the CRA-2004 had not changed since the CCA. Codes added to the CRA-2004 PA since the CCA were MODFLOW, PEST, and DRSPALL. Each of the CRA-2004 PA codes is documented in its own UM, AP, RD, VVP, DD, ID, and VD (see Section 23.4.3.1 for a summary of each document). The DOE used these documents as the primary vehicles to describe the conceptual models, mathematical models, and numerical methods that provided the basis for the theory and the assumptions underlying the computer codes. The DOE included additional documentation in various appendices to the CRA-2004 (e.g., CRA-2004, Appendix PA, Attachment MASS and Attachment SOTERM). The DOE's documentation also contained justification for the use of the models, conceptual model derivation, mathematical derivations, and solution methods used in the codes (see the CRA-2004, Chapter 6.0 and Appendix PA).

23.6.4 EPA's Evaluation of Compliance for the 2004 Recertification

The primary codes that the EPA reviewed include: CUTTINGS_S, MODFLOW, SECOTP2D, SUMMARIZE, PRECCDFGF, CCDFGF, LHS, DRSPALL, PANEL, BRAGFLO, NUTS, FMT, PEST, SANTOS, and ALGEBRA. The EPA found the DOE's description of the theoretical background of each code, provided primarily in the UM and AP, to be adequate. With respect to the documentation pertaining to the method of analysis, the EPA found the descriptions in the AP for each code to be sufficiently complete.

For the CRA-2004, the EPA reevaluated all available documentation on each of the computer codes for completeness, clarity, and logical development of the theoretical bases for the conceptual models used in each computer code. Documentation was considered complete if it

contained sufficient information from which to judge whether the codes were (1) formulated on a sound theoretical foundation, and (2) used properly in the PA analysis.

The EPA reviewed all of the relevant documentation pertaining to the theoretical development and application of the models. For further discussion of the EPA's review of documentation for conceptual models, alternative conceptual models, and the Conceptual Models Peer Review Panel, see Section 23.2, Section 23.3, and Section 23.4. The majority of the information was located in the UM and AP for each code. For the CRA-2004, the DOE's theoretical background for almost all of the codes had not changed since the CCA decision. Since the CCA, the DOE had continued to test the PA codes to verify that they still perform as they did during the CCA. The EPA had periodically reviewed and inspected these activities to verify that the PA codes continue to produce adequate results (U.S. Environmental Protection Agency 2006i and 2006j). The CRA-2004, Appendix PA included the theoretical background, mathematical development, and numerical development of the main PA codes and its use in the CRA-2004 PA analyses.

After the execution of the original CRA-2004 PA, the DOE discovered problems with the method of analysis for a number of input files and computer code errors related to the SUMMARIZE, PRECCDFGF, and CCDFGF sequence of calculations. The EPA requested that the DOE verify that these errors had been corrected and that the codes passed the correct information to assure the analysis methods and assessments achieve correct results (Cotsworth 2005). The DOE modified the codes, corrected the analysis process, and retested to confirm that the errors had been corrected. The DOE also reran parts of the original CRA-2004 PA to assess the impact of these corrections. The EPA found that the DOE had corrected the errors and verified that the code obtained the correct data to perform their analysis for the CRA-2004 PABC (U.S. Environmental Protection Agency 2006c, Section 12.0). The EPA found that the DOE's level of documentation continued to be consistent with the adequate level of documentation produced during the CCA review, and that the DOE continued to be in compliance with section 194.23(c)(1) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

23.6.5 Changes or New Information Since the 2004 Recertification

No changes were made to the documentation procedure of PA computer codes used in the CRA-2009. Thus, there is no new information to be provided as part of the CRA-2009, and the DOE continues to demonstrate compliance with the provisions of section 194.23(c)(1).

23.7 40 CFR § 194.23(c)(2)

23.7.1 Background

40 CFR § 194.23(c)(2) requires (1) general descriptions of the models; (2) discussions on the limits of applicability of each model; (3) detailed instructions for executing the computer codes, including hardware and software requirements; (4) input and output formats with explanations of each input and output variable and parameter (e.g., parameter name and units); (5) listings of input and output files from a sample computer run; and (6) reports on code verification, benchmarking, validation, and QAPs.

23.7.2 1998 Certification Decision

In the CCA, the DOE provided documentation of all models and computer codes; detailed descriptions of data collection, data reduction and analysis, and parameters developed from source data; detailed descriptions of the structure of the computer codes; and a complete listing of computer source codes. The EPA's evaluation found that the CCA and supplementary information included (1) an adequate description of each model used in the calculations; (2) a description of limits of applicability of each model; (3) detailed instructions for executing the computer codes; (4) hardware and software requirements to run these codes; (5) input and output formats with explanations of each input and output variable and parameter; (6) listings of input and output files from sample computer runs; and (7) reports of code verification, benchmarking, validation, and QAPs.

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(2) can be obtained from CARD 23, Section 10.4 (U.S. Environmental Protection Agency 1998a).

23.7.3 Changes in the CRA-2004

As in the CCA, documentation for the CRA-2004 regarding the DOE's compliance with section 194.23(c)(2) is primarily contained in the UM, AP, VD, ID, DD, RD, and VVP for each code. Table 23-5 lists the requirements of section 194.23(c)(2) and where these requirements are addressed in the DOE documents.

23.7.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed all of the relevant documentation pertaining to requirements specified in section 194.23(c)(2) for the following codes: CUTTINGS_S, MODFLOW, SECOTP2D, CCDFGF, LHS, PANEL, BRAGFLO, NUTS, FMT, PEST, DRSPALL, SANTOS, and ALGEBRA (U.S. Environmental Protection Agency 2006c; 2006i; and 2006j). The DOE's code documentation provided enough information for the EPA to understand and execute the models, determine the possible impact of any assumptions, and verify that the codes were tested and quality assured.

The DOE replaced the SECOFL2D flow code used in the CCA with the MODFLOW-2000 flow code. The primary reasons given for the change are (1) that MODFLOW-2000 is well supported by a large user base and is continuing to be developed, while SECOFL2D is not; (2) MODFLOW is designed to operate on multiple computer platforms, while SECOFL2D was designed to work on only the VAX/Alpha platforms; and (3) the new pilot point estimation code, PEST, was designed to use only MODFLOW-2000 (Detwiler 2004b). The EPA determined that MODFLOW-2000 is a reasonable replacement to SECOFL2D and that the MODFLOW/PEST T field estimate combination is a significant improvement over the SECOFL2D/GRASP-INV combination used in the CCA (U.S. Environmental Protection Agency 2006c). The EPA determined that the DOE continued to demonstrate compliance with section 194.23(c)(2) (CARD 23, Section "Evaluation of Compliance for Recertification 194.23(c)," U.S. Environmental Protection Agency 2006f).

Table 23-5. Location of Documentation for Models and Computer Codes Used in PA

Requirement in Compliance Application Guidance	Document Containing Information						
	UM	AP	VD	ID	DD	RD/VVP	SNL QA Procedures[a]
General descriptions of the models	X	X	—	—	X	—	—
Discussions of the limits of applicability of each model	X	X	—	—	X	—	X
Detailed instructions for executing the computer codes	—	X	—	X	X	—	X
Hardware requirements for executing the computer codes	X	X	—	X	—	—	X
Software requirements for executing the computer codes	X	X	—	—	—	—	X
Input and output formats with explanations of each input and output variable and parameter	X	X	—	—	X	—	—
Listings of input and output files from a sample computer run	X	X	—	—	—	—	X
Reports on code verification	—	X	X	—	—	X	X
Reports on benchmarking	—	X	X	—	—	X	X
Reports on validation	—	X	X	—	—	X	X
Reports on QAPs	—	X	—	—	—	—	X

X = Information meeting the requirement is found in this document.
[a] See the CRA-2004, Appendix QAPD, Section 6.0.

23.7.5 Changes or New Information Since the 2004 Recertification

No changes were made to the documentation procedure of PA computer codes used in the CRA-2009. Thus, there is no new information to provide in the CRA-2009, and the DOE continues to demonstrate compliance with provision of section 194.23(c)(2).

23.8 40 CFR § 194.23(c)(3)

23.8.1 Background

40 CFR § 194.23(c)(3) requires detailed descriptions of the computer code structures and a complete listing of computer source codes.

23.8.2 1998 Certification Decision

In the CCA, the DOE provided detailed descriptions of the computer code structure and a complete listing of computer source codes. The EPA's evaluation found that the CCA and supplementary information adequately provided a detailed description of the computer code structures and supplied a complete listing of the computer source code in supplementary documentation to the CCA. The documentation of computer codes described the structure of

computer codes with sufficient detail to allow the EPA to understand how software subroutines are interrelated. The code structure documentation shows how the codes operate to provide accurate solutions of the conceptual models.

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(3) can be obtained from CARD 23, Section 11.4 (U.S. Environmental Protection Agency 1998a).

23.8.3 Changes in the CRA-2004

The ID for each modeling code contains the information relevant to compliance with section 194.23(c)(3). The ID provides the information necessary for the recreation of the code as used in the CRA-2004 PA calculation. With this information, the user can compile the source code and install it on a computer system identical to that used in the CRA-2004 calculations. The ID also includes the source code listing and code compilation information.

23.8.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed all of the relevant documentation, and in particular the ID for each computer code pertaining to the requirements specified in section 194.23(c)(3) for the following codes: CUTTINGS_S, MODFLOW, SECOTP2D, CCDFGF, LHS, PANEL, BRAGFLO, NUTS, FMT, PEST, SANTOS, DRSPALL, SUMMARIZE, and ALGEBRA. The EPA found that the DOE submitted all of the source code listings. The EPA identified no problems with the detailed descriptions of the structure of the computer codes. The CRA-2004 documentation of computer codes continued to adequately describe the structure of computer codes with sufficient detail to allow the EPA to understand how software subroutines were linked and how to execute the PA. The EPA determined that the DOE continues to demonstrate compliance with section 194.23(c)(3) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

23.8.5 Changes or New Information Since the 2004 Recertification

No changes were made to the documentation procedure of PA computer codes used in the CRA-2009. The DOE continues to demonstrate compliance with the provisions of section 194.23(c)(3).

23.9 40 CFR § 194.23(c)(4)

23.9.1 Background

40 CFR § 194.23(c)(4) requires detailed descriptions of data collection, data reduction and analysis, and code input parameters development.

23.9.2 1998 Certification Decision

In the CCA, the DOE provided detailed descriptions of data collection, data reduction and analysis, and code input parameters development. The EPA's evaluation found that the CCA and supplementary information adequately (1) provided a detailed listing of the code input

parameters; (2) listed sampled input parameters; (3) provided a description of parameters and the codes in which they are used; (4) discussed parameters important to releases; (5) described data collection procedures, sources of data, data reduction and analysis; and (6) described code input parameter development, including an explanation of QA activities.

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(4) can be obtained from the CARD 23, Section 12.4 (U.S. Environmental Protection Agency 1998a).

23.9.3 Changes in the CRA-2004

The primary sources of CRA-2004 parameter information are in the CRA-2004, Chapter 6.0 (especially Tables 6-10 to 6-30), Appendix PA, Attachment PAR, and other appendices describing specific computer codes and parameter records. Records of parameters for the CRA-2004 included the following:

- SNL Form NP 9-2-1 WIPP Parameter Entry Form (PEF): All PA parameters are defined using this form, which contains the numerical values and distributions of parameters used as input to PA codes, identifies the code the parameter is used in, and includes information to trace the development of each parameter. The PEF replaced Form 464 used in the CCA PA.

- Requestor Documents or Forms: Requestor documentation described parameters that involved considerable data reduction and analysis by the SNL Principal Investigator or other technical personnel. The Requestor documentation is the second step of PA parameter development. Data reduction and analysis are usually explained at this step. The Requester documentation replaced the Principal Investigator Records Packages (PIRPs) used during the CCA PA.

- Data Records Packages (DRP): These documents are typically generated for parameters derived from empirical testing as a result of laboratory or field measurements (for example, actinide solubility experiments or brine inflow rate measurements in the WIPP underground repository). These packages are generally the first step that links the development of a parameter from the measured data to the values used in the PA.

- APs: These are supplementary documents that generally describe all parameters used by a particular code in the PA calculations.

The main source for parameter documentation is the PEF. The need for further documentation in the other three types of documents depends upon the nature of the parameter, such as whether it is a widely accepted chemical constant (e.g., atomic weight of an isotope) or a value requiring experimental data for verification. Table 23-6 describes the types of information found in each of these four documents and possible paths in documenting parameter record information.

The CCA contained approximately 1,600 parameters and the CRA-2004 contained approximately 1,700 parameters consisting of numerical values or ranges of numerical values that describe different physical and chemical aspects of the repository, the geology and geometry of the area surrounding the WIPP, and possible scenarios for human intrusion. Some parameters are well-established chemical constants, such as Avogadro's number or the universal gas

constant. Other parameters describe attributes unique to the WIPP, such as the solubility and mobility of specific actinides in brines in the WIPP. An example of a parameter related to the geology of the WIPP is the permeability of the rock in the Culebra above the WIPP. The DOE also assigned parameters to consider the effects of human intrusion, such as the diameter of a drill bit used to drill a borehole that might penetrate the repository.

In the documents described above, the DOE described the methods that develop and support the approximately 1,700 parameters used in the CRA-2004. All of the documents listed above are used to explain the full development of parameter values used as inputs to the PA calculations. Table 23-6 indicates the documents that contain information required under section 194.23(c)(4).

23.9.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA, as for the CCA, performed a thorough review of the parameters and parameter development process for the CRA-2004. For the CRA-2004 parameter review, the EPA focused its review on parameters that had changed or were new since the CCA. The EPA's review of the parameters and parameter development is described in detail (U.S. Environmental Protection Agency 2006m, 2006n). The EPA reviewed parameter packages for a sample of approximately 1,700 parameters used in the CRA-2004 PA calculations. The parameter records include WIPP PEFs (NP 9-2-1), requestor documents or forms, DRPs, and APs.

The EPA's review of PA parameters took place in three phases. In 2003, the EPA reviewed the transfer of parameters from the CCA database to a new database system (U.S. Environmental Protection Agency 2006n). Next, the EPA reviewed the parameters changed as a result of the parameter transfer to the CRA-2004 PA calculations (U.S. Environmental Protection Agency 2006n). The EPA found 128 new parameters and 203 changes to existing parameters. Many of the parameter changes were due to revisions of the waste inventory values in the PA calculations and new parameter values used in the new spallings code, DRSPALL. The EPA was able to verify that the new and changed parameters were adequately recorded in the WIPP parameter database and that most of these parameters were justified and traceable to adequate supporting documentation. Finally, the EPA reviewed the parameter changes and documentation for values changed for the CRA-2004 PABC calculations required by the EPA to confirm the impact of code errors and parameter changes on the PA compliance results (U.S. Environmental Protection Agency 2006m).

The EPA found minor concerns at each phase of the review. Ultimately, the DOE corrected each concern, and the EPA verified that parameters used in the CRA-2004 were adequately developed, documented, and traceable. The EPA determined that the DOE continued to comply with section 194.23(c)(4) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

During the EPA's completeness review, stakeholders commented on the drilling rate used in the CRA-2004 PA calculations. During meetings with stakeholders in July of 2004, comments arose regarding the drilling rate used in the CRA-2004 and suggested that a number twice the existing rate should be used in PA calculations. In a December 3, 2004 email, the EPA informed the DOE that they were required to evaluate the impact of using twice the CRA-2004 PA drilling

Table 23-6. Location of Required Information on Parameters Used in Codes for PA

Requirement in Compliance Application Guidance	Document Containing Information							
	PEF	PIRP	DRP	AP	CRA-2004[a]	Att. PAR[b]	App. QAPD[c]	Parameter Database
Detailed listings of code input parameters	—	—	—	—	—	—	—	X
Detailed listings of the sampled parameters	—	—	—	—	—	X	—	X
Codes in which the parameters were used	X	—	—	X	—	—	—	X
Computer code names of the sampled parameters	X	—	—	X	—	—	—	X
Descriptions of the data sources	X	X	X	X	—	—	—	X
Descriptions of the parameters	—	—	—	X	X	X	—	X
Descriptions of the data collection procedures	—	X	X	—	—	—	—	—
Description of the data reduction and analysis	—	X	X	X	—	—	—	—
Descriptions of code input parameter development	—	—	X	—	—	—	—	—
Discussions of the linkage between input parameter information and data used to develop the input information	—	X	X	X	—	—	—	X
Discussions of the importance of the sampled parameters relative to final releases	—	—	—	X	—	—	—	—
Discussions of correlations among sampled parameters and how these are addressed in PA	—	—	—	—	—	X	—	—
Listing of the data sources used to establish parameters (e.g., experimentally derived, standard textbook values)	X	X	X	X	—	—	—	X
Data reduction methodologies used for PA parameters	—	X	X	X	—	—	—	—
Explanation of QA activities	—	—	—	—	X	—	X	—

X = Information meeting the requirement is found in this document.

[a] See CRA-2004, Chapter 6.0 for parameter descriptions and CRA-2004, Chapter 5.0 for an explanation of QA activities.

[b] CRA-2004, Appendix PA, Attachment PAR.

[c] CRA-2004, Appendix QAPD.

rate. The analysis was conducted and the DOE documented the results (Kanney and Kirchner 2004). The EPA reviewed the DOE's response and noted that doubling the drilling rate does increase predicted releases, but that the results are still well within regulatory release limits.

Ultimately, the EPA was able to determine that the DOE continued to be in compliance with section 194.23(c)(4) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

23.9.5 Changes or New Information Since the 2004 Recertification

For the CRA-2009, there are 90 new parameters and 15 modified parameters (Fox 2008, Table 6). The 15 modified parameters and 10 of the 90 new parameters are a result of corrections and parameter updates. The remaining 80 new parameters arose from the capability improvements added to the BRAGFLO computer code. More discussion of the CRA-2009 parameters is found in Fox (2008).

As in the CRA-2004, the information used to show detailed descriptions of data collection procedures, data reduction and analysis, and code input parameter development was provided in the PEFs that the DOE prepared for each of the CRA-2009 PA parameters (see Fox 2008). Therefore, the DOE continues to provide documentation of the parameter development and thus continues to demonstrate compliance with the provision of section 194.23(c)(4).

23.10 40 CFR § 194.23(c)(5)

23.10.1 Background

40 CFR § 194.23(c)(5) requires documentation of any necessary licenses for all models and computer codes.

23.10.2 1998 Certification Decision

The DOE did not use any software that requires a license, so the EPA found that the DOE demonstrated compliance with section 194.23(c)(5).

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(5) can be obtained from CARD 23, Section 13.1 (U.S. Environmental Protection Agency 1998a).

23.10.3 Changes in the CRA-2004

As in the CCA, no licenses from software vendors were required to operate the codes essential for the WIPP PA. Most of the computer codes for the WIPP PA were developed and programmed by the DOE or its contractors as custom software, and require no license to execute or use the computer codes documented in the CCA and supplementary materials. MODFLOW and PEST are public domain codes and are readily accessible.

23.10.4 EPA's Evaluation of Compliance for the 2004 Recertification

As the DOE did not use any software that requires a license, the EPA determined that the DOE continued to comply with section 194.23(c)(5) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

23.10.5 Changes or New Information Since the 2004 Recertification

No new codes were added for the CRA-2009 PA and no software requiring a license was used. Thus, there is no new information to provide in the CRA-2009, and the DOE continues to demonstrate compliance with the provisions of section 194.23(c)(5).

23.11 40 CFR § 194.23(c)(6)

23.11.1 Background

40 CFR § 194.23(c)(6) requires an explanation of the manner in which models and computer codes incorporate the effects of parameter correlation.

23.11.2 1998 Certification Decision

In the CCA, the DOE provided an explanation of the manner in which models and computer codes incorporate the effects of parameter correlation. The EPA's evaluation found that the CCA and supplementary information adequately discussed how the effects of parameter correlation are incorporated, explained the mathematical functions that describe these relationships, and described the potential impacts on the sampling of uncertain parameters. The CCA also adequately documented the effects of parameter correlation for both conceptual models and the formulation of computer codes, and appropriately incorporated these correlations in the PA.

A complete description of the EPA's 1998 Certification Decision for section 194.23(c)(6) can be obtained from CARD 23, Section 14.4 (U.S. Environmental Protection Agency 1998a).

23.11.3 Changes in the CRA-2004

User-specified parameter correlations for sampled parameters were introduced into the CRA-2004 PA calculations using the Latin Hypercube Sampling (LHS) computer program. The DOE used two types of parameter correlations: user-specified and induced. User-specified (explicit) parameter correlations are input to the LHS computer code using a correlation matrix (or table).

When values sampled using the LHS computer code are used to calculate other values in the PA calculations, an induced correlation parameter relationship is created. This is the prevalent method of parameter correlation in the WIPP PA.

The DOE implemented parameter correlations in the WIPP PA using the LHS computer code (CRA-2004, Appendix PA, Section PA-5.4). CRA-2004 parameter correlations are described in the CRA-2004, Appendix PA, Attachment PAR, Section 4.0.

23.11.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA determined that parameter correlations were adequately explained in the CRA-2004, Appendix PA, Attachment PAR, Section PAR-4.0 and were adequately incorporated. The EPA also found that the CRA-2004 presented an adequate explanation of the manner in which models and computer codes incorporated the effects of parameter correlations. The EPA determined that the DOE continued to comply with section 194.23(c)(6) (CARD 23, Section "Recertification Decision 194.23(c)," U.S. Environmental Protection Agency 2006f).

23.11.5 Changes or New Information Since the 2004 Recertification

The description of the parameter correlations used in the CRA-2009 PA can be found in Fox (2008, Section 4.0). No changes were made in the parameter correlations since the CRA-2004 PABC, except that the conditional relationship between the inundated and humid microbial cellulose degradation rates was modified from the CRA-2004 PABC methodology. For the CRA-2004 PABC, the conditional relationship was enforced in the preprocessing step for the BRAGFLO calculations by setting the humid rate equal to the inundated rate if the sampled humid rate was higher than the inundated rate for a single vector. Changing these values this way introduced a small error into the sensitivity analysis because the regression analysis was based on the sampled value rather than the conditional values.

For the CRA-2009 PA, a conditional relationship was applied so that the sampled inundated rate is used as the maximum in the sampling for the humid rate. This conditional relationship results in a correlation of 0.74 between the humid and inundated rates (Kirchner 2008a). The conditional relationship was applied during the LHS process. The LHSEDIT utility was developed to account for this conditional relationship. The implementation and verification of the LHSEDIT utility is discussed in Kirchner (2008a).

The DOE continues to provide an explanation of the manner in which models and computer codes incorporate the effects of parameter correlation and thus demonstrate compliance with the provisions of section 194.23(c)(6).

23.12 40 CFR § 194.23(d)

23.12.1 Background

The DOE must provide the EPA free access to PA models and computer codes.

23.12.2 1998 Certification Decision

During the review of the CCA, the DOE provided the EPA with ready access to computer hardware required to perform independent computer simulations. Therefore, the EPA found the DOE in compliance with the requirements of 40 CFR § 194.23(d).

A complete description of the EPA's 1998 Certification Decision for section 194.23(d) can be obtained from CARD 23, Section 15.4 (U.S. Environmental Protection Agency 1998a).

23.12.3 Changes in the CRA-2004

No specific changes were made to the CRA-2004 to demonstrate compliance with section 194.23(d). The DOE provided access for the EPA during the CRA-2004 to PA models and computer codes.

23.12.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA expected the DOE to identify points of contact to facilitate the process for the EPA to perform independent simulations, provide ready access to the hardware and software needed to perform simulations related to the CRA-2004 evaluation, and assist the EPA personnel in exercising the DOE computer codes.

The DOE provided contacts to assist the EPA in operating the hardware needed to perform the independent computer simulations necessary to verify the simulations related to the CRA-2004. The DOE provided the EPA and authorized personnel with unrestricted access to this computer hardware and software.

Based on adequate support and access to PA computer codes, input files, and PA-related documentation, the EPA determined that the DOE continued to comply with the requirements for section 194.23(d) (CARD 23, Section "Recertification Decision 194.23(d)," U.S. Environmental Protection Agency 2006f).

23.12.5 Changes or New Information Since the 2004 Recertification

No specific changes were made to the CRA-2009 to demonstrate compliance with section 194.23(d). Thus, the DOE will continue to provide the EPA with unrestricted access to the computer hardware and software and the DOE continues to demonstrate compliance with the provisions of section 194.23(d).

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Waste Characterization
(40 CFR § 194.24)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Waste Characterization
(40 CFR § 194.24)

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Acronyms and Abbreviations

%	percent
AK	acceptable knowledge
AMWTF	Advanced Mixed Waste Treatment Facility
CAO	Carlsbad Area Office
CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
Ci	curie
CPR	cellulose, plastic and rubber
CRA	Compliance Recertification Application
DBR	Direct Brine Release
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FMT	Fracture-Matrix Transport
gal	gallon
GWB	generic weep brine
HLW	high-level waste
INL	Idaho National Laboratory
kg	kilogram
LANL	Los Alamos National Laboratory
LHS	Latin Hypercube Sampling
LWA	Land Withdrawal Act
M	molar
m^3	cubic meters
NDA	nondestructive assay
NDE	nondestructive examination
NMED	New Mexico Environment Department
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
PDP	performance demonstration program
QA	quality assurance

QAO	quality assurance objective
QAPP	Quality Assurance Program Plan
RFETS	Rocky Flats Environmental Technology Site
RH-TRU	remote-handled transuranic
RTR	real-time radiography
SNL	Sandia National Laboratories
TRU	transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
VE	visual examination
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WIPP	Waste Isolation Pilot Plant
WTWBIR	WIPP Transuranic Waste Baseline Inventory Report
WUF	Waste Unit Factor
WWIS	WIPP Waste Information System
yr	year

Elements and Chemical Compounds

Am	americium
An	actinide
An(III)	general actinide in the +3 oxidation state
An(IV)	general actinide in the +4 oxidation state
An(V)	general actinide in the +5 oxidation state
CH_4	methane
Cm	curium
CO_2	carbon dioxide
Cs	cesium
EDTA	ethylenediaminetetraacetic acid
$f(CO_2)$	fugacity of carbon dioxide
$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	hydromagnesite
Mg	magnesium
$Mg(OH)_2$	brucite
MgO	magnesium oxide
Np	neptunium
pH	the negative, common logarithm of the activity of H^+
Pu	plutonium
Sr	strontium
Th	thorium
$Th(OH)_4$	thorium hydrate
U	uranium

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24.0 Waste Characterization (40 CFR § 194.24)

24.1 Requirements

§ 194.24 Waste Characterization

(a) Any compliance application shall describe the chemical, radiological and physical composition of all existing waste proposed for disposal in the disposal system. To the extent practicable, any compliance application shall also describe the chemical, radiological and physical composition of to-be-generated waste proposed for disposal in the disposal system. These descriptions shall include a list of the waste components and their approximate quantities in the waste. This list may be derived from process knowledge, current non-destructive examination/assay, or other information and methods.

(b) The Department shall submit in the compliance certification application the results of an analysis which substantiates:

(1) That all waste characteristics influencing containment of waste in the disposal system have been identified and assessed for their impact on disposal system performance. The characteristics to be analyzed shall include, but shall not be limited to: solubility; formation of colloidal suspensions containing radionuclides; production of gas from the waste; shear strength; compactability; and other waste-related inputs into the computer models that are used in the performance assessment.

(2) That all waste components influencing the waste characteristics identified in paragraph (b)(1) of this section have been identified and assessed for their impact on disposal system performance. The components to be analyzed shall include, but shall not be limited to: metals; cellulosics; chelating agents; water and other liquids; and activity in curies of each isotope of the radionuclides present.

(3) Any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to significantly influence the containment of the waste in the disposal system.

(c) For each waste component identified and assessed pursuant to paragraph (b) of this section, the Department shall specify the limiting value (expressed as an upper or lower limit of mass, volume, curies, concentration, etc.), and the associated uncertainty (i.e., margin of error) for each limiting value, of the total inventory of such waste proposed for disposal in the disposal system. Any compliance application shall:

(1) Demonstrate that, for the total inventory of waste proposed for disposal in the disposal system, WIPP complies with the numeric requirements of §194.34 and §194.55 for the upper or lower limits (including the associated uncertainties), as appropriate, for each waste component identified in paragraph (b)(2) of this section, and for the plausible combinations of upper and lower limits of such waste components that would result in the greatest estimated release.

(2) Identify and describe the method(s) used to quantify the limits of waste components identified in paragraph (b)(2) of this section.

(3) Provide information which demonstrates that the use of process knowledge to quantify components in waste for disposal conforms with the quality assurance requirements found in Section 194.22.

(4) Provide information which demonstrates that a system of controls has been and will continue to be implemented to confirm that the total amount of each waste component that will be emplaced in the disposal system will not exceed the upper limiting value or fall below the lower limiting value described in the introductory text paragraph (c) of this section. The system of controls shall include, but shall not be limited to: Measurement; sampling; chain of custody records; record keeping systems; waste loading schemes used; and other documentation.

(5) Identify and describe such controls delineated in paragraph (c)(4) of this section and confirm that they are applied in accordance with the quality assurance requirements found in Section 194.22.

(d) The Department shall include a waste loading scheme in any compliance application, or else performance assessments conducted pursuant to § 194.32 and compliance assessments conducted pursuant to § 194.54 shall assume random placement of waste in the disposal system.

(e) Waste may be emplaced in the disposal system only if the emplaced components of such waste will not cause:

(1) The total quantity of waste in the disposal system to exceed the upper limiting value, including the associated uncertainty, described in the introductory text to paragraph (c) of this section; or

(2) The total quantity of waste that will have been emplaced in the disposal system, prior to closure, to fall below the lower limiting value, including the associated uncertainty, described in the introductory text to paragraph

(c) of this section.

(f) Waste emplacement shall conform to the assumed waste loading conditions, if any, used in performance assessments conducted pursuant to §194.32 and compliance assessments conducted pursuant to §194.54.

(g) The Department shall demonstrate in any compliance application that the total inventory of waste emplaced in the disposal system complies with the limitations on transuranic waste disposal described in the WIPP LWA.

(h) The administrator will use inspections and records, such as audits, to verify compliance with this section.

24.2 Background

The U.S. Department of Energy (DOE) first demonstrated and documented compliance with the U.S. Environmental Protection Agency's (EPA's) radioactive waste disposal requirements found in 40 CFR Part 191 (U.S. Environmental Protection Agency 1993) in its Compliance Certification Application (CCA) (U.S. Department of Energy 1996a). The EPA reviewed the CCA against their Certification Criteria, found in 40 CFR Part 194 (U.S. Environmental Protection Agency 1996), and certified that the DOE's Waste Isolation Pilot Plant (WIPP) complies with the radioactive waste disposal regulations set forth in 40 CFR Part 191 Subparts B and C (Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste) (U.S. Environmental Protection Agency 1998a). In their demonstration of compliance, the DOE developed a computational modeling system to predict the future performance of the repository for 10,000 years (yrs) after closure. The system, called WIPP Performance Assessment (PA), must consider both natural and man-made processes and events that affect the disposal system.

The WIPP PA requires many input parameters to represent the complex coupled processes that are expected to occur throughout the 10,000-yr regulatory time period. Some of these parameters relate directly to the transuranic (TRU) waste inventory. The TRU waste inventory includes information about materials in the waste (wood, metal, soil, etc.), materials used to package waste (steel drums, plastic liners, etc.), emplacement materials (cellulose, plastic, and rubber [CPR]), radionuclides in the waste, and key chemicals in the waste that are expected to impact or have a role in the performance of the repository. The TRU waste information needed as input to WIPP PA is waste volumes, waste materials, packaging materials, emplacement materials, radionuclide activities, complexing agents (ethylenediaminetetraacetic acid [EDTA], acetate, citrate, oxalate, acetic acid, citric acid, and oxalic acid), and oxyanions (sulfate, nitrate, and phosphate).

TRU waste inventory has been reported by the DOE since 1994. The first inventory was reported as the *Waste Isolation Pilot Plant Transuranic Waste Baseline Inventory Report* (WTWBIR) (U.S. Department of Energy 1994). This report was followed by Revision 1 of the WTWBIR (U.S. Department of Energy 1995a) and two additional baseline reports, *Transuranic Waste Baseline Inventory Report* (TWBIR) Revisions 2 and 3 (U.S. Department of Energy 1995b and 1996b, respectively).

The TWBIR Revisions 2 and 3, included in the CCA, Appendix BIR, reported the TRU waste inventory basis for the CCA WIPP PA and the Performance Assessment Verification Test (PAVT) (U.S. Department of Energy 1997). Following the receipt of the CCA PAVT analysis,

the EPA ruled in May 1998 that the WIPP met the requirements for permanent disposal of TRU waste (U.S. Environmental Protection Agency 1998a).

The first shipment of radioactive TRU waste from the nation's nuclear weapons complex arrived at the WIPP site in late March 1999. This marked the time for subsequent recertification of the WIPP every five years after initial waste receipt, as required by the Land Withdrawal Act (LWA) (U. S. Congress 1996). Thus the first Compliance Recertification Application (CRA), CRA-2004, was submitted to the EPA by the DOE in March 2004. In the CRA-2004, the DOE prepared a TRU waste inventory that was published in Appendix DATA, Attachment F and associated annexes.

During its review of the PA submitted in the CRA-2004, the EPA directed the DOE to conduct the CRA-2004 Performance Assessment Baseline Calculation (PABC) (Cotsworth 2005). Leigh, Trone, and Fox (2005) defined the inventory for the CRA-2004 PABC. This inventory information was later published in the Transuranic Baseline Inventory Report-2004 (U.S. Department of Energy 2006).

Following the receipt of the CRA-2004 PABC analysis, the EPA ruled on March 29, 2006 that the DOE demonstrated continued compliance with the requirements of 40 CFR § 194.24 and the repository was recertified (U.S. Environmental Protection Agency 2006a).

The inventory for the CRA-2009 PA is the same inventory used for the CRA-2004 PABC. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008a) was published and provides updated inventory information. The DOE anticipates this inventory update will have only a small impact on normalized releases relative to the CRA-2009 PA, and will not be significant for compliance. The details of the inventory used for CRA-2009 are presented in the CRA-2004 PABC inventory summarized in *TRU Waste Inventory for the 2004 Compliance Recertification Application Performance Assessment Baseline Calculation* (Leigh, Trone, and Fox 2005).

24.3 1998 Certification Decision

24.3.1 40 CFR § 194.24(a)

In accordance with the requirements of 40 CFR § 194.24(a), the DOE provided in the CCA a description of existing TRU waste, a list of approximate quantities of waste components, and descriptions for to-be-generated TRU waste to the extent practicable. This information was provided by the DOE in the form of waste profiles that were reviewed by EPA. Upon completion of the review of these profiles, the EPA found the DOE in compliance with section 194.24(a) (Compliance Application Review Document [CARD] 24, Section 24.A.6 [pp. 24-7 through 24-9], U.S. Environmental Protection Agency 1998b).

24.3.2 40 CFR § 194.24(b)(1)

In accordance with the requirements of 40 CFR § 194.24(b)(1), the DOE presented the results of its waste characteristic and components analyses in the CCA, Chapter 4.0 and Appendices MASS, WCA, SOTERM, and SA. The DOE indicated that the following characteristics were

expected at the time of the CCA to have a significant effect on disposal system performance: radionuclide solubilities (including oxidation state distributions); formation of colloidal suspensions containing radionuclides; production of gas from the waste (hydrogen, and microbial substrate/nutrients for methane (CH_4) gas generation); shear strength, compactability (waste compressibility), and particle diameter; radioactivity in curies (Ci) for each isotope; and TRU radioactivity at closure.

These characteristics were included in the PA for the CCA. The EPA concluded that the DOE generally performed a thorough and well documented analysis, adequately identified all waste characteristics and, except for actinide (An) solubility and shear strength, appropriately assessed them as PA input parameters. The CCA PAVT was run using modified parameters, which satisfied the EPA's concerns (CARD 23, p. 23-10 and Section 12.4 [pp. 23-42 through 23-68], U.S. Environmental Protection Agency 1998c, and CARD 24, Section 24.B.6 [pp. 24-26 through 24-31], U.S. Environmental Protection Agency 1998b).

24.3.3 40 CFR § 194.24(b)(2)

In accordance with the requirements of 40 CFR § 194.24(b)(2), the DOE identified a number of waste components and characteristics that would be important to performance. The EPA reviewed these components and characteristics and identified several issues with the DOE's treatment of them in the CCA PA. However, through independent analysis and changes made in the CCA PAVT, these issues were resolved and the EPA determined that the DOE complied with this section (CARD 24, Section 24.C.5 [pp. 24-40 through 24-41], U.S. Environmental Protection Agency 1998b).

24.3.4 40 CFR § 194.24(b)(3)

In accordance with the requirements of 40 CFR § 194.24(b)(3), the DOE provided a list of those waste characteristics and components that were excluded from consideration in the PA for various reasons. The EPA had questions pertaining to assumptions and conclusions made by the DOE regarding organic ligands, but concluded that DOE's treatment of organic ligands in the PA was adequate based on relevant literature and bounding assumptions using 1000 times the EDTA concentrations expected to be present in the repository (CARD 24, Section 24.D.5 [pp. 24-43 through 24-44], U.S. Environmental Protection Agency 1998b).

24.3.5 40 CFR §§ 194.24(c)(1), (e)(1), (e)(2)

In accordance with the requirements of 40 CFR §§ 194.24(c)(1), (e)(1), and (e)(2), the DOE specified the limiting value of the following waste material components: ferrous metals (minimum 2×10^7 kilograms [kg]); CPR (maximum 2×10^7 kg); free water emplaced with the waste (maximum 1,684 cubic meters [m^3]); and nonferrous metals (metals not containing iron) (minimum 2×10^3 kg). In addition to these limits, the DOE provided plausible combinations of upper and lower limits and a rationale for these limits, the results of modeling code runs, the demonstration of numeric compliance, and the greatest release estimates. These limits, model runs, maximum calculated releases, and release estimates are found to be adequately described according to the EPA. (CARD 24, Section 24.F.5 [pp. 24-58 through 24-65], U.S. Environmental Protection Agency 1998b).

The EPA also agreed that the PA appropriately accounted for the upper and lower limits because fixed values were used.

In a determination of compliance with sections 194.24(e)(1) and (e)(2), the EPA reviewed the DOE's description of system controls, chain of custody information, controls in place to track WIPP TRU waste, waste record keeping and accountability systems, and WIPP Waste Acceptance Criteria (WAC) requirements and controls. The EPA reviewed the CCA and determined that the DOE adequately referenced and summarized the WIPP WAC in the CCA (CARD 24, Section 24.H.5 [pp. 24-80 through 24-84], U.S. Environmental Protection Agency 1998b).

24.3.6 40 CFR § 194.24(c)(2)

In accordance with 40 CFR § 194.24(c)(2), the DOE proposed using nondestructive examination (NDE). Real-time radiography (RTR) and visual examination (VE) were used to quantify the amounts of specific waste material components in TRU waste. The DOE described numerous nondestructive assay (NDA) instrument systems to determine radionuclides in the waste and described the equipment and instrumentation for NDA, RTR, and VE found in facilities. The DOE also provided information about performance demonstration programs (PDP) intended to show that data obtained by each NDA method could meet data quality objectives established by the DOE including sensitivity, precision, and accuracy relative to limiting values.

The EPA found the methods described, when implemented appropriately, would be adequate to characterize the important waste material components and radionuclides in TRU waste (CARD 24, Section 24.I.6 [pp. 24-87 through 24-89], U.S. Environmental Protection Agency 1998b, and U.S. Environmental Protection Agency 1996).

24.3.7 40 CFR § 194.24(c)(3)

In accordance with 40 CFR § 194.24(c)(3), the EPA determined that the DOE adequately described the use of acceptable knowledge (AK) only for legacy debris waste at the Los Alamos National Laboratory (LANL) (Dials 1997; U.S. Environmental Protection Agency 1996; CARD 24; U.S. Environmental Protection Agency 1998b).

24.3.8 40 CFR § 194.24(c)(4)

In accordance with the requirements of 40 CFR § 194.24(c)(4), the DOE described the system of documented controls used for waste characterization activities that described the management, operations, and quality assurance (QA) aspects of the program ensuring data completeness, accuracy, and discrepancy resolution prior to waste receipt at the WIPP. The DOE indicated that this system of controls would be monitored by the DOE/Carlsbad Field Office (CBFO) audit and surveillance program. In addition, the DOE provided descriptions of the documentation, data fields, and features of the WIPP Waste Information System (WWIS).

The EPA determined that the DOE provided an adequate description of the system controls and processes for maintaining centralized command and control over TRU waste characterization activities. This was inspected and verified by the EPA at LANL. Conditions 2 and 3 of the 1998

Certification Decision specified that the DOE was prohibited from shipping waste for disposal at the WIPP until the EPA approved site-specific waste characterization programs and controls (CARD 24, Section 24.H.5 [pp. 24-80 through 24-84], U.S. Environmental Protection Agency 1998b).

24.3.9 40 CFR § 194.24(c)(5)

In accordance with the requirements of 40 CFR § 194.24(c)(5), the DOE described the PDP for NDA as required by the WIPP Quality Assurance Program Plan (QAPP). Under this CBFO program, the PDP standards address activity ranges relative to WAC limits, QAPP quality assurance objectives (QAO), and NDA method detection limits. (See CARD22 U.S. Environmental Protection Agency 1998b, for additional discussion of QA for waste characterization activities.) The EPA reviewed the updated PDP Plan for NDA and concluded that the DOE provided adequate information regarding the PDP for NDA for LANL and Rocky Flats Environmental Technology Site (RFETS) at the time of inspections. The EPA confirmed through inspections at LANL that the system of controls and the measurement techniques described and implemented at LANL were adequate to characterize waste and ensure compliance with the limits of waste components for disposal at the WIPP (CARD 22, Section 22.B-5 [pp. 22-7 through 22-8], U.S. Environmental Protection Agency 1998b). RFETS was later certified to ship waste to WIPP.

24.3.10 40 CFR §§ 194.24(d) and (f)

In accordance with the requirements of 40 CFR §§ 194.24(d) and (f), the DOE had (1) assumed random waste loading and (2) evaluated the potential consequences resulting from the nonrandom loading of the highest-activity waste stream containing at least 810 drums in WIPP. As a result of the evaluation, the DOE determined that a final waste loading plan was in fact unnecessary for the WIPP. The EPA therefore concluded that the DOE adequately cross-referenced the resultant waste distribution assumptions from the waste loading plan with the waste distribution assumptions used in the PA by random distribution of radioactive waste in the repository (CARD 24, Section 24.J.6 [pp. 24-94 through 24-96], U.S. Environmental Protection Agency 1998b).

24.3.11 40 CFR § 194.24(g)

In accordance with the requirements of 40 CFR § 194.24(g), the DOE identified the following LWA limits to demonstrate compliance:

- Curie limits for remote-handled (RH) transuranic (TRU) (RH-TRU) waste: 5.1 million Ci (approximately 1.89×10^{17} becquerels).

- Total capacity of RH and contact-handled (CH) transuranic (TRU) (CH-TRU) waste that may be disposed: 6.2 million ft^3 (175,564 m^3).

- RH-TRU waste will not exceed 1,000 rem per hour, no more than 5 percent (%) by volume of RH-TRU will exceed 100 rem per hour, and RH-TRU will not exceed 23 Ci per liter maximum activity level (averaged over the volume of the canister).

In addition, the DOE provided numerous tables that presented the WIPP waste inventory in terms of activity (in Ci) and total volumes (in m^3). The EPA reviewed this information, including the process the DOE outlined for controlling the waste and the use of the WWIS, and determined that the DOE had an adequate program for tracking and controlling the waste (CARD 24, Section 24.K.5 [pp. 24-98 through 24-99], U.S. Environmental Protection Agency 1998b).

24.3.12 40 CFR § 194.24(h)

The EPA found the DOE in compliance with provisions of 40 CFR § 194.24(h). Discussion of inspections and records, such as audits is addressed by the EPA in CARD 22 (U.S. Environmental Protection Agency 1998d).

24.4 Changes in the CRA-2004

24.4.1 40 CFR § 194.24(a)

To meet the requirements of section 194.24(a), the DOE described and categorized the TRU waste currently emplaced in the WIPP and the waste that existed or was expected to be generated at the DOE TRU waste sites in the CRA-2004. The DOE developed a descriptive methodology for collecting and grouping waste information obtained from each TRU waste site. The DOE also described and categorized the TRU waste that was currently emplaced in the WIPP and the waste that existed or was expected to be generated at the DOE TRU waste sites. The emplaced waste was tracked as reported in the WWIS and was included in the CRA-2004 inventory. The details of the CRA-2004 inventory are presented in the CRA-2004, Chapter 4.0: Appendix TRU WASTE; and Appendix DATA, Attachment F.

As a result of responses to questions from the EPA during their review of the CRA-2004 PA, the DOE was directed to conduct a new PA for recertification to incorporate inventory changes as well as other technical changes (Cotsworth 2005). The new inventory components and radiological estimates were reported in TWBIR-2004 (U.S. Department of Energy 2006) and subsequently summarized in the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005).

24.4.1.1 Inventory Description

The CRA-2004 PABC Inventory Report, Table 4 (Leigh, Trone, and Fox 2005) lists the volumes of emplaced CH-TRU waste as of September 30, 2002 (the cutoff for inclusion in the CRA-2004 PA) and August 1, 2005 (the cutoff for inclusion in the CRA-2004 PABC). Table 5 of the same report lists the stored and projected CH-TRU waste estimates used for the CCA, CRA-2004 PA, and the CRA-2004 PABC. The projected inventory information is derived from the updated waste stream profile forms, and reflects each site's best determination of the waste expected to be generated and is originally presented in the CRA-2004, Chapter 4.0, Section 4.1.3. Leigh, Trone, and Fox (2005), Tables 9 and 10, show the anticipated nonradioactive components of the TRU waste inventory.

For PA to model a full repository, the DOE used a scaling factor in the same manner used in the CCA. However, unlike in the CCA, the CRA-2004 also used this scaling methodology on RH-

TRU waste. The techniques of inventory scaling are presented in TWBIR 2004 (U.S. Department of Energy 2006).

24.4.1.2 Number of Curies

The radionuclide activity expected to be placed in the WIPP decreased from the CCA estimate of 3.44 million Ci to 2.32 million Ci in the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005, Section 4.4, p. 36). Table 14 of the CRA-2004 PABC Inventory Report listed the activity by radionuclide for the CCA PA, the CRA-2004 PA, and the CRA-2004 PABC.

Below are the new inventory items since 1998 that were included in the CRA-2004 PA and the CRA-2004 PABC inventory.

- Idaho National Laboratory (INL) Buried Waste—DOE included the INL pre-1970 buried waste in the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005) as a result of an April 2003 Federal District Court judgment against the DOE on the buried waste. The CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005) estimated 17,998 m^3 of TRU waste in five waste streams from the pre-1970 buried waste at INL.

- Supercompacted Waste—Supercompacted waste from INL's Advanced Mixed Waste Treatment Facility (AMWTF) was included in the CRA-2004 PABC TRU waste inventory estimate. After an extensive analysis of this waste (Marcinowski 2003), the EPA concluded that the supercompacted waste could be considered within the existing waste envelope and PA. The EPA approved the disposal of the supercompacted waste (Marcinowski 2004). Prior to shipping this waste, the EPA conducted a waste characterization inspection of the AMWTF (Gitlin 2005).

- Hanford Tank Waste—The DOE's Office of River Protection determined that waste from 12 of the 177 tanks at the Hanford site was TRU waste or would be TRU waste after treatment. A description of these tanks and their waste streams and generating process are shown in CARD 24, Table 24-1 (U.S. Environmental Protection Agency 1998b). Patterson (2005a) and Patterson (2005b) present the DOE's documentation for these TRU tanks.

- Hanford Waste from K-Basin—The DOE's CRA-2004 PABC TRU waste inventory also included two waste streams, RL-W445 and RL-W446, consisting of ~50 m^3 of waste, from the Hanford K-East and K-West Basins (Patterson 2005a and 2005b).

- Container Types—Container types new to the CRA-2004 PABC inventory included: ten-drum overpack, 5 × 5 × 8 boxes, 100-gallon (gal) drums, and pipe overpacks within drums. The container types were considered in the CRA-2004 PABC inventory development process since it was important to estimate the amount of CPR in the WIPP (Leigh, Trone, and Fox 2005, Section 4.2, p. 30).

- Organic Ligands—Four organic ligands were included in the Fracture-Matrix Transport (FMT) calculations of An solubilities: acetate, citrate, EDTA, and oxalate (Detwiler 2004a). Further discussion on organic ligands for the CCA can be found in the CCA, Appendix SOTERM, Section 5.0, and CARD 24, Section 24.C.5 [pp. 24-40 and 24-41] (U.S.

Environmental Protection Agency 1998b). Organic ligands are further discussed in the CRA-2004 PA (Attachment SOTERM (Section 5.0, p. 42) and U.S. Environmental Protection Agency 2006d).

Changes and details on the inventory process and description are discussed further in CARD 24 (U.S. Environmental Protection Agency 2006c).

24.4.2 40 CFR § 194.24(b)(1)

There were no major changes to the waste characteristics between the CCA PAVT and the CRA-2004 PABC, but the DOE did change some of the waste components used in the PA. These changes are summarized in Table 24-2 of CARD 24 (U.S. Environmental Protection Agency 2006c) and are presented in Table 24-1 below.

24.4.2.1 Assessment of Waste Characteristics and Waste Characteristic Input Parameters

In the CCA, the DOE identified several waste characteristics as being potentially important to the PA (the CCA, Appendix WCA, Section WCA.6, pp. WCA-42 through WCA-43) based on available information, including uncertainties and WIPP system characterization. These analyses were summarized in the CCA, Appendices WCA, SOTERM, and MASS, and were augmented by the DOE's responses to the EPA comments (CARD 24, Sections 24.B.5 and 24.B.6 [pp. 24-12 through 24-31], U.S. Environmental Protection Agency 1998b). The CRA-2004 identifies the same important characteristics, and also states that organic ligands could be important to solubility. The CRA-2004 PABC, therefore, includes the ligands in the solubility calculations (Brush and Xiong 2005).

24.4.2.2 Solubility

The DOE originally stated in the CCA that solubility of actinides was among the major characteristics of the radionuclides expected to affect disposal system performance (the CCA, Appendix WCA, Section WCA.4, pp. WCA-30 through WCA-34). The DOE assessed the solubility of thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), and americium (Am) (Appendix SOTERM, U.S. Department of Energy 1996a).

In addition, the DOE assumed that cesium (Cs) and strontium (Sr) were completely (100%) soluble, therefore the concentrations of these two radionuclides were determined from the quantities listed in the inventory (the CCA, Appendix WCA, p. 30).

The DOE used the FMT geochemical modeling code and its associated database to calculate solubilities. No changes were made to the FMT code or conceptual models for the CRA-2004 PA or the CRA-2004 PABC. However, revisions were made to the input FMT database since the CCA PAVT. These changes included the addition of new aqueous An species to the database and revisions to existing species data because of the availability of new experimental data. (See Appendix PA, Attachment SOTERM, U.S. Department of Energy 2004.)

Table 24-1. Significance and Changes in Components and Characteristics

Waste Component or Characteristic Used in PA	Increase or Decrease From CCA to CRA-2004 PABC	Significance
Radioactivity (Ci/m^3)	Decrease	Used in calculating releases
Solubility	Increase and decrease, depending on oxidation state	Higher solubility can lead to higher releases
Organic ligands—complexing agents	Similar amounts	Increases solubility
Amount of Metals	Decrease	Maintains reducing environment, but also contributes to gas generation
Amount of CPRs	Increase	May increase gas generation from microbial processes
Oxyanions: nitrate, sulfate, and phosphate	Similar, but overall increase	Nutrients for microbes - affects gas generation
Cement	Decrease	Volume related component
Shear Strength	No change	Affects mechanical releases during low waste shear strength
Particle Diameter	The CRA-2004 PABC used the particle diameter determination from expert panel findings during the original certification.	Used to calculate spallings releases
Formation of colloidal suspensions	No change in parameterization	Colloids can facilitate transport of radionuclides in groundwater

The DOE used the generic weep brine (GWB) Salado brine chemistry formulation instead of the Brine A formulation used in the CCA PA and PAVT. The most significant differences between the brine formulations were the lower magnesium concentration and higher sulfate concentration in GWB relative to Brine A. Comparison of geochemical modeling results using the two brine formulations indicated that GWB brines had slightly lower predicted An(III) solubilities and higher An(V) solubilities compared to Brine A.

24.4.2.3 Performance Assessment Parameters Related to Solubility

The solubility of actinides in the III, IV, V, and VI oxidation states for both the Castile and Salado brines were calculated by the DOE with the assumption that pH and the fugacity of

carbon dioxide ($f(CO_2)$) were controlled by the brucite ($Mg(OH)_2$) –hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) buffer. The solubilities from the CCA and the CRA-2004 are listed in Table 24-3 of CARD 24 (U.S. Environmental Protection Agency 2006c).

The uncertainty ranges for the actinides in the CRA-2004 PA were the same as those used in the CCA (Bynum 1996). The uncertainties in the An solubilities were used to define the range for Latin Hypercube Sampling (LHS) of the An concentrations in the PA, assuming a log cumulative distribution (CARD 24, Section 24.B.5 [pp. 24-15 and 25-16], U.S. Environmental Protection Agency 1998b).

24.4.2.4 Formation of Colloidal Suspensions Containing Radionuclides

Formation of colloidal suspensions was evaluated by the DOE as an important group of waste characteristics. Actinides can be mobilized in colloidal form as intrinsic colloids or absorbed on nonradioactive colloidal particles. In the CCA, the DOE determined that four types of colloids may be present in the WIPP repository: intrinsic colloids, mineral fragment colloids, humic colloids, and microbial colloids (the CCA, Appendix WCA, Section WCA. 4.2, pp. WCA-34 through WCA-36). These colloids were modeled in the CRA-2004 PABC and were unchanged from the CCA (see CARD 24, Sections 24.B.5 and 24.B.6 [pp. 24-12 through 24-31], U.S. Environmental Protection Agency 1998b, and CCA Appendix SOTERM, Section 6.0, U.S. Department of Energy 1996a).

The DOE implemented the colloidal An source term differently in the CRA-2004 PA than in the CCA. In the CCA, the DOE assumed all vectors would have a microbial colloid contribution to the An source term. For the CRA-2004 PA, the DOE assumed there would be microbial colloid transport only in vectors with microbial degradation. In the CRA-2004 PABC it was assumed that all vectors included microbial activity and thus included microbial colloid transport.

24.4.2.5 Production of Gas From the Waste (Including Microbial Substrate and Nutrients)

Gas generation included hydrogen gas generation as well as carbon dioxide (CO_2) and CH_4 generation by microbial degradation. Anoxic corrosion produces hydrogen gas and microbial action on microbial substrates such as CPR, as well as other microbial nutrients (nitrate, sulfate and phosphate), which produce CO_2 and CH_4.

The same conceptual model was used for microbial gas generation in the WIPP repository for both the CCA and the CRA-2004. Information about the models used for the CCA and the CRA-2004 can be found in the CCA, Appendix SOTERM, Section SOTERM-8.2.2 and the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-2.2.2, respectively.

Microbial gas generation rates used in the average stoichiometry model were based on experimental data from microbial consumption of papers (cellulose) under inundated and humid conditions (Wang and Brush 1996). A gas-generation rate is determined in BRAGFLO (fluid flow code) for the humid and inundated rates based on the effective liquid saturation (CRA-2004, Chapter 6.0, Section 6.4.3.3). These gas generation rates were calculated from the initial

linear part of the experimental curve of CO_2 as a function of time (the CRA-2004, Appendix PA, Attachment PAR; Wang and Brush 1996).

For the CRA-2004 PABC, the DOE requested a change to the gas generation rate PA parameters based on the DOE's review of additional experimental data collected over the last 10 years (Nemer and Stein 2005; Nemer, Stein, and Zelinski 2005). The gas generation experiments exhibited two rates: an initial higher rate, and a second lower rate. The DOE proposed to the EPA that the long-term rate be the gas generation rate used in the PA calculations, with the initial higher rate incorporated as an initial higher pressure.

The DOE used LHS in the CRA-2004 PA for the following gas-generation-related parameters:

- Inundated steel corrosion rate
- Probability of microbial degradation of plastics and rubbers (in the event of microbial gas generation)
- Biodegration rate of inundated and humic cellulosics
- Factor β for microbial reaction

24.4.2.6 Performance Assessment Parameters Related to Shear Strength, Compactability (Compressibility), and Particle Diameter

There were no changes in these parameters from the CCA PAVT through the CRA-2004 PABC.

24.4.2.7 Radioactivity in Curies

In the CCA (Sections 3.1 and 3.2; Appendix WCA), the DOE indicated that the radioactivity of each isotope was important to the PA because it directly affected the waste unit factor (WUF) (number of million Ci of TRU isotopes in the WIPP inventory) (see the CCA, Appendix WCA, Table WCA-1). Since the same approach was used in the CRA-2004, the approach is summarized here.

The following radionuclides were determined at the time of the CCA to be important by the DOE (the CCA, Appendix WCA, Figure WCA-4):

- Cuttings/cavings/spallings release: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{233}U, ^{234}U, ^{90}Sr, ^{137}Cs, ^{244}Cm
- Direct Brine release (DBR): ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{229}Th, ^{230}Th, ^{232}Th, ^{237}Np, ^{243}Cm, ^{244}Cm, ^{245}Cm
- Long-term groundwater release: ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{241}Am, ^{233}U, ^{234}U, ^{229}Th, ^{230}Th

The DOE indicated that U and Th isotopes were required in DBR assessments because, although they comprise negligible fractions of the total EPA unit, they did influence the total quantity of dissolved radionuclides (the CCA, Appendix WCA, p. WCA-22). In addition, the DOE

indicated that although EPA units for ^{90}Sr and ^{137}Cs at the time of the WIPP's closure were significant, they are not included in direct release of brine because they rapidly decay within the first few hundred years after closure and result in "negligible impact on the PA" (the CCA, Appendix WCA, p. WCA-26). In addition, the DOE indicated that if a DBR occurred early after closure, the total brine released would be minimal and the ^{90}Sr and ^{137}Cs would still, therefore, play a minor role in compliance (the CCA, Appendix WCA, p. WCA-26).

The DOE justified the radionuclide list for the long-term groundwater pathway (releases to the Culebra Dolomite Member of the Rustler Formation [hereafter referred to as Culebra]) in the CCA, Appendix WCA, Section WCA.3.2.3, pp. WCA-26 through WCA-27.

In the CRA-2004 PABC, the selection of isotopes for modeling transport in the disposal system with NUTS and PANEL was described in the CRA-2004, Appendix TRU WASTE, Section TRU WASTE-2.0. PANEL runs included nearly all isotopes of the six actinides studied in the Actinide Source Term Program: Th, U, Np, Pu, Am, and curium (Cm). NUTS runs explicitly included five isotopes: ^{230}Th, ^{234}U, ^{238}Pu, ^{239}Pu, and ^{241}Am (Garner and Leigh 2005).

24.4.2.8 PA Parameters Related to Radioactivity in Curies of Each Isotope

The DOE used the information from the update of the CCA inventory to define the isotope inventory for the CRA-2004 PA (the CRA-2004, Chapter 4.0). The CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005, Table 14, p. 37) provides the radioactivity in Ci of each isotope used in the CRA-2004 PABC.

24.4.2.9 TRU Radioactivity at Closure

The CRA-2004 PABC Inventory Report, Table 14 (Leigh, Trone, and Fox 2005) lists the DOE inventory at closure, based upon the September 2002 cutoff and the CRA-2004 PABC update as described in Section 24.4.1. The CRA-2004 PABC Inventory Report indicated that the inventory estimate was 2.32×10^6 Ci and the WUF was 2.32, with inventory activity decayed to the year 2033.

24.4.2.10 PA Parameters Related to TRU Radioactivity at Closure

The 2.32 WUF was the number of millions of curies of alpha-emitting TRU radionuclides with half-lives longer than 20 years used in the calculation of the EPA normalized unit. Overall, activity at 2033 for all TRU radionuclides has decreased from 2.55×10^6 Ci reported in the CCA to 2.48×10^6 Ci in the CRA-2004 inventory estimate to 2.32×10^6 Ci in the CRA-2004 PABC inventory estimate. The DOE discussed the WUF value in the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005, p. 36).

24.4.3 40 CFR § 194.24(b)(2)

The DOE indicated that ferrous metals, cellulose, organic chelating agents, radioactivity in curies of each isotope, α-emitting TRU radionuclides with half-life greater than 20 years, solid waste components (e.g., soils and cementitious materials), sulfates and nitrates were expected to have a significant effect on disposal system performance and so were used in the CCA PA, CRA-2004

PA, and the CRA-2004 PABC. Most of the inventory amounts of the listed components changed and were discussed in the CRA-2004, Appendix PA, Attachment SOTERM, Table SOTERM-4; Leigh, Trone, and Fox 2005; and U.S. Environmental Protection Agency 2006e. The only significant change was the incorporation of organic ligands in the An solubility PA calculations. The DOE updated the FMT thermodynamic databases with information related to organics to account for the organic ligands' affect on An solubility (the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-5.0). Organic ligand inventories were recalculated for the CRA-2004 PABC (Brush and Xiong 2005).

Changes and details on the effect of components on disposal system performance are discussed further in CARD 24 (U.S. Environmental Protection Agency 2006c).

24.4.4 40 CFR § 194.24(b)(3)

The DOE provided a list of waste characteristics and components that were excluded from consideration in the PA for various reasons, such as negligible impact (the CCA, Appendix WCA, Table WCA-4 and CRA-2004 Appendix TRU WASTE, Section TRU WASTE-6.0). The effect of organic ligands, however, is incorporated into the CRA-2004 PABC (Brush and Xiong 2005).

24.4.5 40 CFR §§ 194.24(c)(1), (e)(1), and (e)(2)

For the CRA-2004 PA, the DOE did not make any changes to the limits identified in the CCA or their implementation in the CRA-2004 PA. In reviewing the CRA-2004 PA, the EPA identified that the packaging materials for the INL supercompacted waste were omitted from the CPR total, but these packaging materials were included in the CRA-2004 PABC as part of the inventory estimate. See CARD 24 (U.S. Environmental Protection Agency 2006c) for further discussion.

24.4.6 40 CFR § 194.24(c)(2)

As noted in 40 CFR § 194.24(b), the DOE did not modify the list of CCA components and characteristics requiring quantification. Therefore, the CRA-2004 did not identify any significant changes to the measurement techniques used in the waste characterization program (i.e., VE, RTR, AK, and NDA). In addition, the CRA-2004 did not propose changes to the current waste characterization program through use of different NDA and NDE characterization methodologies. The CRA-2004 indicated that the location of NDA and NDE methodology documentation and information regarding QAOs had changed since the CCA. There were also several minor changes to the characterization program. The changes the EPA identified are specified in CARD 24 (U.S. Environmental Protection Agency 2006c).

24.4.7 40 CFR § 194.24(c)(3)

The CRA-2004 was revised to show that the AK process was presented in the CH-TRU WAC. The CH-TRU WAC was revised to include more discussion of AK with respect to radionuclides (U.S. Department of Energy 2002). Modifications made to the CH-TRU WAC since the CCA that were pertinent to AK included the use of existing AK collected prior to the implementation of a QA program under 40 CFR § 194.22(a), methods for confirming isotopic ratios using AK,

required and supplemental AK documentation, discrepancy resolution and data limitation identification, and AK-radioassay data measurement comparisons as a means to assess comparability. Existing AK collected prior to the implementation of a QA program under section 194.22(a) may be qualified by peer review, corroborating data, confirmatory testing, or collection of data under an equivalent QA program. See CARD 24 (U.S. Environmental Protection Agency 2006c) for further discussion.

24.4.8 40 CFR § 194.24(c)(4)

The DOE uses the WWIS to track data for emplaced waste in the WIPP. For the CCA, the WWIS used Oracle (Version 7) and for the CRA-2004, the WWIS used Oracle (Version 9): otherwise, there were no changes. In the CRA-2004, a statement was included, "additional computing system upgrades may be implemented in the future." See CARD 24 (U.S. Environmental Protection Agency 2006c) for further discussion.

24.4.9 40 CFR § 194.24(c)(5)

The DOE described the changes to the PDP in the CRA-2004, Chapter 4.0, Section 4.3.3.1 PDP (p. 4-49). There were three significant changes in this section relative to the CCA: (1) the QAPP is no longer referenced as the document defining the PDP QAO requirements, (2) the PDP Plan was removed as a reference and replaced by the statement that "the NDA PDP plans are revised as required," and (3) the section no longer contains a detailed description of the isotopes to be analyzed and the configuration of the PDP tests. Other minor changes are addressed in CARD 24 (U.S. Environmental Protection Agency 2006c).

The DOE also revised the quality document hierarchy for waste characterization activities by making the Carlsbad Area Office (CAO) Quality Assurance Program Document a higher-tier document and the QAPP of lesser importance. This new document hierarchy is shown in the CRA-2004, Chapter 4.0, Figure 4-3, which replaced the CCA, Chapter 4.0, Figure 4-6.

24.4.10 40 CFR §§ 194.24(d) and (f)

The DOE did not use a performance-based waste loading scheme for waste emplacement in WIPP, and the DOE assumed random waste loading in its performance and compliance assessments. Prior to the CRA-2004, the EPA requested that DOE analyze waste loading with respect to supercompacted waste, and the DOE identified that clustering of waste would not affect performance (Marcinowski 2003, Park and Hansen 2003, and Marcinowski 2004). See CARD24 (U.S. Environmental Protection Agency 2006c) for further discussion.

24.4.11 40 CFR § 194.24(g)

The DOE uses the WWIS to track the limitations on TRU waste disposal described in the WIPP LWA. For the CCA, the WWIS used Oracle (Version 7) and for the CRA-2004, the WWIS used Oracle (Version 9). Otherwise, there were no changes. In the CRA-2004, a statement was included: "additional computing system upgrades may be implemented in the future." See CARD 24 (U.S. Environmental Protection Agency 2006c) for further discussion.

24.4.12 40 CFR § 194.24(h)

The EPA found the DOE in compliance with provisions of section 194.24(h). Discussion of inspections and records, such as audits, is addressed by EPA in CARD 22 (U.S. Environmental Protection Agency 2006b).

24.5 EPA's Evaluation of Compliance for the 2004 Recertification

24.5.1 40 CFR § 194.24(a)

The EPA reviewed the CRA-2004 and supplemental information to determine whether it provided a sufficiently complete description of the chemical, radiological, and physical composition of the emplaced, existing, and to-be-generated waste proposed for disposal in the WIPP. The EPA also reviewed the DOE's description of the approximate quantities of waste components (for both existing and to-be-generated waste). The EPA considered whether the DOE's waste descriptions were of sufficient detail to enable the EPA to conclude that the DOE did not overlook any component that is present in TRU waste and has significant potential to influence releases of radionuclides.

Based on the EPA's review and evaluation of this information and the consideration of public comments, the EPA determined that the DOE continued to comply with the requirements of section 194.24(a) (U.S. Environmental Protection Agency 2005d, 2006c, 2006e, 2006f).

24.5.1.1 Chemical, Physical, and Radiological Description of Existing Waste

The EPA reviewed descriptions of the chemical, radiological, and physical components of the waste which were documented in the CRA-2004 and supporting documents. This information was collected using similar methods as during the CCA and the process used was determined to be reasonable by the EPA.

The EPA concluded on the basis of this information that the CRA-2004 and supplemental information adequately described the chemical, radiological, and physical characteristics of each waste stream proposed for disposal at the WIPP. The EPA further concluded that the information presented by the DOE in the CRA-2004 provides adequate characterization of existing WIPP waste for use in PA.

The EPA concluded that the DOE's development of the disposal inventory was sufficient for PA purposes. The EPA agreed with the DOE that the use of projected waste inventory for scaling the CH-TRU WIPP inventory to meet the total WIPP capacity was appropriate. The DOE's use of the inventory scaling process was similar to that used in the CCA and was adequate for projecting inventory estimates.

24.5.1.2 Waste Forms and Packaging: Supercompacted Waste

The EPA approved the disposal of supercompacted waste from AMWTF at the WIPP (Marcinowski 2004). The DOE's CRA-2004 characterized, represented, and considered supercompacted waste from INL in the recertification inventory.

24.5.1.3 Waste Forms and Packaging: Container Types

The DOE's assortment of containers was expected to meet the metal limit regardless of the container type, because they all are metal containers. The EPA found the container types used in the CRA-2004 PA to be reasonable.

24.5.1.4 Waste Forms and Packaging: Inclusion of Waste Packaging in Inventory

During the initial review of the recertification application, the EPA found that the DOE did not include emplacement materials in the CRA-2004 PA calculations (Cotsworth 2004a). These materials could contribute to gas generation. The DOE states (Detwiler 2004b) that this material accounted for only a 12.7% increase in CPR if it is included in the PA and that there would be no effect on compliance if it were included in the PA. However, the DOE did include the additional emplacement material volume and mass in the CRA-2004 PABC (Leigh, Trone, and Fox 2005, Section 1.3.3, p. 11), thus the emplacement materials are reflected in the release estimates. The CRA-2004 PABC shows that the WIPP still complies with the new CPR amounts in the inventory. Thus the use of increased CPR amounts was adequate, and the amount used in the CRA-2004 PABC established a new limit.

24.5.1.5 Number of Curies, Waste Streams, and Volume

The DOE estimated the activity in curies in the inventory on a site-by-site, waste-stream-by-waste-stream level. The EPA required that the DOE produce a "list of the waste components and their approximate quantities." The EPA reviewed the estimate in the CRA-2004, Chapter 4.0 and Appendix TRU WASTE, and the TRU Waste Baseline Inventory Database (Los Alamos National Laboratory 2005) and found these materials to contain sufficiently specific information on the species and quantities of individual radioisotopes in the waste.

24.5.1.6 Organic Ligands

The EPA requested that the DOE provide additional information regarding the possible effects of organic ligands concentrations on An solubilities in the WIPP repository (Cotsworth 2004b). In their response, the DOE described the results of a series of calculations designed to determine the sensitivity of An(III), An(IV), and An(V) solubilities to increases in organic ligand concentrations and the possible effects of microbially produced acetate and lactate. The EPA reviewed the updated calculations related to the effect of organic ligands on An solubility and determined that organic ligands are potentially important (U.S. Environmental Protection Agency 2006d). The DOE did include the effects of solubility of organic ligands in the CRA-2004 PABC and the CRA-2004 and supplemental information: therefore, the EPA found that the DOE appropriately included organic ligands in the CRA-2004 PABC (U.S. Environmental Protection Agency 2006f).

24.5.1.7 Hanford Waste

In the CRA-2004, the DOE identified that it included waste from 12 tanks from Hanford. This included nine tanks of CH-TRU waste and three tanks of RH-TRU waste. The volume of the CH-TRU waste was estimated to be ~3,932 m^3 (~2% of the total CH-TRU waste and ~2% of the

total inventory) and the RH-TRU waste was estimated at ~4,469 m^3 (~63% of total RH-TRU waste, ~2.5% of the total inventory). The DOE stated that these 12 tanks were considered TRU waste although the tanks were managed as high-level waste (HLW). Furthermore, the DOE pointed out, if the waste was HLW, then by law it could not go to the WIPP. The DOE included waste from the 12 tanks in the CRA-2004 PA and the CRA-2004 PABC and began discussion about establishing a TRU waste determination process in the future.

The EPA allowed this waste to be included in the PA inventory for recertification and the DOE demonstrated that with the Hanford tank waste, the WIPP continues to comply with the EPA's disposal regulations. However, it was noted that before any Hanford tank waste could be shipped to the WIPP, the DOE must demonstrate during characterization that the waste is, in fact, TRU waste that can legally go to the WIPP (CARD 24; U.S. Environmental Protection Agency 2006c).

24.5.1.8 K-Basin Waste

The sludges from the K-Basin storage pools consist of debris, silt, sand, and material from operations of the pools at Hanford. The 50.4 m^3 of sludges contaminated with radionuclides associated with spent nuclear fuel that was exposed to water in the pools were included in the CRA-2004 PABC.

The EPA allowed this waste in the PA inventory because the waste form was similar to other waste going to the WIPP, was low in volume, and required processing and characterization before being shipped to the WIPP. In addition, EPA stated the DOE must demonstrate that the waste meets the technical and legal requirements prior to disposal.

24.5.1.9 INL Waste

The pre-1970 buried waste included in the CRA-2004 PABC (Leigh et. al. 2005) is found in the CRA-2004, Appendix DATA, Attachment F, Annex I as waste stream IN-Z001. It was designated as non-WIPP TRU waste, but the DOE decided to include it in the CRA-2004 PABC because of a 2003 judgment against the DOE related to its removal at INL. This waste was not included in the CRA-2004 PA because the court judgment came after the September 30, 2002 cutoff date for inventory development (see Leigh, Trone, and Fox 2005; Lott 2004). This waste appeared to be similar to other WIPP waste streams, but must still meet the WIPP WAC and remains subject to the EPA's inspection and approval process before being disposed of at the WIPP.

24.5.1.10 Other Issues

The DOE identified and corrected one error between the CRA-2004 PA and the CRA-2004 PABC: the LANL CH-TRU waste stream LA-TA-55-48. This waste stream was a low-volume, high-radioactivity waste stream that skewed the results of the PA cumulative contamination distribution factors upward. Upon further review, the DOE identified that this waste stream was mischaracterized; the Pu fissile gram equivalent mass was greater than shipping requirements allowed (Crawford 2004). The DOE reevaluated the waste stream, and modified the waste stream radioactivity and volume for the CRA-2004 PABC. Since this was an estimate and the

waste will be characterized before going to the WIPP, the waste stream correction was found to be reasonable.

24.5.2 40 CFR § 194.24(b)(1)

For the CCA, the EPA reviewed information on waste characteristics and components in a number of technical documents. This review encompassed references, experimental programs, logical arguments, and modeling. The EPA determined all relevant waste characteristics and components were identified and evaluated. For the CRA-2004, the EPA focused on changes and new information that could affect the DOE's analyses and findings.

The EPA concluded that, with the combination of the CRA-2004, supplemental information, and the CRA-2004 PABC, the DOE continued to comply with the requirements for section 194.24(b)(1) (U.S. Environmental Protection Agency 2006c).

24.5.2.1 Solubility

The EPA's review identified two areas in which the DOE did not adequately address solubility. First, the DOE did not update the U(VI) solubility to incorporate new data that became available since the certification decision. The data indicated that the U(VI) solubility should be higher than that used by the DOE in the CRA-2004 PA. Second, the DOE did not update the solubility uncertainty ranges used for An solubility oxidation states based on new data.

For the CRA-2004 PABC, the EPA stated that the solubility of U(VI) needed to be changed to a fixed value of 1×10^{-3} molar (M) because of experimental data that became available after the CCA. In addition, the EPA required that new solubility uncertainty ranges, based on the FMT database and currently available experimental solubility data, be incorporated into the CRA-2004 PABC. The DOE made additional changes to the calculation of the An(III), An(IV), and An(V) solubilities based on revised thermodynamic data for the An(IV) actinides, a different Salado brine formulation, and revised concentrations of organic ligands. These changes were properly implemented as discussed in Section 7 of *Technical Support Document for* S*ection 194.24: Evaluation of the Compliance Recertification Actinide Source Term and Culebra Dolomite Distribution Coefficient Values* (U.S. Environmental Protection Agency 2005b).

A summary of changes and improvements incorporated into the calculation of An solubilities for the CRA-2004 PABC that have been implemented since the CCA PAVT include the following:

- Organic ligand complexation data was incorporated into the FMT thermodynamic database so the effects of organic ligands on An(III), An(IV) and An(V) solubilities can be calculated directly. The organic ligand concentration changes, which in all cases but oxalate are defined by the inventory, were the result of corrections to the masses of organic ligands identified in the CRA-2004 PABC inventory (Leigh, Trone, and Fox 2005) and the minimum estimated brine volume required for a release from the repository.

- The TRU waste inventory data, including actinides, was updated.

- The FMT thermodynamic data base for actinides was updated and used to calculate the An(III), An(IV), and An(V) solubilities. Most importantly, the free energy formation constant value for thorium hydrate ($Th(OH)_4$)(aq) was lowered, leading to better agreement between experimental and modeling results (Xiong 2005).

- Magnesium oxide (MgO)-reacted Salado GWB and Castile (ERDA-6) brines were used to calculate An solubilities. GWB, which has a lower magnesium (Mg) and higher sulfate content, replaces Brine A as the Salado brine formulation for An solubility calculations (Brush et al. 2006).

- Instantaneous equilibria among major GWB and ERDA-6 relevant minerals was assumed and the chemical environment was made more uniform due to the elimination of nonmicrobial vectors in PA.

- Correction of the minimum brine volume necessary for DBR (Stein 2005).

- Revision of the estimated U(VI) solubility to 0.001 M account for the new data (U.S. Environmental Protection Agency 2005b).

- Recalculation of An solubility uncertainties based on a much larger number of solubility measurements, with separate distributions developed for the An(III), An(IV), and An(V) solubilities (Xiong, Nowak, and Brush 2005).

24.5.2.2 Colloids

The CCA PAVT included microbial colloid transport of actinides for all vectors. The CRA-2004 PA included different assumptions about the colloidal source term concentrations for microbial and nonmicrobial vectors, with no microbial colloid transport of actinides assumed for nonmicrobial vectors. However, for the CRA-2004 PABC, it was assumed that all vectors included microbial activity. Therefore, the DOE included microbial colloid transport of actinides for all CRA-2004 PABC vectors (Brush 2005). This approach was, therefore, the same for the CCA PAVT and CRA-2004 PABC, and was consistent with the EPA's direction that all vectors include microbial activity.

24.5.2.3 Production of Gas from the Waste

Microbial degradation of CPR may influence WIPP repository performance because of its effects on repository chemistry and gas generation. The EPA reviewed the approach and assumptions used by the DOE to model microbial degradation for the CRA-2004 PA. The EPA's comments to the DOE focused on the probability of significant microbial degradation, the nature of the microbial degradation reactions likely to occur in the repository, and microbial gas generation rates. As a result of the EPA's review and comments, the DOE changed the modeling of microbial degradation processes for the CRA-2004 PABC. Specifically, the EPA instructed the DOE to assume that microbial degradation of CPR would occur in all CRA-2004 PABC vectors.

During the review of the CRA-2004 PA, the DOE informed the EPA that the microbial gas generation experiments had continued and additional information related to microbial gas

generation rates in the WIPP repository had become available since the CCA PA and the CCA PAVT. In the letter (Cotsworth 2005) directing the DOE to perform the CRA-2004 PABC, the EPA allowed the DOE to propose a new gas generation rate scheme based on the new experimental data.

At the EPA's direction, the DOE changed the probability of microbial degradation to account for new evidence regarding the presence and viability of microbes capable of degrading CPR in the WIPP repository. The revised probability parameters resulted in microbial degradation in all vectors for the CRA-2004 PABC. However, the DOE asserted that uncertainties remained regarding the viability of microbes in the repository because of different conditions in the repository compared to the conditions in the experiments. The DOE therefore introduced an additional sampled parameter, BIOGENFC. This parameter, which has a uniform distribution from 0 to 1, was multiplied by the microbial gas generation rates to effectively reduce the humid and inundated microbial gas generation rates from the experimentally determined long-term rates.

24.5.3 40 CFR §§ 194.24(b)(2) and (b)(3)

The concentrations of organic ligands were reevaluated for the CRA-2004 PABC An solubility calculations based on a revised estimate of the minimum amount of brine that could lead to a release from the repository. In addition, new data regarding the possible complexation of An(IV) by EDTA were identified. These data were evaluated to determine the potential significance of EDTA to the An solubility calculations for WIPP repository conditions.

During the EPA's review of the important waste components, the EPA identified that only organic ligands had been addressed differently than in the CCA. Organic ligands could increase An solubility, but the EPA determined that the DOE had adequately included their effects in the CRA-2004 PABC (U.S. Environmental Protection Agency 2006c).

24.5.4 40 CFR §§ 194.24(c)(1), (e)(1), and (e)(2)

In the CCA, the EPA found that the DOE identified those waste components that required limits, and that the limits were reasonable and quantifiable. The EPA's main concern was that the waste components be kept to levels that keep the repository in compliance with the disposal standards. The waste components of special concern were the amounts of CPR and their potential to generate gases that contribute to increased pressure in the repository.

As with the CCA, the DOE did not provide the associated uncertainty for the waste material component limits in the CRA-2004. The EPA identified two related issues regarding this claim of no uncertainty. The first was to ensure that the inventory remains within the waste component limits established by the DOE, and the second is that the performance of the repository was not compromised by the uncertainty in the inventory. This section required that the DOE identify the associated uncertainty for each limiting value. In the CRA-2004, as in the CCA, the DOE stated that the waste material component limits were fixed values with no associated uncertainties.

However, the EPA requested that the DOE review the issue of uncertainty. The DOE states (Leigh 2006, p. 6) that the "sum of the weights of individual components in a container can at most differ from the total weight of the container by 5 percent." For the CCA, the EPA agreed with this approach, since the limiting value could be used to represent the "upper end" of an uncertainty value. However, the lack of information on the waste component inventory was of concern for the future, especially with the CPR materials, since they had the greatest potential to affect performance.

Since the inventory emplaced in the WIPP is currently at a fraction of the total inventory expected in the future, and since a significant fraction of the inventory is still estimated and to be emplaced in the future, the EPA found that the use of point estimates is acceptable for the waste components and radionuclides for this recertification. In addition, the EPA found that, since only a limited amount of waste has been emplaced, the inventory and its associated uncertainty is below the respective limiting values. However, the EPA suggested the DOE improve its knowledge of the measurement uncertainty for the next recertification and include these uncertainties into the PA process (U.S. Environmental Protection Agency 2006c).

24.5.5 40 CFR § 194.24(c)(2)

Since the 1998 certification decision, the waste characterization program has been implemented at several DOE waste generator sites. This represented a change in activities since approval of the CCA, because only LANL was approved at that time. Since 1998, the EPA approved waste characterization at the larger generator sites, namely the AMWTF, Hanford, INL, RFETS, and Savannah River Site. In addition, characterization was approved at the small generator sites: Lawrence Livermore National Laboratory and the Nevada Test Site. These sites continued to characterize CH-TRU waste for disposal at the WIPP through the CRA-2004.

Based on the EPA's review of the CRA-2004, including the new information and references presented therein, the EPA agreed that the methods used to quantify the limits of waste components had not changed substantially since the 1998 certification decision. The EPA kept abreast of all the changes to the program, including information source document changes that transpired after the EPA's 1998 certification decision. Changes implemented up to the 2002 CH-TRU WAC and Waste Analysis Plan (WAP) referenced in the CCA had not affected the site's abilities to adequately quantify waste components in individual containers. The DOE, therefore, continued to require each waste site to characterize radiological contents of every container of CH-TRU waste streams destined for WIPP disposal using the EPA-approved NDA systems. Similarly, each site continued to examine each TRU waste container to ensure the absence of prohibited items using the EPA-approved RTR and/or VE procedures (U.S. Environmental Protection Agency 2006c).

24.5.6 40 CFR § 194.24(c)(3)

The EPA's WIPP regulations required the DOE to "provide information which demonstrates that the use of process knowledge to quantify components in waste for disposal conforms with the quality assurance requirements found in 40 CFR § 194.22" (U.S. Environmental Protection Agency 1996, p. 5240).

The EPA found the information presented in section 194.24(c)(3) of the CRA-2004 adequate and that the adherence of TRU waste sites to the CRA-2004-based AK process will allow them to meet their regulatory obligation.

24.5.7 40 CFR § 194.24(c)(4)

The EPA determined that the general description of the WWIS in the CRA-2004 was adequate (CARD 24, pp. 24-44, U.S. Environmental Protection Agency 2006c). Hardware modifications and software upgrades described in the CRA-2004 were necessary to maintain system reliability, security, and performance. The EPA reviewed the WWIS during its inspections of the WIPP and TRU waste generator sites and was aware of the changes to the WWIS since the CCA. The EPA determined that the WWIS adequately gathers, stores, and processes information pertaining to TRU waste destined for or disposed of at the WIPP (U.S. Environmental Protection Agency 2006c).

The DOE stated that a majority of the 130 WWIS data fields were pertinent to demonstrate compliance with TRU waste transportation and disposal requirements. The EPA verified that the DOE adequately tracked more than these 130 data fields in the WWIS. The DOE had not changed its tracking methodology and in fact has added parameters to be tracked in the WWIS.

24.5.8 40 CFR § 194.24(c)(5)

The QAPP and the Methods Manual were replaced by the WAC and the New Mexico Environment Department (NMED) WAP for the CRA-2004. The EPA was aware of these changes to the program requirements documents. The wording changes regarding the description of the PDP test and the removal of the PDP plan did not affect the EPA's ability to ensure that the DOE has implemented a series of intercomparability tests for NDA equipment that develop similar results. The elimination of the PDP test description from the CRA-2004 requires that the DOE make available to the EPA the PDP plans and test descriptions so the EPA could ensure that the program was indeed acting as a "true blind sample" program. The change in PDP certification from the facility to the equipment was acceptable.

The EPA continued to ensure, through audits and inspections, that the waste characterization program met QA requirements sufficiently. The inspection program was the primary method by which the EPA determined the implementation of QA controls to the waste characterization program.

The DOE's changes to the PDP program did not affect the EPA's ability to assess the implementation of quality controls to the waste characterization program. The wording changes allowed the DOE more flexibility in developing PDP tests. The changes to the QA document hierarchy do not lessen the implementation of quality controls to the waste characterization program.

Based on the EPA's review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continues to comply with the requirements for section 194.24(c)(5) (U.S. Environmental Protection Agency 2006c).

24.5.9 40 CFR §§ 194.24(d) and (f)

In PAs, the DOE has assumed random waste emplacement. In the CCA, the EPA asked for additional analysis assuming clustering of waste. The DOE performed an analysis and showed that clustering waste streams would not significantly affect PA results. Indeed, RFETS waste was eventually clustered in the WIPP (Park and Hansen 2003). In addition, the EPA required the DOE to conduct another analysis assuming nonrandom waste emplacement as part of the review of supercompacted waste from INL. The results showed that nonrandom placement of waste was not significant (e.g., CRA-2004, Appendix PA, Attachment MASS, Section MASS-21.0). Thus, no waste loading assumptions were necessary in PA calculations for CRA-2004.

Based on the EPA's review and evaluation of the CRA-2004 and supplemental information provided by the DOE, and because DOE showed that waste loading assumptions were not necessary for use in PA, the EPA determined that the DOE continues to comply with the requirements for sections 194.24(d) and (f) (U.S. Environmental Protection Agency 2006c).

24.5.10 40 CFR § 194.24(g)

The DOE has several years of experience with the WWIS and, through the EPA's inspections, the DOE has shown the WWIS to be effective in tracking and controlling waste disposed of at the WIPP. The DOE had not characterized or shipped any RH-TRU waste at the time of the CRA-2004.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continues to comply with the requirements for section 194.24(g) (U.S. Environmental Protection Agency 2006c).

24.5.11 40 CFR § 194.24(h)

The EPA found the DOE in compliance with provisions of section 194.24(h). Discussion of inspections and records, such as audits is addressed by the EPA in CARD 22 (U.S. Environmental Protection Agency 2006b).

24.6 Changes or New Information Since the 2004 Recertification

24.6.1 40 CFR § 194.24(a)

To meet the requirements of section 194.24(a) in CRA-2004, the DOE described and categorized the TRU waste currently emplaced in the WIPP at that time and the waste that existed at various DOE facilities. The details of the inventory used for CRA-2009 are presented in the CRA-2004, Chapter 4.0 and Appendix TRU WASTE, and the CRA-2004 PABC inventory (see Appendix BIR) was summarized in the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005). The combination of the inventory presented in the CRA-2004, Appendix TRU WASTE, and the CRA-2004 PABC Inventory Report is referred to as the CRA-2004 PABC Inventory Report. The inventory for the CRA-2009 PA is the same inventory used for the CRA-2004 PABC. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008a) was published and provides updated inventory information.

The DOE anticipates this inventory update will have only a small impact on normalized releases relative to the CRA-2009 PA, and will not be significant for compliance. Therefore, the DOE is in compliance with section 194.24(a).

24.6.2 40 CFR § 194.24(b)(1)

There were no changes to the waste characteristics between the CRA-2004 PABC inventory and the CRA-2009 inventory, but the DOE did add inventory parameters used in the PA. Leigh, Trone, and Fox (2005) give a comprehensive description of the projected inventory used for the CRA-2004 PABC. The CRA-2009 PA used the CRA-2004 PABC inventory with one set of modifications. The CRA-2004 PABC included CPR materials in the waste and container (packaging) materials that were also used in the CRA-2009 PA, but the CPR contents in emplacement materials were erroneously omitted from the CRA-2004 PABC (Nemer 2007). To correct this omission, six new parameters representing the density of CPR materials in emplacement materials were created and used in the CRA-2009 PA. Four additional parameters, which represent the density of cellulose and rubber materials in container (packaging) materials, were also created for the CRA-2009 PA (Nemer 2007).

Table 24-2 lists the names and descriptions of the CPR parameters used in the CRA-2009 PA, including the 10 additional parameters. The addition of the four container (packaging) CPR parameters is done solely for bookkeeping purposes, since container (packaging) materials do not contain cellulose or rubber materials, as seen by the zero values in Table 24-2. The CRA-2009 PA used all the CPR parameters shown in Table 24-2.

There were no changes between the CRA-2004 PABC and CRA-2009 PA in the methodology and data used to calculate An solubilities or their colloidal concentration in the WIPP brine. The microbial assumptions and gas generation rates associated with this also remain unchanged in the CRA-2009 PA. Therefore, the DOE is in compliance with section 194.24(b)(1).

24.6.3 40 CFR § 194.24(b)(2)

The DOE determined that the components identified below were expected to have a significant effect on disposal system performance (see the CCA, Appendix WCA), and so were used in the CRA-2004 PABC.

- Ferrous metals
- Cellulose and chelating agents (i.e., organic ligands) as they pertain to enhanced An mobility
- Radioactivity in curies of each isotope
- α-emitting TRU radionuclides, $t_{1/2} > 20$ years ($t_{1/2}$ is the half-life)
- Radionuclides
- Solid waste components (e.g., soils and cementitious materials)

Table 24-2. CPR Parameters Used in the CRA-2009 PA

Name	Description	Value (kg/m^3)
WAS_AREA: DCELLCHW	Average density of cellulosics in CH-TRU waste materials	60.0
WAS_AREA: DCELLRHW	Average density of cellulosics in RH-TRU waste materials	9.3
WAS_AREA: DCELCCHW[a]	Average density of cellulosics in CH-TRU waste container (packaging) materials	0.0
WAS_AREA: DCELCRHW[a]	Average density of cellulosics in RH-TRU waste container (packaging) materials	0.0
WAS_AREA: DCELECHW[a]	Average density of cellulosics in CH-TRU waste emplacement materials	1.22
WAS_AREA: DCELERHW[a]	Average density of cellulosics in RH-TRU waste emplacement materials	0.0
WAS_AREA: DPLASCHW	Average density of plastic in CH-TRU waste materials	43.0
WAS_AREA: DPLASRHW	Average density of plastic in RH-TRU waste materials	8.0
WAS_AREA: DPLSCCHW	Average density of plastic in CH-TRU waste container (packaging) materials	17.0
WAS_AREA: DPLSCRHW	Average density of plastic in RH-TRU waste container (packaging) materials	3.1
WAS_AREA: DPLSECHW[a]	Average density of plastic in CH-TRU waste emplacement materials	8.76
WAS_AREA: DPLSERHW[a]	Average density of plastic in RH-TRU waste emplacement materials	0.0
WAS_AREA: DRUBBCHW	Average density of rubber in CH-TRU waste materials	13.0
WAS_AREA: DRUBBRHW	Average density of rubber in RH-TRU waste materials	6.7
WAS_AREA: DRUBCCHW[a]	Average density of rubber in CH-TRU waste container (packaging) materials	0.0
WAS_AREA: DRUBCRHW[a]	Average density of rubber in RH-TRU waste container (packaging) materials	0.0
WAS_AREA: DRUBECHW[a]	Average density of rubber in CH-TRU waste emplacement materials	0.0
WAS_AREA: DRUBERHW[a]	Average density of rubber in RH-TRU waste emplacement materials	0.0

[a]Newly created for the CRA-2009 PA.

- Sulfates
- Nitrates

These components in the CRA-2009 inventory have not changed from the CRA-2004 PABC inventory that was used for the CRA-2004 recertification decision. Therefore, the DOE is in compliance with section 194.24(b)(2).

24.6.4 40 CFR § 194.24(b)(3)

The DOE provided a list of those waste characteristics and components that were excluded from consideration in the PA for various reasons, such as negligible impact (the CRA-2004, Appendix TRU WASTE, Section TRU WASTE-6.0 and in Appendix PA-2009). There were no changes in the exclusion decisions for the important waste components and characteristics in the CRA-2009 PA since the CRA-2004 recertification decision. Therefore, the DOE is in compliance with section 194.24(b)(3).

24.6.5 40 CFR §§ 194.24(c)(1), (e)(1), and (e)(2)

The inventory used for the CRA-2009 PA is the same as the CRA-2004 PABC inventory. Therefore, the waste components and their associated uncertainties for the CRA-2009 have not changed since the CRA-2004 PABC. The only change from the CRA-2004 PABC is the change of the emplaced MgO.

In April 2006, the DOE submitted a Planned Change Request for EPA approval to reduce the MgO excess factor from 1.67 to 1.2 (Moody 2006). To justify its request, the DOE used reasoned arguments regarding health-related transportation risks to the public, the cost of emplacing MgO, and the uncertainties inherent in predicting the extent of microbial consumption of CPR materials during the 10,000-yr WIPP regulatory period. The EPA responded that the "DOE needs to address the uncertainties related to MgO effectiveness, the size of the uncertainties, and the potential impact of the uncertainties on long-term performance" (Gitlin 2006).

The DOE carried out an uncertainty analysis (Vugrin, Nemer, and Wagner 2006) and several supporting analyses (Brush and Roselle 2006; Brush et al. 2006; Clayton and Nemer 2006; Deng et al. 2006; Kanney and Vugrin 2006; Kirchner and Vugrin 2006) in response to the EPA's request for additional information on the uncertainties related to MgO effectiveness. Appendix MgO-2009, Section MgO-6.2.4.4 provides a complete description of the DOE uncertainty analyses. As part of this effort, Kirchner and Vugrin (2006) quantified the uncertainties in the estimates of the CPR material quantities emplaced in WIPP disposal rooms. Their analysis was based on the differences between the masses of CPR materials measured by RTR and VE, paired by waste container. They assumed that the VE measurements were the more accurate values and, because they observed no significant bias in the RTR measurements in a room, Kirchner and Vugrin (2006) then used Monte Carlo methods "to simulate potential errors in the RTR measurements and to construct a distribution representing the uncertainty in the CPR [materials] in a room" and concluded that "the uncertainty [standard deviation] on the total mass of CPR [materials] in a room would be less than 0.3%."

Based on these results, measurement uncertainty in the mass of CPR materials is not expected to significantly impact the expected mass of CPR materials in a room and consequently to have little impact on repository performance. In addition, to date, a limited amount of waste has been emplaced relative to total capacity of the repository. It follows that the inventory and its associated uncertainty remains below the limiting value for the mass of CPR in the CRA-2009 PA, and the DOE remains in compliance with sections 194.24(c)(1), (e)(1), and (e)(2).

24.6.6 40 CFR § 194.24(c)(2)

As noted in section 194.24(b), the DOE did not modify the list of CRA-2004 components and characteristics requiring quantification. Therefore, the CRA-2009 did not identify any significant changes to the measurement techniques used in the waste characterization program (i.e., VE, RTR, AK, NDA).

Since the CRA-2004, the WIPP has received RH-TRU waste. RH-TRU waste normally contains more gamma emitting radionuclides than the CH-TRU waste (mostly ^{137}Cs), and the characterization method used to determine radionuclide activity is a Dose-to-Curie methodology as identified in *Remote-Handled TRU Waste Characterization Program Implementation Plan*, Revision 0D (U.S. Department of Energy 2003). RH-TRU waste normally contains more metal container material parameters because the preferred method for hot-cell operation is to place the waste into 30 or 55 gal drums before placement into the RH-TRU canister. The addition of RH-TRU waste does not modify the list of components and characteristics requiring quantification. Therefore, the DOE is in compliance with section 194.24(c)(2).

24.6.7 40 CFR § 194.24(c)(3)

Since CRA-2004, the AK process is now presented in the WIPP WAC, Revision 6.2 (U.S. Department of Energy 2008b) for both the CH-TRU and RH-TRU waste. The WIPP WAC has been revised to include more discussion of AK with respect to radionuclides (WAC, Appendix A). Modifications made to the WAC since the CRA-2004 that are pertinent to AK include the following:

- Use of existing AK collected prior to the implementation of a QA program under section 194.22(a) may be qualified in accordance with an alternative methodology and employs one or more of the following methods: peer review, corroborating data, confirmatory testing, and collection of data under an equivalent QA program for both the CH-TRU and RH-TRU waste.

- Methods for confirming isotopic ratios using AK (i.e., methods pertinent to sites generating weapons grade Pu vs. heat grade) for both the CH-TRU and RH-TRU waste.

- Required and supplemental AK documentation for both the CH-TRU and RH-TRU waste.

- Discrepancy resolution and data limitation identification for both the CH-TRU and RH-TRU waste.

- AK radioassay data measurement comparisons as a means to assess comparability for both the CH-TRU and RH-TRU waste.

These modifications effectively focused on the WIPP WAC to address specific allowances and requirements with respect to AK needs for radionuclide data on both the CH-TRU and RH-TRU waste. The revised WAP (New Mexico Environment Department 2008) retains AK requirements of data assembly, compilation, etc., included in the CRA-2004 and CCA. Therefore, the DOE is in compliance with section 194.24(c)(3).

24.6.8 40 CFR § 194.24(c)(4)

The WWIS used the Oracle (Version 9) database management system at the time of CRA-2004 as described in CRA-2004, Chapter 4.0, Section 4.3.2. The current computing system uses Oracle (Version 10g). The CRA-2004, Appendix TRU WASTE, Section TRU WASTE-5.0, briefly describes the WWIS as part of a system of controls that address sections 194.24(c)(4) and (c)(5), requirements for computer software for nuclear facility applications. Since the submittal of the CRA-2004, the WWIS has been updated to include data fields required for the disposal of RH-TRU waste. WWIS was also modified by the addition of data fields to meet additional tracking and control requirements imposed on RH-TRU waste by the LWA. The WWIS was also updated since the CRA-2004 to track the amount of MgO emplaced in the repository. This addition was added to ensure the excess factor of 1.2 is met throughout the repository. The WWIS User's Manual, Appendix F (U.S. Department of Energy 2008c), contains the WWIS Data Dictionary that defines each data field for CH-TRU and RH-TRU waste. Therefore, the DOE is in compliance with section 194.24(c)(4).

24.6.9 40 CFR § 194.24(c)(5)

The DOE describes the PDP program in the CRA-2004, Chapter 4.0, Section 4.3.3.1 PDP (p. 4-49). Both the *Performance Demonstration Program Plan for Nondestructive Assay of Boxed Wastes for the TRU Waste Characterization Program*, Revision 1 (U.S. Department of Energy 2008d) and *Performance Demonstration Program Plan for Nondestructive Assay of Drummed Wastes for the TRU Waste Characterization Program*, Revision 1 (U.S. Department of Energy 2005) have been revised since the CRA-2004. The most important changes to these documents were implemented to better represent current practices, simplify and clarify the scoring section, clarify the explanation of the derivation of scoring criteria, and update the two NDA PDP Plans to be consistent with one another. The *Performance Demonstration Program Plan for Analysis of Simulated Headspace Gases*, Revision 6.1 (U.S. Department of Energy 2007) has also been revised since CRA-2004. The most important changes describe the relationship between the Carlsbad Technical Assistance Contractor and the commercial suppliers of the HSG PDP services, as well as the standard gases used to prepare the HSG PDP samples. Prior to this revision, the HSG PDP sample preparation contractor was a DOE National Laboratory. Therefore, the DOE is in compliance with section 194.24(c)(5).

24.6.10 40 CFR §§ 194.24(d) and (f)

The CRA-2009 has not changed in reference to provisions in sections 194.24(d) and (f) since the CRA-2004 decision. Therefore, the DOE is in compliance with sections 194.24(d) and (f).

24.6.11 40 CFR § 194.25(g)

The CRA-2009 inventory is unchanged from the CRA-2004 PABC inventory. Since the CRA-2004, the DOE has characterized and shipped RH-TRU waste. The WWIS was also modified by the addition of data fields to meet additional tracking and control requirements imposed on RH-TRU waste by the LWA. Therefore, the DOE is in compliance with section 194.24(g).

24.6.12 40 CFR § 194.24(h)

The DOE continues to comply with the inspection and records requirements. This is discussed in Section 22 of this application. Therefore, the DOE is in compliance with section 194.24(h).

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Future States Assumptions
(40 CFR § 194.25)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Future States Assumptions
(40 CFR § 194.25)

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Acronyms and Abbreviations

CCA	Compliance Certification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEPs	feature, event, and process
PA	performance assessment
SO-C	screened out consequence
SO-R	screened out regulatory
T field	transmissivity field
UP	undisturbed performance
WIPP	Waste Isolation Pilot Plant

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25.0 Future States Assumptions (40 CFR § 194.25)

25.1 Requirements

§ 194.25 Future States Assumptions

(a) Unless otherwise specified in this part or in the disposal regulations, performance assessments and compliance assessments conducted pursuant to the provisions of this part to demonstrate compliance with § 191.13, § 191.15 and part 191, subpart C shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions.

(b) In considering future states pursuant to this section, the Department shall document in any compliance application, to the extent practicable, effects of potential future hydrogeologic, geologic and climatic conditions on the disposal system over the regulatory time frame. Such documentation shall be part of the activities undertaken pursuant to § 194.14, Content of compliance certification application; § 194.32, Scope of performance assessments; and § 194.54, Scope of compliance assessments.

(1) In considering the effects of hydrogeologic conditions on the disposal system, the Department shall document in any compliance application, to the extent practicable, the effects of potential changes to hydrogeologic conditions.

(2) In considering the effects of geologic conditions on the disposal system, the Department shall document in any compliance application, to the extent practicable, the effects of potential changes to geologic conditions, including, but not limited to: Dissolution; near surface geomorphic features and processes; and related subsidence in the geologic units of the disposal system.

(3) In considering the effects of climatic conditions on the disposal system, the Department shall document in any compliance application, to the extent practicable, the effects of potential changes to future climate cycles of increased precipitation (as compared to the present conditions).

25.2 Background

The U.S. Environmental Protection Agency's (EPA's) purpose in issuing the Compliance Criteria at 40 CFR § 194.25 (U.S. Environmental Protection Agency 1996) was to minimize the impact of inherently conjectural specifications of future states on the compliance application. The EPA has found no acceptable methodology to predict the future state of society, science, languages, or other characteristics of mankind. However, the EPA does believe that established scientific methods can make plausible predictions regarding the future state of geologic, hydrogeologic, and climactic conditions. Therefore, section 194.25 stipulates that the future state will resemble present conditions except for those relating to hydrogeologic, geologic, and climatic conditions. For example, the population density and land ownership patterns in the Waste Isolation Pilot Plant's (WIPP's) surrounding regions are assumed to remain consistent with today's conditions for the next 10,000 years. However, section 194.25 requires that performance and compliance assessments include dynamic analyses of changes in the geology, hydrology, and climatic conditions during the regulatory time frame.

25.3 1998 Certification Decision

Future state assumptions that are relevant to 40 CFR § 194.25(a) and may affect the containment of waste were identified by the U.S. Department of Energy (DOE) in the Compliance Certification Application (CCA), Chapter 6.0, Section 6.2 and Appendices SCR and MASS (U.S. Department of Energy 1996). Many of these future state assumptions were derived from the

development of features, events, and processes (FEPs) that are potentially relevant to the performance of the waste disposal system, and can be found in the CCA, Appendix SCR (e.g., solution mining and anthropogenic climate changes). FEPs are screened using specific criteria to determine what phenomena and components of the disposal system can and should be dealt with in PA calculations.

In its certification decision, the EPA first determined whether all FEPs and appropriate future state assumptions were identified and developed by the DOE. The EPA then evaluated the DOE's criteria to eliminate (screen out) inapplicable or irrelevant FEPs and associated assumptions. The EPA also analyzed whether there were potential variations in the DOE's assumed characteristics and determined whether the future state assumptions were in compliance with section 194.25(a).

The EPA's CCA review found no potentially significant omissions in the lists of FEPs, and no major inadequacies in the CCA's descriptions of FEPs and related future state assumptions. The EPA concluded that the DOE adequately described all the future state assumptions applicable under section 194.25(a) (U.S. Environmental Protection Agency 1998a).

To comply with 40 CFR §§ 194.25(b)(1), (b)(2), and (b)(3), the DOE identified and described the hydrogeologic FEPs and related future state assumptions retained for further evaluation and inclusion in performance assessment (PA) calculations in the CCA, Chapter 6.0, Section 6.3. The DOE describes the effects of potential changes to hydrogeologic conditions on the disposal system in the CCA, Chapter 6.0, Sections 6.4.6 and 6.4.9 and Appendices SCR, TFIELD, and MASS. The DOE describes the effects of potential changes to geologic conditions on the disposal system in the CCA, Chapter 6.0, Sections 6.2, 6.4.6, 6.5.4, and Appendices SCR and MASS. The DOE identifies and describes the effects of potential changes to future climate cycles of increased precipitation on the repository in the CCA, Chapter 6.0, Section 6.4.9.

The EPA concluded that the DOE adequately addressed the impacts of potential hydrogeologic, geologic, and climate changes to the disposal system (U.S. Environmental Protection Agency 1998a). The EPA further stated that the CCA included all relevant elements of the PA and compliance assessments and was consistent with the requirements of section 194.25.

25.4 Changes in the CRA-2004

For the CRA-2004, the DOE reevaluated all WIPP FEPs and made improvements and clarifications to several FEP descriptions, arguments, and screening decisions. The results of the FEPs reassessment were presented in the 2004 Compliance Recertification Application (CRA-2004), Appendix PA, Attachment SCR (U.S. Department of Energy 2004). The CRA-2004, Appendix PA, Attachment SCR, Table SCR-1 summarizes these changes.

25.5 EPA's Evaluation of Compliance for the 2004 Recertification

To evaluate compliance with section 194.25 requirements, the EPA reviewed the CRA-2004 documentation, including Chapters 2.0, 6.0, 7.0, and 9.0; Appendix PA, Attachment SCR; Attachment TFIELD; and Attachment MASS. As in the 1998 Certification Decision (U.S. Environmental Protection Agency 1998b), the EPA first determined whether all FEPs and

appropriate future state assumptions were identified and developed by the DOE. The EPA then evaluated the DOE's criteria to eliminate (screen out) inapplicable or irrelevant FEPs and associated assumptions. The EPA also analyzed whether there were potential variations in the DOE's assumed characteristics and determined whether the future state assumptions were in compliance with section 194.25(a).

25.5.1 40 CFR § 194.25(a)

The EPA verified that all appropriate FEPs were included in the list provided by the DOE for section 194.25(a). The EPA reviewed any changes in FEPs, including all screened-in and screened-out FEPs related to future states, to verify that their selections were made correctly. The EPA's FEPs review is documented in the CRA-2004 Technical Support Document for section 194.25, 40 CFR § 194.32, and 40 CFR § 194.33 (U.S. Environmental Protection Agency 2006a).

25.5.2 40 CFR § 194.25(b)(1)

The EPA reexamined any hydrogeologic conditions that may have changed since the CCA review. The EPA determined that the DOE's review of FEPs related to hydrogeologic conditions and screening arguments was complete and that the conclusions drawn were appropriate. Changes in the hydrology at and around the WIPP site, such as water level changes in monitor wells and changes in potash mining, were appropriately included in PA modeling by updated changes in the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra) transmissivity fields (T fields). See the CRA-2004 Compliance Application Review Document 25 for more information (U.S. Environmental Protection Agency 2006b).

25.5.3 40 CFR § 194.25(b)(2)

The EPA reexamined the DOE's characterization of future geologic conditions in the CRA-2004 documents (U.S. Environmental Protection Agency 2006a). The EPA reexamined issues that were reviewed during the CCA, such as tectonics and deformation assumptions; fracture development and fault movement; ground shaking and seismic assumptions; volcanic and magmatic activity; metamorphic activity; shallow, lateral, and deep dissolution assumptions; and mineralization assumptions. The EPA also reviewed the CRA-2004 screening arguments related to geological screening decisions. The EPA determined that the DOE's geologic screening arguments are reasonable and adequate.

25.5.4 40 CFR § 194.25(b)(3)

As in the CCA, the EPA's review of climatic condition changes focused on applicable FEPs. The EPA found that new information since the CCA does not impact FEPs or screening decisions related to climate change (U.S. Environmental Protection Agency 2006b).

25.5.5 The 2006 Recertification Decision

Based on a review and evaluation of the CRA-2004, Chapters 2.0, 6.0, 7.0, and 9.0; Appendix PA, Attachment SCR; Attachment TFIELD; Attachment MASS; and an assessment of changes

since 1998, the EPA determined that the DOE continued to comply with the requirements of section 194.25 (U.S. Environmental Protection Agency 2006c).

25.6 Changes or New Information Since the 2004 Recertification

25.6.1 40 CFR § 194.25(a)

The DOE has reevaluated the basis of the WIPP FEPs for the CRA-2009. The results of this reevaluation are found in Appendix SCR-2009. Conclusions drawn from Appendix SCR-2009 are also summarized in Section 32.

As described in Appendix SCR-2009, no screening decisions previously made using the future states assumption in section 194.25(a) have changed (although additional information may have been added to their descriptions); there continue to be 16 FEPs screened out based on this provision. Table 25-1 lists the 16 FEPs eliminated from PA calculations using the future states assumption.

Because there have been no changes to the conditions and bases for FEPs screened out using the future states assumption, the DOE continues to be in compliance with the requirements of section 194.25(a).

25.6.2 40 CFR § 194.25(b)

40 CFR § 194.25(b) requires consideration of future hydrogeologic, geologic, and climate conditions during the regulatory time frame. Table 25-2, below, lists those FEPs that are screened into PA calculations according to the criteria in section 194.25(b). There have been no changes to the screening decisions for those FEPs that represent the hydrogeologic, geologic, and climatic conditions in the future; they continue to be represented in performance calculations.

Section 1 of Clayton (2008) lists the changes to the PA system used for the CRA-2009 calculations. None of the changes made for the CRA-2009 performance calculations affect the implementation of the FEPs screened in according to section 194.25(b).

In summary, no changes have been made to screening decisions for those FEPs that represent the hydrologic, geologic, and climate-related conditions for the WIPP, and no changes have been made to the representation of these elements within the PA system. Therefore, the DOE remains in compliance with the requirements of sections 194.25(b)(1), (b)(2), and (b)(3).

Table 25-1. FEPs Screened Out Using the 40 CFR § 194.25(a) Criterion[a]

EPA FEP I.D.	FEP Name	Change Summary
H6	Archeological investigations	None
H7	Drilling associated with thermal energy production	None
H10	Liquid waste disposal	None
H11	Hydrocarbon storage	None
H14	Mining for other resources (not potash)	None
H15	Excavation activities associated with tunneling	None
H16	Construction of underground facilities	None
H40	Changes in land use	None
H47	Anthropogenic climate change – Greenhouse gas effects	None
H48	Anthropogenic climate change – Acid rain	None
H49	Anthropogenic climate change – Damage to the ozone layer	None
H53	Changes in agricultural practices – Arable farming	None
H54	Changes in agricultural practices – Ranching	None
H55	Changes in agricultural practices – Fish farming	None
H56	Demographic change, urban developments, and technological developments	None
H58	Solution mining – Potash	None

[a] These screening classifications are consistent with current screening arguments and classifications as presented in Appendix SCR-2009.

Table 25-2. FEPs Screened In According to 40 CFR § 194.25(b)[a]

EPA FEP I.D.	FEP Name	Issue	Screening Classification	Method of Representation In PA
N1	***Stratigraphy***	Disposition and properties of geological formations in control of system performance.	Included in the Undisturbed Performance (UP) scenario	BRAGFLO grid incorporates relevant stratigraphic units.
N2	***Brine reservoirs***	Pressurized brine reservoirs may be present in the Castile beneath the controlled area.	Included in the Disturbed Performance scenarios	The potential for brine pocket intrusion is represented by the parameter PBRINE in the E1 scenario.
N16	***Shallow Dissolution***	Percolation of groundwater and dissolution in the Rustler may increase transmissivity.	UP	The effects of shallow dissolution, as in Nash Draw, on the transmissivity of the Culebra are represented in the Culebra T-field generation and calibration process.

[a] There have been no technical changes to this information since the CRA-2004, other than the correction of errors.

Table 25-2. FEPs Screened In According to 40 CFR § 194.25(b)[a] (Continued)

EPA FEP I.D.	FEP Name	Issue	Screening Classification	Method of Representation In PA
N23	***Saturated Groundwater Flow***	Groundwater flow beneath the water table is important to disposal system performance.	UP	Groundwater flow is represented by the Culebra T fields.
N24	***Unsaturated Groundwater Flow***	The presence of air or other gas phases may influence groundwater flow.	UP	Unsaturated flow is a precursor to recharge to the Culebra, which is accounted for in the boundary conditions for the Culebra T fields.
N25	***Fracture Flow***	Groundwater may flow along fractures as well as through interconnected pore space.	UP	Fracture flow is represented by the dual-porosity Culebra transport model.
N27	***Effects of Preferential Pathways***	Groundwater flow may not be uniform, and may occur along particular pathways.	UP	Preferential pathways are accounted for in the calibration of Culebra T fields to transient hydraulic test responses.
N33	***Groundwater Geochemistry***	Groundwater geochemistry influences actinide retardation and colloid stability.	UP	Salado and Castile brine geochemistry are accounted for in actinide solubility values. Culebra brine geochemistry is accounted for in the retardation factors used in PA calculations of actinide transport.
N39	***Physiography***	The physiography of the area is a control on the surface water hydrology.	UP	Relevant aspects of the physiography are incorporated in the Culebra T fields.
N53	***Groundwater Discharge***	The amount of water leaving the groundwater system to rivers, springs, and seeps affects the groundwater hydrology.	UP	Groundwater discharge is accounted for in the boundary conditions for the Culebra T fields.
N54	***Groundwater Recharge***	The amount of water passing into the saturated zone affects the groundwater hydrology.	UP	Groundwater recharge is accounted for in the boundary conditions for the Culebra T fields.
N55	***Infiltration***	The amount of water entering the unsaturated zone controls groundwater recharge.	UP	Infiltration is accounted for in the boundary conditions for the Culebra T fields.

[a] There have been no technical changes to this information since the CRA-2004, other than the correction of errors.

Table 25-2. FEPs Screened In According to 40 CFR § 194.25(b)[a] (Continued)

EPA FEP I.D.	FEP Name	Issue	Screening Classification	Method of Representation In PA
N56	***Changes in Groundwater Recharge and Discharge***	Changes in climate and drainage pattern may affect the amount of water entering and leaving the groundwater system.	UP	Changes in groundwater recharge and discharge are accounted for in the Climate Index factor.
N59	***Precipitation (e.g., Rainfall)***	Rainfall is the source of water for infiltration and stream flow.	UP	Future variations in precipitation are accounted for in the Climate Index factor.
N60	***Temperature***	The temperature influences how much precipitation evaporates before it reaches streams or enters the ground.	UP	Future variations in temperature are accounted for in the Climate Index factor.
N61	***Climate Change***	Temperature and precipitation will vary as natural changes in the climate take place.	UP	Future climate change is accounted for in the Climate Index factor.

[a] There have been no technical changes to this information since the CRA-2004, other than the correction of errors.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Peer Review
(40 CFR § 194.27)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Peer Review
(40 CFR § 194.27)

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Acronyms and Abbreviations

CAO	Carlsbad Area Office
CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
CMR	Chemistry and Metallurgical Research
CPR	cellulose, plastic, and rubber
CRA	Compliance Recertification Application
CTAC	CBFO Technical Assistance Contractor
DOE	U.S. Department of Energy
DRZ	Disturbed Rock Zone
EEG	Environmental Evaluation Group
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
LANL	Los Alamos National Laboratory
MP	Management Procedure
NAS	National Academy of Sciences
NEA/OECD	Nuclear Energy Agency/Organization for Economic Cooperation and Development
OSR	Off-Site Source Recovery
QA	quality assurance
QAPD	Quality Assurance Program Document
RH-TRU	remote-handled transuranic
RSI	Institute for Regulatory Science
SNL	Sandia National Laboratories
TRU	transuranic
VE	visual examination
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

Elements and Chemical Compounds

Am	americium
CO_2	carbon dioxide
MgO	magnesium oxide
Pu	plutonium

27.0 Peer Review (40 CFR § 194.27)

27.1 Requirements

§ 194.27 Peer Review

(a) Any compliance application shall include documentation of peer review that has been conducted, in a manner required by this section, for:

(1) Conceptual models selected and developed by the Department;

(2) Waste characterization analyses as required in § 194.24(b); and

(3) Engineered barrier evaluation as required in § 194.44.

(b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG–1297, ''Peer Review for High-Level Nuclear Waste Repositories,'' published February 1988. (Incorporation by reference as specified in § 194.5.)

(c) Any compliance application shall:

(1) Include information that demonstrates that peer review processes required in paragraph (a) of this section, and conducted prior to the implementation of the promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG–1297 and approved by the Administrator or the Administrator's authorized representative; and

(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals.

27.2 Background

According to 40 CFR § 194.27 (U.S. Environmental Protection Agency 1996), the U.S. Department of Energy (DOE) is required to conduct peer review evaluations related to conceptual models, waste characterization analyses, and a comparative study of engineered barriers. A peer review involves an independent group of experts who perform an in-depth critique of assumptions, calculations, extrapolations, alternative interpretations, methodology and acceptance criteria employed, and conclusions drawn in the original work. Peer review confirms the adequacy of the work (U.S. Nuclear Regulatory Commission 1988). The required peer reviews must be performed in accordance with NUREG-1297, *Peer Review for High-Level Nuclear Waste Repositories* (U.S. Nuclear Regulatory Commission 1988), which establishes guidelines for the conduct of a peer review exercise. 40 CFR § 194.27(c)(2) also requires the DOE to document in the compliance application any additional peer reviews beyond those explicitly required. These additional peer reviews will be identified in this section as informal peer reviews.

For the formal peer reviews performed before submitting the Compliance Certification Application (CCA) (U.S. Department of Energy 1996a), the DOE developed Carlsbad Area Office (CAO) Team Procedure 10.5, *Peer Review* (U.S. Department of Energy 1996b) to guide all Waste Isolation Pilot Plant (WIPP) peer reviews and to show a process compatible with section 194.27 and NUREG-1297 requirements. For the Compliance Recertification Assessment (CRA) of 2004 (CRA-2004) (U.S. Department of Energy 2004a), the DOE updated this procedure to Carlsbad Field Office (CBFO) Management Procedure (MP) 10.5, *Peer Review* (U.S. Department of Energy 2002). MP 10.5 has been revised several times since 2002, and the

latest version (Rev. 7, 7/25/07) provides the criteria for selecting the peer review panel, peer review process used, review plan development requirements, peer review report preparation requirements, and many other aspects of the peer review process.

27.3 1998 Certification Decision

For the CCA, the DOE completed the required peer reviews and documented them in the CCA, Chapter 9.0 and Appendix PEER. The CCA, Chapter 9.0 and Appendix PEER, also contains documentation demonstrating that the DOE's procedures and plans for the required peer reviews are compatible with NUREG-1297. Peer reviews conducted after promulgation of 40 CFR Part 194 and intended to demonstrate compliance with section 194.27 were subject to the requirements of the pertinent procedures and plans. To assess the peer review process during the CCA, the EPA conducted an audit of the DOE's quality assurance (QA) records for peer review (U.S. Environmental Protection Agency 1997). The audit consisted of an extensive review of the DOE's records and interviews of DOE staff and contractors responsible for managing the required peer reviews.

The U.S. Environmental Protection Agency's (EPA's) certification decision was published in U.S. Environmental Protection Agency (1998a). The EPA found the DOE in compliance with the requirements of section 194.27. The EPA's independent audit established that the DOE had conducted and documented the required peer reviews in a manner compatible with NUREG-1297. The EPA also determined that the DOE adequately documented additional peer reviews in the CCA (see Compliance Application Review Document [CARD] 27, U.S. Environmental Protection Agency 1998b).

27.4 Changes in the CRA-2004

The DOE performed two conceptual model peer reviews between the CCA and the CRA-2004. These include the Salado Flow Conceptual Model Peer Review in March 2003 (see CRA-2004, Chapter 9.0, Section 9.3.1.3.4) and the Spallings Model Peer Review in September 2003 (see CRA-2004, Chapter 9.0, Section 9.3.1.3.5).

External informal peer reviews that fall under section 194.27(c)(2) requirements were also performed during this period. Reviews conducted by the National Academy of Sciences (NAS), the International Atomic Energy Agency (IAEA), Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA/OECD), Institute for Regulatory Science (RSI), and the Environmental Evaluation Group (EEG) are described in the CRA-2004, Chapter 9.0, and the reports are included in the CRA-2004, Appendix PEER-2004.

27.5 EPA's Evaluation of Compliance for the 2004 Recertification

The following is the EPA's evaluation of the DOE's compliance with Section 194.27 (the CRA-2004, Chapter 9.0 and Appendix PEER-2004) as contained in the EPA's Recertification Decision (U.S. Environmental Protection Agency, 2006a) and the accompanying CARD 27 (U.S. Environmental Protection Agency, 2006b).

The EPA reviewed the new DOE MP 10.5, Rev. 5 (U.S. Department of Energy 2003a) and determined that it was adequately comparable with section 194.27 requirements and NUREG-1297 guidance. The DOE followed the MP 10.5, Rev. 5, for the Salado Flow Conceptual Model Peer Review (U.S. Department of Energy 2003b) and the Spallings Model Peer Review (U.S. Department of Energy 2003c). The EPA attended and reviewed each of the conceptual model peer reviews as they were performed and reviewed all documents related to each peer review. The EPA's review verified that the process used by the DOE to perform these peer reviews was compatible with NUREG-1297 requirements. The EPA completed its Salado Flow Conceptual Model Peer Review Report in June 2003 (U.S. Environmental Protection Agency 2003a), and the Spallings Model Peer Review in December 2003 (U.S. Environmental Protection Agency 2003b).

The Salado Flow Conceptual Model Peer Review was performed from April 2002 to March 2003. The final report was published in March 2003 (U.S. Department of Energy 2003d). This peer review evaluated changes to 3 of 24 conceptual models: Disposal System Geometry, Repository Fluid Flow, and Disturbed Rock Zone (DRZ). The three conceptual models were changed because of new information gained after the original certification or changes to conceptual model assumptions mandated by the EPA in the final CCA decision, such as the Option D panel closure condition. Changes included modification of the computational grid to accommodate the new panel closure requirement, shaft simplification, changes in fluid flow paths, and changing from a constant DRZ porosity to a range of values for the halite and anhydrite layers (U.S. Department of Energy 2003d). The peer review panel accepted the proposed changes. The EPA reviewed the peer review plan (U.S. Department of Energy 2003b) and the final peer review report (U.S. Department of Energy 2003d) for the Salado Flow Conceptual Model Peer Review. The EPA also observed the actual performance of the peer review, evaluated the process for the selection of the review panel, observed the interaction of the review panel with the DOE and Sandia National Laboratories (SNL), and reviewed the documents produced during and as a result of the peer review. The EPA determined that the peer review process and the implementation of MP 10.5 met the requirements of section 194.27 and the guidance in NUREG-1297 (U.S. Environmental Protection Agency 2003a).

The Spallings Model Peer Review was performed from July 2003 to October 2003. The final report was published in October 2003 (U.S. Department of Energy 2003e). This model was changed because the original conceptual peer review found the CCA's spallings model to be inadequate (although the spallings volumes used in the CCA were found to be reasonable) and the EPA expected the DOE to develop a new spallings model before the first recertification in 2004. The new spallings model includes three major elements: consideration of multiphase flow processes in the intrusion borehole, consideration of fluidization and transport of waste particulates from the intact waste mass to the borehole, and a numerical solution for the coupled mechanical and hydrological response of the waste as a porous medium (U.S. Department of Energy 2003e and 2004b). The DOE developed a new numerical code to implement the new spallings conceptual model, which was written to calculate the volume of WIPP solid waste that may undergo material failure and be transported to the surface as a result of a drilling intrusion. The peer review panel accepted the proposed changes. The EPA reviewed the peer review plan (U.S. Department of Energy 2003c) and the final peer review report (U.S. Department of Energy 2003e) and found them to adequately fulfill the requirements of section 194.27 and NUREG-1297. The EPA observed the actual performance of the peer review, evaluated the process for

the selection of the panel, observed the interaction of the panel with the DOE and SNL, and reviewed the documents produced during and as a result of the peer review. The EPA determined the peer review process and the implementation of MP 10.5 met the requirements of section 194.27 and the guidance in NUREG-1297 (U.S. Environmental Protection Agency 2003b).

The EPA conducted desktop evaluations of other reviews done since the CCA for compliance with section 194.27(c)(2). These include those done by the NAS, IAEA, NEA/OECD, RSI, and EEG from October 1996 to September 2003. The EPA found these reviews to be useful, reasonable, and helpful to the WIPP project, and determined that they reasonably fulfilled the requirements of section 194.27(c)(2).

The EPA did not receive any public comments on the DOE's continued compliance with the peer review requirements of section 194.27. Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE (U.S. Department of Energy 2004a, Chapter 9.0 and Appendix PEER-2004), the EPA (2006a and 2006b) determined that the DOE continued to comply with the requirements for section 194.27.

27.6 Changes or New Information since the 2004 Recertification

27.6.1 LANL Sealed Sources Peer Review

A peer review on "sealed sources" was conducted for the Off-Site Source Recovery (OSR) Project at Los Alamos National Laboratory (LANL) in December 2003 (Los Alamos National Laboratory 2003).

Actinide-containing sealed sources (those containing plutonium-238 [^{238}Pu], plutonium-239 [^{239}Pu], and americium-241 [^{241}Am]) were generated over the past 60 years. Due to radiological risks posed by these materials, the OSR Project at LANL was responsible for gathering these sources for proper control and disposal. To support disposal of these sources at the WIPP, the OSR proposed using existing data from original production, transportation, or source control documents as the basis for determining radiological information required by the EPA.

This peer review panel was convened to review the adequacy of the available data to reasonably determine the radionuclide content for compliance with the WIPP Contact-Handled Transuranic (TRU) Waste Acceptance Criteria (WAC). These records include original manufacturing records; shipping data sheets; source control information, such as the Nuclear Materials Management and Safeguards System; and other corroborating sources of information, such as sealed source engraved markings. Nuclear Regulatory Commission/Agreement State regulatory approval data and U.S. Department of Transportation records were collected to support the assignment of radiological properties.

The Peer Review Panel concluded the following (Los Alamos National Laboratory 2003):

> The historical documents gathered by the OSR Project were originally prepared in a controlled manner. Strict adherence to procedures under the oversight of quality assurance programs assured that these sources and their associated production documents were prepared with a high degree of care and certainty. The nature of the source production work itself and the historically successful

performance of these sources for their intended purposes support this observation. In addition, the feed material batches to produce these sources were generated with close tolerances. These narrow tolerances were necessary to satisfy Material Type (MT) requirements in the production of defense materials, as well as the manufacture of sources to defined specifications.

The Peer Review Panel concluded that the various data records collected provide either uniquely, or as the sum of several individual records, adequate documentation for determining the radionuclide type, radionuclide content/activity, and either the date of manufacture or some other more conservative date for the purpose of decay correction. The Peer Review Panel concluded that these data were adequate for assigning, with a high degree of certainty, the radiological information required for the disposal of this material at the WIPP.

The EPA did not observe or audit this peer review.

27.6.2 LANL Remote-Handled TRU Waste Visual Examination Data Verification Peer Review

A peer review on *Los Alamos National Laboratory Remote-Handled Waste Visual Examination Data Verification* was performed in April 2007. Details of this peer review are contained in Time Solutions Corporation (2007a).

This peer review was an in-depth analysis and evaluation of visual examination (VE) data that were originally created by technicians at LANL for remote-handled- (RH-) transuranic (TRU) (RH-TRU) waste. The RH-TRU waste was derived from cleanup and decommissioning of hot cells located in Wing 9 of the Chemistry and Metallurgical Research (CMR) building at LANL during 1986-1992. During the cleanup process, LANL technicians recorded in CMR Laboratory Notebook #23744 descriptions of activities conducted and waste materials packaged. Data contained in that notebook were later used to assist in documenting the containerized waste so that it could be transported and stored at an on-site facility. The RH-TRU waste generated at Wing 9 of the CMR is intended for disposal at the WIPP. The data used by LANL for onsite transportation and storage were not created under the requirements of the current WIPP Quality Assurance Program Document (QAPD). Peer reviews are specifically recognized as a means for qualifying data not generated under a WIPP-approved QA program. The purpose of this peer review was to arrive at an expert opinion on whether the data are technically sufficient to determine if current data quality objectives and quality assurance objectives can be met.

For this peer review, a Peer Review Plan was developed that met the requirements of DOE MP 10.5, Rev. 6 (U.S. Department of Energy 2005). A three-member Peer Review Panel of independent, technically qualified experts was assembled to determine whether or not the VE data were technically robust enough for decisions concerning the residual liquid content and physical form of the waste. It was the unanimous opinion of the panel that the VE data may be used for those purposes.

While a number of criteria must be met to assure waste acceptance at the WIPP, this peer review was concerned with only two: (1) the volume of residual liquid content and (2) classifying the physical form of the waste. The scope of the peer review was to evaluate whether the technical information contained in the original data records prepared by LANL technicians is adequate for evaluating the residual liquid content in the waste and for classifying the waste as either (1)

homogeneous solids, (2) soils/gravel, or (3) debris. The scope did not include determining the residual liquid content of the waste or placing the waste into the correct physical form category, nor did it include determining if other (or all) WAC have been met.

The peer review was held in Albuquerque, NM, April 9–12, 2007. Organizations represented at the meeting included the DOE-CBFO, the EPA, Washington TRU Solutions, and the CBFO Technical Assistance Contractor (CTAC). The peer review process and documents created during the peer review are subject to all of the protocols described in the QAPD and MP 10.5. The DOE-CBFO Office of Quality Assurance, with support from CTAC, conducted the audit of the peer review process and found that it was satisfactorily performed and documented (see Appendix AUD-2009, Table AUD-3, Audit # A-07-23).

As a result of a peer review conducted according to the procedures contained in MP 10.5 and subject to the assumptions and limitations contained in Sections 6.1 and 6.2 of the peer review report, the Peer Review Panel concluded without dissent that with respect to the LANL RH-TRU Waste VE data:

- The data are sufficient for decision-making with respect to the volume of residual liquid contained in the RH-TRU waste.
- The data are sufficient for decision-making with respect to classifying the physical form of the RH-TRU waste.
- The data are complete with respect to the RH-TRU waste generated during hot cell cleaning and decommissioning at Wing 9 of the CMR at LANL.

The EPA examined the Panel's report in the context of its technical scope and results to understand the process followed and its relevance to the EPA's baseline inspection of the RH-TRU waste characterization program conducted at LANL on May 8 – 10, 2007. The EPA concluded that the results of the peer review were reasonable (U.S. Environmental Protection Agency 2008, p. 44).

27.6.3 WIPP Revised DRZ and Cuttings and Cavings Submodels Peer Review

In 2007, the DOE proposed modifications that would affect 2 of the 24 conceptual models in the Performance Assessment Baseline Calculation, the EPA's current performance assessment baseline from the CRA-2004. It was determined that since these proposed modifications would impact the conceptual models, an independent technical peer review on the adequacy of the proposed changes to the approved conceptual models should be performed in accordance with the requirements of section 194.27. Before the peer review was completed, the DOE decided in October 2007 to postpone considering the proposed modifications. The peer review panel prepared a report (Time Solutions Corporation 2007b) to document their interim findings.

27.6.4 The RSI Expert Review of the DOE's Use of MgO

In 2005 and 2006, the RSI of Alexandria, VA, reviewed the DOE's use of magnesium oxide (MgO) in the WIPP disposal rooms, paying particular attention to the need to emplace additional

MgO in rooms with super-compacted waste. This review was conducted at the request of the DOE and the results were submitted to the EPA in 2006 in support of the DOE's Planned Change Request for reducing the MgO excess factor from 1.67 to 1.2. The RSI expert panel met for two days in July 2005 in Carlsbad, NM, where the DOE scientists presented the technical justification for reducing the MgO excess factor. The RSI expert panel met again for two days in September 2005 in Albuquerque, NM, where the DOE scientists responded to several issues raised by the panel. The panel's findings were published in Institute for Regulatory Science (2006).

In its deliberations, the panel assessed the biodegradation potential of the WIPP waste, particularly the cellulosics, plastics, and rubbers (CPRs) in the waste under the projected physical and chemical conditions of the WIPP repository for the 10,000-year regulatory period. It also examined the role of MgO in consuming the carbon dioxide (CO_2) expected to be produced as a result of biodegradation. The panel concluded that most of the MgO will be available for chemical reaction; only a small fraction of the CPR material is likely to be biodegraded to produce CO_2, and it is therefore likely that the EPA release standards would be met even if there is less MgO than the quantity required to consume all the CO_2 produced. Therefore, the panel concluded that the 67% MgO excess factor is not necessary.

The EPA considered this review when evaluating the DOE request to reduce the quantity of MgO required to be emplaced in the WIPP repository. More details on this expert review can be found in Appendix MgO-2009 (Section MgO-6.2.4.1) (Reyes 2008).

The WIPP remains in compliance with the requirements of section 194.27.

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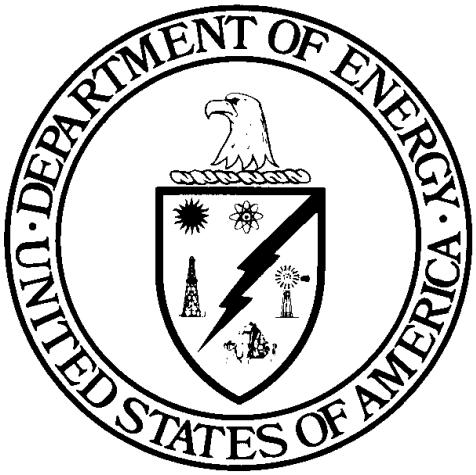
Application of Release Limits
(40 CFR § 194.31)



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Application of Release Limits
(40 CFR § 194.31)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
Ci	curies
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
m^3	cubic meters
MCi	million-curie
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
RH-TRU	remote-handled transuranic
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WUF	waste unit factor

Elements and Chemical Compounds

Am	americium
Cs	cesium
Pu	plutonium
Sr	strontium
Y	yttrium
^{137m}Ba	metastable barium-137

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31.0 Application of Release Limits (40 CFR § 194.31)

31.1 Requirements

> § 194.31 Application of Release Limits
>
> The release limits shall be calculated according to part 191, appendix A of this chapter, using the total activity, in curies that will exist in the disposal system at the time of disposal.

31.2 Background

The radioactive waste disposal regulations at 40 CFR Part 191 (U.S. Environmental Protection Agency 1993) include requirements for the containment of radionuclides. The containment requirements specify that releases from a disposal system to the accessible environment must not exceed the release limits set forth in Part 191, Appendix A, Table 1. To calculate the applicable release limits for the Waste Isolation Pilot Plant (WIPP), information is needed on the expected total curie content in the repository. However, because the inventory estimates are updated as part of the recertification effort, and because the curie content of the waste inventory in the repository will change over time as a result of natural decay and in-growth of radionuclides, the U.S. Department of Energy (DOE) must establish an inventory for use in performance assessment (PA) and must determine a date for decay purposes to be used as a reference point for calculating the curie content of waste. 40 CFR § 194.31 (U.S. Environmental Protection Agency 1996) specifies that release limits should be calculated based on the curie content at the time of disposal (that is, after the end of the operational period, when the shafts of the repository have been backfilled and sealed). This approach was used by DOE in all previous compliance applications and is also being used for the 2009 Compliance Recertification Application (CRA-2009). The inventory for the CRA-2009 PA is the same inventory used for the CRA-2004 PABC. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008) was published and provides updated inventory information. The DOE anticipates this inventory update will have only a small impact on normalized releases relative to the CRA-2009 PA, and will not be significant for compliance. Therefore, the DOE is in compliance with section 194.24(a) (U.S. Environmental Protection Agency 1994).

31.3 1998 Certification Decision

The U.S. Environmental Protection Agency (EPA) stated in Compliance Application Review Document (CARD) 31 (U.S. Environmental Protection Agency 1998) that they expected the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) to estimate curies of each radionuclide in the disposal system at the time of disposal, and provide sample calculations of release limits, including the relative contribution of each radionuclide to the normalized releases. The EPA later determined as part of their compliance determination that the CCA PA and the EPA-mandated Performance Assessment Verification Test (PAVT) were calculated using release limits developed in accordance with Part 1, Appendix A.

A complete description of EPA's 1998 Certification Decision for compliance with section 194.31 can be obtained from CARD 31 (U.S. Environmental Protection Agency 1998).

31.4 Changes in the CRA-2004

In the CRA-2004, the DOE used updated versions of the same computer codes as those used in the CCA and CCA PAVT to decay the radionuclide inventory and calculate EPA units per cubic meter of waste (Fox 2003). The only change of note was the CRA-2004 inventory, which is discussed in the CRA-2004, Appendix DATA, Attachment F, the CRA-2004, Appendix TRU WASTE, and in CARD 24 (U.S. Environmental Protection Agency 2006a).

Since the radioactivity in each waste stream is not measured at the same time, the waste stream activities were decay-corrected to December 31, 2001, using the computer code ORIGEN2 Version 2.2 (Oak Ridge National Laboratory 2002). The total radioactivity in the repository is based on contact-handled (CH) transuranic (TRU) (CH-TRU) waste volumes of each radionuclide and then scaled to WIPP's maximum allowable CH-TRU volume (168,485 cubic meters (m^3)). The scaling factor for each type of waste is calculated by subtracting the stored and emplaced waste volumes from the disposal limit value (for disposal volumes of CH-TRU waste [168,485 m^3] and remote-handled (RH) transuranic (TRU) (RH-TRU) waste [7,079 m^3]) and dividing this value by the projected waste volume.

The total radioactivity associated with CH-TRU and RH-TRU wastes from the CCA PAVT, CRA-2004, and CRA-2004 PABC are shown in Table 31-1. These RH-TRU waste values are substantially lower than the RH-TRU waste limit of 5.1 million-curie (MCi) specified in the WIPP Land Withdrawal Act (PL102-579).

Table 31-2 shows that the 5 radionuclides with the highest activity in the waste—Americium (Am)-241, Plutonium (Pu)-238, ^{239}Pu, ^{240}Pu, and ^{241}Pu—contribute 97% of the total CH-TRU waste activity in the CRA-2004 PABC, 97% in the CRA-2004, and 99% in the CCA PAVT.

Similar information on the five radionuclides with the highest activity in the RH-TRU waste is presented in Table 31-3.

For use in the PA, these inventories are decayed using the computer code to the year 2033, the assumed closure date for the WIPP, and to various dates up to 10,000 years after closure to obtain the radioactivity profiles as a function of time (e.g., see the CRA-2004, Appendix PA, Attachment PAR, Table PAR-50).

Table 31-1. Total Radioactivity Associated with CH-TRU and RH-TRU Wastes

Analysis	CH-TRU Waste Total Activity (Ci)	RH-TRU Waste Total Activity (Ci)
CCA PAVT[a,c]	6.4×10^6	1.0×10^6
CRA-2004[b,c]	5.3×10^6	1.3×10^6
CRA-2004 PABC[b,d]	4.7×10^6	1.6×10^6

[a] Decayed through 1995
[b] Decayed through 2001
[c] Values from the CRA-2004, Appendix DATA, Attachment F, Annex B, Table DATA-F-B-27
[d] Values from Transuranic Waste Baseline Inventory Report 2004, Table B.1-27 (U.S. Department of Energy 2006).

Table 31-2. Radionuclides with Highest Activity in the CH-TRU Waste Inventory

Radionuclide	Radioactivity in CCA PAVT[a,c] (Ci)	Radioactivity in CRA-2004[b,c] (Ci)	Radioactivity in CRA-2004 PABC[b,d] (Ci)
^{241}Am	4.4×10^5	4.0×10^5	4.8×10^5
^{238}Pu	2.6×10^6	1.6×10^6	1.5×10^6
^{239}Pu	7.9×10^5	6.6×10^5	5.8×10^5
^{240}Pu	2.1×10^5	(1.1×10^5)[e]	9.4×10^4
^{241}Pu	2.3×10^6	(2.4×10^6)[f]	2.0×10^6
Fraction of Total Inventory	99%	97%	97%

[a] Decayed through 1995
[b] Decayed through 2001
[c] Values directly from the CRA-2004, Appendix DATA, Attachment F, Annex B, Table DATA-F-B-27
[d] Values directly from Transuranic Waste Baseline Inventory Report 2004, Table B.1-27 (U.S. Department of Energy 2006).
[e] Value incorrectly reported in CARD 31 as 2.40×10^6 (U.S. Environmental Protection Agency 2006b).
[f] Value incorrectly reported in CARD 31 as 5.18×10^6 (U.S. Environmental Protection Agency 2006b).

Table 31-3. Radionuclides with Highest Activity in the RH-TRU Waste Inventory

Radionuclide	Radioactivity in CCA PAVT[a,c] (Ci)	Radioactivity in CRA-2004[b,c] (Ci)	Radioactivity in CRA-2004 PABC[b,d] (Ci)
^{137m}Ba	2.0×10^5	3.4×10^5	3.9×10^5
^{137}Cs	2.2×10^5	3.7×10^5	4.3×10^5
^{241}Pu	1.4×10^5	1.1×10^5	1.3×10^5
^{90}Sr	2.1×10^5	2.5×10^5	3.2×10^5
^{90}Y	2.1×10^5	2.4×10^5	3.2×10^5
Fraction of Total Inventory	96%	98%	98%

[a] Decayed through 1995
[b] Decayed through 2001
[c] Values directly from the CRA-2004, Appendix DATA, Attachment F, Annex B, Table DATA-F-B-28
[d] Values directly from Transuranic Waste Baseline Inventory Report 2004, Table B.1-28 (U.S. Department of Energy 2006).

According to Part 1, Appendix A, Table 1 (Note 1e), release limits for the radionuclides specified in the rule are based on "an amount of TRU waste containing one million curies of alpha-emitting TRU radionuclides with half-lives greater than 20 years." To obtain release limits for use in the PA, the release limits per MCi specified in Part 191, Appendix A, Table 1 must be multiplied by a factor that defines the number of MCi of TRU radionuclides in the inventory. For PA purposes, this factor, defined as the WUF or unit of waste, is expressed as

$$f_w = \frac{\sum W_f}{10^6 Ci} \qquad \text{(Eq. 31.1)}$$

where f_w is the WUF and W_f is the WIPP-scale inventory in curies of each alpha-emitting TRU radionuclide with a half-life of 20 years or more. The DOE identified a total of 138 radionuclides expected to be present in the waste based on the CRA-2004 PABC inventory. Of these, 17 meet the definition of TRU waste in Part 191, Appendix A, Table 1 for calculating the WUF. Table 2 of Leigh and Trone (2005) identify these nuclides and determine that they contribute 2.32×10^6 Ci at closure, resulting in a WUF of 2.32 in the CRA-2004 PABC. CRA-2004, Appendix TRU WASTE, and the CRA-2004 PABC Inventory Report (Leigh, Trone, and Fox 2005) discuss in detail the waste unit factor (WUF) calculations and the radionuclides important to the calculations.

31.5 EPA's Evaluation of Compliance for the 2004 Recertification

The CRA-2004 PABC Inventory Report (U.S. Department of Energy 2006) was completed following the submittal of the CRA-2004 and was used in the CRA-2004 PABC calculations. Though this inventory was issued following the CRA-2004, it was included in the EPA's evaluation of the CRA-2004. The EPA reviewed the information collected by the DOE related to the waste inventory for the CRA-2004 PA and the CRA-2004 PABC, and conducted verification calculations on the data used by the DOE in the CRA-2004 PA (CARD 24, U.S. Environmental Protection Agency 2006a, and U.S. Environmental Protection Agency 2006c, Sections 3.4 and 4.4). The methodologies for calculating the WUF and release limits in the CRA-2004 PABC were unchanged from those used in the CCA and the CRA-2004, and the EPA determined that the approach used was appropriate and acceptable for the CRA-2004 PA (U.S. Environmental Protection Agency 2006d).

To verify whether the ORIGEN2 Version 2.2 decay calculations were performed correctly, the EPA carried out independent calculations of the decay of the inventory. These calculations showed that, on a spot-check basis, the ORIGEN2 values derived by the DOE and used in EPAUNI[1] (Sandia National Laboratories 2003) were correct (CARD 31, U.S. Environmental Protection Agency 2006b). During the CRA-2004 review, the EPA reviewed the codes and determined that they adequately performed the decay calculations. The EPA determined that the approach used by the DOE was appropriate and acceptable for the CRA-2004 PA (U.S. Environmental Protection Agency 2006a).

[1] EPAUNI is a computer code that calculates the activity per m^3 for each waste stream at a discrete set of times.

31.6 Changes or New Information since the 2004 Recertification

The CRA-2009 PA maintains the same inventory and WUF values that were used in the CRA-2004 PABC (Leigh, Trone, and Fox 2005) and previously accepted by the EPA. The CRA-2004 PABC inventory was the last published inventory at the time the PA calculation for the CRA-2009 commenced. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008) was published and provides updated inventory information. The DOE anticipates this inventory update will have only a small impact on normalized releases relative to the CRA-2009 PA, and will not be significant for compliance. The DOE's approach to demonstrating compliance with the application of release limits has not changed from that used in the CRA-2004 and CRA-2004 PABC, and therefore continues to comply with section 194.31.

31.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Scope of Performance Assessments
(40 CFR § 194.32)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Scope of Performance Assessments
(40 CFR § 194.32)

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Acronyms and Abbreviations

CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
DP	disturbed performance
EPA	U.S. Environmental Protection Agency
EP	event and process
FEP	feature, event, and process
HCN	Historic, Current, and Near-Future
mi	mile
PA	Performance Assessment
QA	quality assurance
SKI	Statens Kärnkraftinspektion (Swedish Nuclear Inspectorate)
SO-C	screened out-consequence
SO-P	screened out-probability
SO-R	screened out-regulation
UP	undisturbed performance
WIPP	Waste Isolation Pilot Plant

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32.0 Scope of Performance Assessments

32.1 Requirements

§ 194.32 Scope of Performance Assessment

(a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

(b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

(c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

(d) Performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years.

(e) Any compliance application(s) shall include information which:

(1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;

(2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and

(3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

32.2 Background

Performance Assessment (PA) is a process that assesses the likelihood that the Waste Isolation Pilot Plant (WIPP) will meet the release limits specified by 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993) for 10,000 years after disposal. The PA process must consider both natural and man-made processes and events that have an effect on this disposal system.

40 CFR § 194.32 (U.S. Environmental Protection Agency 1996) requires that PAs include the effects of excavation mining, drilling, fluid injection, and future development of leases. In addition, PA must also include the effects of current activities such as secondary oil recovery methods (waterflooding), disposal of natural brine, and solution mining to extract brine in the vicinity of the repository. Section 194.32 requires identification of all features, events, and processes (FEPs), or sequences or combinations of processes and events, that could occur during the regulatory time frame that may affect the repository.

Therefore, the PA methodology for the WIPP includes compiling and screening a comprehensive list of FEPs relevant to disposal system performance. Those FEPs with the potential to affect performance are represented in scenarios and quantitative calculations using a system of linked

computer models. These models describe the interaction of the repository with the natural system, both with and without human intrusion. For the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the U.S. Department of Energy (DOE) compiled a comprehensive list of FEPs, which was subjected to a screening process leading to the set of relevant FEPs used in PA to demonstrate the WIPP's compliance with the long-term disposal standards.

The screening criteria shown below were used to determine whether to include FEPs in conceptual models and performance scenarios:

- Screened Out-Regulation (SO-R): For example, future human-initiated events and processes (EPs) may be excluded from consideration for regulatory reasons (e.g., deliberate drilling intrusions). 40 CFR § 194.25(a) requires that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic, or climatic conditions.

- Screened Out-Probability (SO-P): 40 CFR § 194.32(d) states that PA need not consider processes and events that have less than 1 in 10,000 chance of occurring over 10,000 years.

- Screened Out-Consequence (SO-C): The DOE eliminated some FEPs based on their consequences according to the following two criteria:

  – Insignificant Consequences. The DOE eliminated FEPs where there was a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions. These FEPs are designated SO-C.

  – Beneficial FEPs. FEPs that are potentially beneficial to disposal system or subsystem performance were eliminated to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations, or when incorporation would incur unreasonable difficulties. This is considered a conservative decision. These FEPS are designated SO-C Beneficial (e.g., the accumulation of radioactive contaminants in soils).

The FEPs retained in the PA were accounted for under calculations of either the undisturbed performance (UP) or disturbed performance (DP) (see the CCA, Chapter 6.0, Sections 6.2.2.2 and 6.2.2.3).

- UP includes the predicted behavior of the disposal system assuming it is not disrupted by human intrusion or the occurrence of unlikely natural events.

- DP includes the predicted behavior of the disposal system assuming disruption by human intrusion or other actions, including future drilling and mining activities.

32.3 1998 Certification Decision

32.3.1 40 CFR § 194.32(a)

In the CCA, the DOE discusses the origin and development of the WIPP FEPs list, as well as well-defined screening criteria in the CCA, Appendix SCR. A list of the WIPP-relevant FEPs is also provided in the CCA, Chapter 6.0, Section 6.2. The DOE identified approximately 237 FEPs in three major categories: natural (N), waste- and repository-induced (W), and human-initiated (H). Of particular importance to the performance of the disposal system were those FEPs dealing with mining, deep drilling, and shallow drilling. The CCA and supporting documents illustrated the process used by the DOE to implement the FEPs in scenarios relevant to PA.

The U.S. Environmental Protection Agency (EPA) evaluated the adequacy of the natural FEPs appropriate to the disposal system and how these were considered in the PA. The EPA also evaluated the DOE's consideration of mining and drilling in the PA. The EPA performed a critical review of each step in the DOE FEP selection process for the CCA, including identification and listing of the potentially disruptive FEPs, screening of these FEPs, combination of FEPs to form scenarios, screening of scenarios, and the final formation of scenarios for use in the CCA PA.

The EPA concluded that the initial FEP list assembled by the DOE was sufficiently comprehensive. This list appropriately screened out EPs on the basis of probability, consequence, or regulatory requirements. The EPA concluded that the DOE considered and incorporated into PA numerous natural EPs, mining, and deep drilling. The EPA concluded that the DOE considered shallow drilling and appropriately screened it out on the basis of low consequence. The DOE also appropriately followed regulatory requirements when it did not consider future fluid injection activities (U.S. Environmental Protection Agency 1998a).

32.3.2 40 CFR § 194.32(b)

The CCA describes how mining is incorporated into the PA, including information on mining rates and probabilities, the application of institutional controls, hydraulic conductivity variations as a result of mining, and the extent of minable reserves (see the CCA, Chapter 6.0, Section 6.4.6.2.3). The DOE identified potash as the only natural resource currently being mined near the WIPP. The DOE used the EPA-specified frequency of mining and probability when considering changes in hydraulic conductivity up to 1,000 times the base hydraulic conductivity of the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra). In its calculation of the potash area to be mined, the DOE considered minable reserves inside and outside the controlled area (the CCA, Appendix DEL, Section DEL.4.2.4).

In reviewing the DOE's compliance with 40 CFR § 194.32(b), the EPA considered whether the CCA included a detailed, accurate, and comprehensive analysis of mined resources in the WIPP area and sufficient information to demonstrate how mining probability was determined. Specifically, the EPA examined the validity of the DOE's potash reserve estimates, including the DOE's assumptions regarding potash reserve location, quality, and minable horizons. The EPA also examined the CCA to determine how hydraulic conductivity in the supra-Salado units was

modified to address changes that could be caused by mining over the 10,000-year regulatory period (U.S. Environmental Protection Agency 1998a).

The EPA's review of minable reserves found that the DOE identified current minable thicknesses and horizons near the WIPP. The DOE's estimate roughly corresponds to that identified in an EPA technical memorandum (Peake 1996). The EPA recognized that this is not necessarily representative of the entire Delaware Basin, and it is conceivable that additional reserves could be mined in the WIPP area. However, speculation of this nature would extend to other horizons or reserves, which is beyond the intent of section 194.32(b). The EPA therefore concurred with the DOE's approach.

The EPA also found that the DOE assumed mined resources will be completely removed from the controlled area within the century in which mining occurs, and complete removal of mineral resources was assumed to occur only once over the regulatory time frame, in accordance with section 194.32(b). The DOE assumed that mining will be done via room and pillar or other conventional methods, and solution mining of potash will not take place because of mineralogical and economic constraints.

Finally, the EPA determined that mining was properly incorporated in PA through the application of the 1 to 1,000 multiplier for hydraulic conductivity in the calculated transmissivity field for the Culebra. The CCA, Appendix TFIELD and related documentation include information pertinent to this application of the transmissivity multiplier.

32.3.3 40 CFR § 194.32(c)

In the CCA, the DOE identified appropriate events and analyses of their effects on the disposal system, as well as the effects of existing boreholes. The EPA considered how these events affected the disposal system and whether the DOE addressed the potential for slant drilling. The EPA also examined whether the DOE addressed potentially exploitable existing leases.

The DOE concluded that oil and gas exploration and exploitation and water and potash exploration are the only human-initiated activities that need to be considered for PA (see the CCA, Chapter 6.0, Section 6.3.2). The DOE divided human-initiated activities into two categories: (1) those that have been Historic, Current, and Near-Future (HCN); and (2) those that may happen in the future after disposal (Future). Human-initiated activities included three different drilling-related intrusion scenarios used in PA based on the screening analysis, designated by the DOE as E1, E2, and E1E2 (see the CCA, Chapter 6.0, Section 6.3.2). The E1 scenario assumed penetration of a panel by a borehole drilled through the repository, which then strikes a brine pocket present in the underlying Castile. The E2 scenario included all future boreholes that penetrate a panel but do not strike an underlying brine pocket within the Castile. The E1E2 scenario was defined as the occurrence of multiple boreholes that intersect a single waste panel, with at least one of the events being an E1 occurrence.

The EPA evaluated the DOE's compliance with 40 CFR § 194.32(c) and determined that the DOE had used a reasonable approach to screen human-initiated activities that might impact the repository. The EPA concluded that, based on the discussion in the CCA, Appendix SCR, the DOE considered the appropriate issues, and the technical conclusions reached by the DOE

regarding screening of oil and gas exploration and extraction activities were valid (U.S. Environmental Protection Agency 1998a).

32.3.4 40 CFR § 194.32(d)

The DOE listed FEPs eliminated from PA based on probability, and described why they were not included. The DOE used this requirement to screen out FEPs such as nuclear criticality, galvanic coupling, formation of new faults, glaciation, and impact of large meteorites.

The EPA examined the screening arguments and information in the CCA, Appendix SCR to assess the traceability of assumptions, approximations, and measures of uncertainties. The EPA examined the DOE's approach to determine whether it was well documented and adequately justified. The EPA examined assigned probabilities to determine whether they were appropriate, documented, and in accordance with EPA regulatory requirements, and examined the sufficiency of all data in terms of quantity and adequacy. In conclusion, the EPA concurred with the events and processes that were screened out by the DOE using the low-probability criterion (U.S Environmental Protection Agency 1998a).

32.3.5 40 CFR § 194.32(e)

32.3.5.1 40 CFR § 194.32(e)(1)

40 CFR § 194.32(e)(1) specifies that all potential FEPs that may occur during the regulatory time period be identified and considered. In this criterion, a time frame of interest is applied to FEPs that may affect the disposal system. This criterion specifies "the regulatory time frame," which begins at repository closure and continues for 10,000 years in the future. This is in contrast to that specified in section 194.32(c), where the time period of interest is HCN.[1]

The CCA, Appendix SCR, identified the processes and events, or sequences and combinations of processes and events, included in PA, including natural and human-initiated processes and events. The CCA, Appendix SCR provided a comprehensive analysis of all FEPs that may affect WIPP performance. In addition, the CCA, Appendix SCR and its attachments document the development of the WIPP FEPs list and describe its origin from over 1,200 FEPs identified through various international repository programs. The broad and comprehensive beginning of the WIPP FEPs list helps to assure that all potential WIPP-relevant FEPs can be properly identified. After refinement of the initial list, the DOE's FEPs identification process resulted in approximately 237 FEPs that were retained for screening.

The EPA reviewed the DOE's initial FEPs listings at each stage of development and review to determine whether it was comprehensive. In addition, the EPA examined information sources used by the DOE to compile the FEPs lists for completeness and accuracy of technical information. The EPA concluded that the DOE identified those events and processes, and sequences or combinations of events and processes, that may occur during the regulatory time period and affect the repository. The EPA concluded that these FEPs represented those most

[1] Human-initiated FEPs are screened for both the HCN and Future time periods (i.e., sections 194.32(c) and 194.32(e)(1)).

critical in terms of affecting the disposal repository (U.S. Environmental Protection Agency 1998a).

32.3.5.2 40 CFR § 194.32(e)(2)

40 CFR § 194.32(e)(2) states that combinations of events and processes must be included in PA. To accomplish this, the DOE formulated conceptual models and scenarios that incorporated each of the FEPs screened in during the screening processes detailed in the CCA, Appendix SCR. The DOE developed scenarios to represent both undisturbed and disturbed system performance. FEPs were included into scenarios ranging from the effects of deep and shallow drilling and mining to undisturbed disposal system performance. In the CCA, Chapter 6.0, Section 6.2, Table 6-6, the DOE identifies the specific locations in the CCA where information on the modeling of the individual FEP can be found.

The EPA reviewed the CCA to determine whether FEPs and subsequent scenarios were appropriately screened, adequately justified, and completely supported. In addition, the EPA examined combinations of FEPs and scenarios included in PA. The EPA concluded that DOE used a process (i.e., the Statens Kärnkraftinspektion (SKI) [Stenhouse, Chapman, and Sumerling 1993] list modified to suit conditions at the WIPP site) that identified the processes, events, or sequences or combinations of processes and events. As part of this process, the DOE adequately addressed and evaluated the effects of mining, deep drilling, and shallow drilling. The DOE evaluated the FEPs and sequences of FEPs through calculations, estimates of probability, and comparisons to regulatory requirements. The EPA concluded that the DOE appropriately identified, listed, and discussed the FEPs and the effects of the sequences and combinations of FEPs that result in modeled scenarios (U.S. Environmental Protection Agency 1998a).

32.3.5.3 40 CFR § 194.32(e)(3)

40 CFR § 194.32(e)(3) requires that FEPs not included in PA calculations be adequately documented and justified. The DOE identified approximately 237 FEPs in the CCA, Appendix SCR and the CCA, Chapter 6.0, Section 6.3. For each FEP, DOE provided a description and a generalized rationale for screening classifications. Of the 237 FEPs analyzed, 154 were screened out on the basis of regulations (SO-R), low consequence (SO-C), or probability (SO-P). The CCA, Appendix SCR included the DOE's screening rationale for each of the 237 CCA FEPs.

To verify the DOE's compliance with this section, the EPA reviewed the information in the CCA, Appendix SCR and also conducted audits to verify the proper execution of quality assurance (QA) programs for all items and activities important to the containment of waste in the repository, including items and activities related to FEPs. As a result of these EPA audits, the EPA concluded that QA programs were properly executed for FEP-related items and activities, and that the DOE had demonstrated compliance with the requirements of section 194.32 (U.S. Environmental Protection Agency 1998a).

32.4 Changes in the CRA-2004

For the Compliance Recertification Application of 2004 (CRA-2004) (U.S. Department of Energy 2004) and the subsequent Performance Assessment Baseline Calculation, the DOE

revaluated all WIPP FEPs to determine if any had changed or if new FEPs needed to be added. The DOE's reevaluation resulted in only a few changes to the FEPs analysis. Wagner, Kirkes, and Martell (2003) concluded that of the original 237 FEPs included in the CCA, 106 did not change, 120 required updates to their FEP descriptions and/or screening arguments, and 7 of the original baseline FEPs screening decisions required a change from their original screening decision. Four of the original baseline FEPs were deleted or combined with other closely related FEPs, and two new FEPs were added to the baseline. These two FEPs were previously addressed in an existing FEP; they were separated for clarity. Therefore, for the CRA-2004, reevaluation resulted in a new FEPs baseline consisting of 235 FEPs, but did not change the CCA conceptual models or the scenarios developed for PA.

32.5 The EPA's Evaluation of Compliance for the 2004 Recertification

For the CRA-2004, the DOE applied the same approach used for the CCA to develop and screen the list of FEPs that may have an effect on the disposal system as that used for the CCA. Since the WIPP FEPs were previously evaluated and approved in the initial certification process, the EPA focused its recertification review on the FEPs that had changed since the 1998 Certification Decision (U.S Environmental Protection Agency 1998b). The EPA verified that the DOE's FEP-development and review process was fundamentally the same as the CCA process, and verified that the DOE's reevaluation properly considered changes since the original certification decision in 1998. The EPA verified that any changes to FEP-screening arguments or FEPs-related discussions were reasonable, appropriate, and complete.

The EPA received one public comment related to the scope of PA. Some stakeholders proposed that karst (FEP N20) should be included in the PA conceptual model development. The EPA reevaluated karst issues raised by stakeholders from the CCA as well as new information made available since the original certification decision. The EPA's review is discussed in *Technical Support Document for Section 194.14/15: Evaluation of Karst at the WIPP Site* (U.S. Environmental Protection Agency 2006a). After a thorough review, the EPA determined that karst should not be screened into the PA process.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.32 (U.S. Environmental Protection Agency 2006b).

32.6 Changes or New Information since the 2004 Recertification

For the CRA-2009, the DOE has identified PA changes implemented since the CRA-2004 and determined their impacts on the FEPs baseline. Changes that affect the FEPs basis are detailed in Appendix SCR-2009. As a result of the reevaluation, 35 FEPs were updated with new information, 1 screening argument has been changed to correct errors discovered during review, and the screening decision for one FEP was changed from SO-R to SO-C. This latter change has no impact on PA calculations because the FEP continues to be excluded from PA, albeit using a different screening rationale. Finally, 10 FEPs have been split into 20 similar, but more specific, FEPs. The following sections present information that demonstrates compliance with the requirements of section 194.32.

32.6.1 40 CFR § 194.32(a)

Changes to the WIPP baseline since the CRA-2004 have been identified and evaluated to determine their impact upon the WIPP FEPs baseline. This reevaluation process is very similar to the process used for the CRA-2004. The FEPs baseline is maintained according to Sandia National Laboratories Specific Procedure 9-4, *Performing FEPS Baseline Impact Assessments for Planned and Unplanned Changes* (Kirkes 2006). For the CRA-2009, there are 70 natural FEPs, 61 human-initiated EPs, and 114 waste and repository FEPs, resulting in 245 WIPP FEPs. The current FEPs baseline is presented in Appendix SCR-2009. Table 32-1 lists the CRA-2009 FEPs and their screening decisions, and summarizes any changes to related information since the CRA-2004.

Table 32-1. CRA-2009 FEPs Summary

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N1	Stratigraphy	No	No change.	UP
N2	Brine Reservoirs	No	No change.	DP
N3	Changes in Regional Stress	No	No change.	SO-C
N4	Regional Tectonics	No	No change.	SO-C
N5	Regional Uplift and Subsidence	No	No change.	SO-C
N6	Salt Deformation	No	No change.	SO-P
N7	Diapirism	No	No change.	SO-P
N8	Formation of Fractures	No	No change.	SO-P UP (Repository)
N9	Changes in Fracture Properties	No	No change.	SO-C UP (Near Repository)
N10	Formation of New Faults	No	No change.	SO-P
N11	Fault Movement	No	No change.	SO-P
N12	Seismic Activity	No	Updated with new seismic data.	UP
N13	Volcanic Activity	No	No change.	SO-P
N14	Magmatic Activity	No	No change.	SO-C
N15	Metamorphic Activity	No	No change.	SO-P
N16	Shallow Dissolution	No	No change.	UP
N18	Deep Dissolution	No	No change.	SO-P
N20	Breccia Pipes	No	No change.	SO-P
N21	Collapse Breccias	No	No change.	SO-P
N22	Fracture Infills	No	No change.	SO-C - Beneficial

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N23	Saturated Groundwater Flow	No	No change.	UP
N24	Unsaturated Groundwater Flow	No	No change.	UP
N25	Fracture Flow	No	No change.	UP
N27	Effects of Preferential Pathways	No	No change.	UP
N26	Density effects on Groundwater Flow	No	No change.	SO-C
N28	Thermal effects on Groundwater Flow	No	No change.	SO-C
N29	Saline Intrusion [Hydrogeological Effects]	No	No change.	SO-P
N30	Freshwater Intrusion [Hydrogeological effects]	No	No change.	SO-P
N31	Hydrological Response to Earthquakes	No	No change.	SO-C
N32	Natural Gas Intrusion	No	No change.	SO-P
N33	Groundwater Geochemistry	No	No change.	UP
N34	Saline Intrusion (Geochemical Effects)	No	No change.	SO-C
N38	Effects of Dissolution	No	No change.	SO-C
N35	Freshwater Intrusion (Geochemical Effects)	No	No change.	SO-C
N36	Changes in Groundwater Eh	No	No change.	SO-C
N37	Changes in Groundwater pH	No	No change.	SO-C
N39	Physiography	No	No change.	UP
N40	Impact of a Large Meteorite	No	Errors identified in screening argument corrected; no change in screening decision.	SO-P
N41	Mechanical Weathering	No	No change.	SO-C
N42	Chemical Weathering	No	No change.	SO-C
N43	Aeolian Erosion	No	No change.	SO-C
N44	Fluvial Erosion	No	No change.	SO-C
N45	Mass Wasting [Erosion]	No	No change.	SO-C
N46	Aeolian Deposition	No	No change.	SO-C
N47	Fluvial Deposition	No	No change.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N48	Lacustrine Deposition	No	No change.	SO-C
N49	Mass Wasting [Deposition]	No	No change.	SO-C
N50	Soil Development	No	No change.	SO-C
N51	Stream and River Flow	No	No change.	SO-C
N52	Surface Water Bodies	No	No change.	SO-C
N53	Groundwater Discharge	No	No change.	UP
N54	Groundwater Recharge	No	No change.	UP
N55	Infiltration	No	No change.	UP
N56	Changes in Groundwater Recharge and Discharge	No	No change.	UP
N57	Lake Formation	No	No change.	SO-C
N58	River Flooding	No	No change.	SO-C
N59	Precipitation (e.g. Rainfall)	No	No change.	UP
N60	Temperature	No	No change.	UP
N61	Climate Change	No	No change.	UP
N62	Glaciation	No	No change.	SO-P
N63	Permafrost	No	No change.	SO-P
N64	Seas and Oceans	No	No change.	SO-C
N65	Estuaries	No	No change.	SO-C
N66	Coastal Erosion	No	No change.	SO-C
N67	Marine Sediment Transport and Deposition	No	No change.	SO-C
N68	Sea Level Changes	No	No change.	SO-C
N69	Plants	No	No change.	SO-C
N70	Animals	No	No change.	SO-C
N71	Microbes	No	No change.	SO-C (UP - for colloidal effects and gas generation)
N72	Natural Ecological Development	No	No change.	SO-C
H1	Oil and Gas Exploration	No	No change.	SO-C (HCN) DP (Future)
H2	Potash Exploration	No	No change.	SO-C (HCN) DP (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H4	Oil and Gas Exploitation	No	No change.	SO-C (HCN) DP (Future)
H8	Other Resources	No	No change.	SO-C (HCN) DP (Future)
H9	Enhanced Oil and Gas Recovery	No	No change.	SO-C (HCN) DP (Future)
H3	Water Resources Exploration	No	Updated with most recent monitoring information.	SO-C (HCN) SO-C (Future)
H5	Groundwater Exploitation	No	Updated with most recent monitoring information.	SO-C (HCN) SO-C (Future)
H6	Archaeological Investigations	No	No change.	SO-R (HCN) SO-R (Future)
H7	Geothermal	No	No change.	SO-R (HCN) SO-R (Future)
H10	Liquid Waste Disposal	No	No change.	SO-R (HCN) SO-R (Future)
H11	Hydrocarbon Storage	No	No change.	SO-R (HCN) SO-R (Future)
H12	Deliberate Drilling Intrusion	No	No change.	SO-R (HCN) SO-R (Future)
H13	Conventional Underground Potash Mining	No	No change.	UP (HCN) DP (Future)
H14	Other Resources (mining for)	No	No change.	SO-C (HCN) SO-R (Future)
H15	Tunneling	No	No change.	SO-R (HCN) SO-R (Future)
H16	Construction of Underground Facilities (for Example Storage, Disposal, Accommodation)	No	No change.	SO-R (HCN) SO-R (Future)
H17	Archaeological Excavations	No	No change.	SO-C (HCN) SO-R (Future)
H18	Deliberate Mining Intrusion	No	No change.	SO-R (HCN) SO-R (Future)
H19	Explosions for Resource Recovery	No	No change.	SO-C (HCN) SO-R (Future)
H20	Underground Nuclear Device Testing	No	No change.	SO-C (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H21	Drilling Fluid Flow	No	Screening argument revised.	SO-C (HCN) DP (Future)
H22	Drilling Fluid Loss	No	Screening argument revised.	SO-C (HCN) DP (Future)
H23	Blowouts	No	No change.	SO-C (HCN) DP (Future)
H24	Drilling-Induced Geochemical Changes	No	No change.	UP (HCN) DP (Future)
H25	Oil and Gas Extraction	No	Screening argument updated.	SO-C (HCN) SO-R (Future)
H26	Groundwater Extraction	No	Screening argument updated.	SO-C (HCN) SO-R (Future)
H27	Liquid Waste Disposal–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)
H28	Enhanced Oil and Gas Production–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)
H29	Hydrocarbon Storage–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H60	Liquid Waste Disposal–IB	N/A – new FEP	This is a new FEP that is similar to H27, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H61	Enhanced Oil and Gas Production–IB	N/A – new FEP	This is a new FEP that is similar to H28, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H62	Hydrocarbon Storage–IB	N/A – new FEP	This is a new FEP that is similar to H29, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H30	Fluid-injection Induced Geochemical Changes	No	No change.	UP (HCN) SO-R (Future)
H31	Natural Borehole Fluid Flow	No	No change.	SO-C (HCN) SO-C (Future, holes not penetrating waste panels) DP (Future, holes penetrating panels)
H32	Waste-Induced Borehole Flow	No	No change.	SO-R (HCN) DP (Future)
H34	Borehole-Induced Solution and Subsidence	No	No change.	SO-C (HCN) SO-C (Future)
H35	Borehole-Induced Mineralization	No	No change.	SO-C (HCN) SO-C (Future)
H36	Borehole-Induced Geochemical Changes	No	No change.	UP (HCN) DP (Future) SO-C (for units other than the Culebra)
H37	Changes in Groundwater Flow Due to Mining	No	No change.	UP (HCN) DP (Future)
H38	Changes in Geochemistry Due to Mining	No	No change.	SO-C (HCN) SO-R (Future)
H39	Changes in Groundwater Flow Due to Explosions	No	No change.	SO-C (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H40	Land Use Changes	No	No change.	SO-R (HCN) SO-R (Future)
H41	Surface Disruptions	Yes	Screening decision changed from SO-R to SO-C to remove inconsistency with rationale.	UP (HCN) SO-C (Future)
H42	Damming of Streams or Rivers	No	No change.	SO-C (HCN) SO-R (Future)
H43	Reservoirs	No	No change.	SO-C (HCN) SO-R (Future)
H44	Irrigation	No	No change.	SO-C (HCN) SO-R (Future)
H45	Lake Usage	No	No change.	SO-R (HCN) SO-R (Future)
H46	Altered Soil or Surface Water Chemistry by Human Activities	No	No change.	SO-C (HCN) SO-R (Future)
H47	Greenhouse Gas Effects	No	No change.	SO-R (HCN) SO-R (Future)
H48	Acid Rain	No	No change.	SO-R (HCN) SO-R (Future)
H49	Damage to the Ozone Layer	No	No change.	SO-R (HCN) SO-R (Future)
H50	Coastal Water Use	No	No change.	SO-R (HCN) SO-R (Future)
H51	Sea water Use	No	No change.	SO-R (HCN) SO-R (Future)
H52	Estuarine Water Use	No	No change.	SO-R (HCN) SO-R (Future)
H53	Arable Farming	No	No change.	SO-C (HCN) SO-R (Future)
H54	Ranching	No	No change.	SO-C (HCN) SO-R (Future)
H55	Fish Farming	No	No change.	SO-R (HCN) SO-R (Future)
H56	Demographic Change and Urban Development	No	No change.	SO-R (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H57	Loss of Records	No	No change.	NA (HCN) DP (Future)
H58	Solution Mining for Potash	No	Updated with information regarding solution activities and plans in the region.	SO-R (HCN) SO-R (Future)
H59	Solution Mining for Other Resources	No	Updated with new information regarding brine wells in the region.	SO-C (HCN) SO-C (Future)
W1	Disposal Geometry	No	No change.	UP
W2	Waste Inventory	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	UP
W3	Heterogeneity of Waste Forms	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	DP
W4	Container Form	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	SO-C – Beneficial
W5	Container Material Inventory	No	No change.	UP
W6	Shaft Seal Geometry	No	Title changed to be specific to shaft seals.	UP
W7	Shaft Seal Physical Properties	No	Title changed to be specific to shaft seals.	UP
W109	Panel Closure Geometry	N/A – new FEP.	Split from W6 to be specific to panel closures.	UP
W110	Panel Closure Physical Properties	N/A – new FEP	Split from W7 to be specific to panel closures.	UP
W8	Shaft Seal Chemical Composition	No	Title changed to be specific to shaft seals.	SO-C Beneficial
W111	Panel Closure Chemical Composition	N/A – new FEP	Split from W8 to be specific to panel closures.	SO-C Beneficial
W9	Backfill Physical Properties	No	No change.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W10	Backfill Chemical Composition	No	No change.	UP
W11	Post-Closure Monitoring	No	No change.	SO-C
W12	Radionuclide Decay and In-Growth	No	No change.	UP
W13	Heat from Radioactive Decay	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-C
W14	Nuclear Criticality: Heat	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-P
W15	Radiological Effects on Waste	No	Updated to reflect the inventory used for the CRA.	SO-C
W16	Radiological Effects on Containers	No	Updated to reflect the inventory used for the CRA.	SO-C
W17	Radiological Effects on Shaft Seals	No	FEP title changed to be specific to shaft seals; screening argument updated to reflect the inventory used for the CRA.	SO-C
W112	Radionuclide Effects on Panel Closures	N/A – new FEP	Split from W17 to be specific to panel closures.	SO-C
W18	Disturbed Rock Zone (DRZ)	No	No change.	UP
W19	Excavation-Induced Changes in Stress	No	No change.	UP
W20	Salt Creep	No	No change.	UP
W21	Changes in the Stress Field	No	No change.	UP
W22	Roof Falls	No	No change.	UP
W23	Subsidence	No	Source of subsidence monitoring data added.	SO-C
W24	Large Scale Rock Fracturing	No	Source of subsidence monitoring data added.	SO-P
W25	Disruption Due to Gas Effects	No	No change.	UP
W26	Pressurization	No	No change.	UP
W27	Gas Explosions	No	No change.	UP

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W28	Nuclear Explosions	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-P
W29	Thermal Effects on Material Properties	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W30	Thermally-Induced Stress Changes	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W31	Differing Thermal Expansion of Repository Components	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W72	Exothermic Reactions	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W73	Concrete Hydration	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W32	Consolidation of Waste	No	No change.	UP
W36	Consolidation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W37	Mechanical Degradation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W39	Underground Boreholes	No	No change.	UP
W113	Consolidation of Panel Closures	N/A – new FEP	Split from W36 to be specific to panel closures.	UP
W114	Mechanical Degradation of Panel Closures	N/A – new FEP	Split from W37 to be specific to panel closures.	UP
W33	Movement of Containers	No	Updated to reference new inventory data.	SO-C
W34	Container Integrity	No	No change.	SO-C Beneficial
W35	Mechanical Effects of Backfill	No	Screening argument updated to reflect reduction in MgO.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W40	Brine Inflow	No	No change.	UP
W41	Wicking	No	No change.	UP
W42	Fluid Flow Due to Gas Production	No	No change.	UP
W43	Convection	No	No change.	SO-C
W44	Degradation of Organic Material	No	New thermal rise calculations referenced.	UP
W45	Effects of Temperature on Microbial Gas Generation	No	New thermal rise calculations referenced.	UP
W48	Effects of Biofilms on Microbial Gas Generation	No	New thermal rise calculations referenced.	UP
W46	Effects of Pressure on Microbial Gas Generation	No	No change.	SO-C
W47	Effects of Radiation on Microbial Gas Generation	No	Screening argument updated with new radionuclide inventory.	SO-C
W49	Gases from Metal Corrosion	No	No change.	UP
W51	Chemical Effects of Corrosion	No	No change.	UP
W50	Galvanic Coupling (Within the Repository)	No	No change.	SO-C
W52	Radiolysis of Brine	No	No change.	SO-C
W53	Radiolysis of Cellulose	No	Screening argument updated with new radionuclide inventory.	SO-C
W54	Helium Gas Production	No	Screening argument updated with new radionuclide inventory.	SO-C
W55	Radioactive Gases	No	Reference made to CRA-2009 inventory data.	SO-C
W56	Speciation	No	No change.	UP in disposal rooms and Culebra. SO-C elsewhere, and SO-C Beneficial in cementitious seals

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W57	Kinetics of Speciation	No	No change.	SO-C
W58	Dissolution of Waste	No	No change.	UP
W59	Precipitation of Secondary Minerals	No	No change.	SO-C Beneficial
W60	Kinetics of Precipitation and Dissolution	No	No change.	SO-C
W61	Actinide Sorption	No	No change.	UP in the Culebra and Dewey Lake; SO-C—Beneficial in the disposal room, shaft seals, panel closures, and other geologic units.
W62	Kinetics of Sorption	No	No change.	UP in the Culebra and Dewey Lake; SO-C—Beneficial in the disposal room, shaft seals, panel closures, and other geologic units.
W63	Changes in Sorptive Surfaces	No	No change.	UP
W64	Effects of Metal Corrosion	No	No change.	UP
W66	Reduction-Oxidation Kinetics	No	No change.	UP
W65	Reduction-Oxidation Fronts	No	No change.	SO-P
W67	Localized Reducing Zones	No	No change.	SO-C
W68	Organic Complexation	No	No change.	UP
W69	Organic Ligands	No	No change.	UP
W71	Kinetics of Organic Complexation	No	No change.	SO-C
W70	Humic and Fulvic Acids	No	No change.	UP
W74	Chemical Degradation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W76	Microbial Growth on Concrete	No	No change.	UP
W115	Chemical Degradation of Panel Closures	N/A – new FEP	Split from W74 to be specific to panel closures.	UP

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W75	Chemical Degradation of Backfill	No	No change.	SO-C
W77	Solute Transport	No	No change.	UP
W78	Colloid Transport	No	No change.	UP
W79	Colloid Formation and Stability	No	No change.	UP
W80	Colloid Filtration	No	No change.	UP
W81	Colloid Sorption	No	No change.	UP
W82	Suspensions of Particles	No	No change.	DP
W83	Rinse	No	No change.	SO-C
W84	Cuttings	No	No change.	DP
W85	Cavings	No	No change.	DP
W86	Spallings	No	No change.	DP
W87	Microbial Transport	No	No change.	UP
W88	Biofilms	No	No change.	SO-C Beneficial
W89	Transport of Radioactive Gases	No	Screening argument updated with CRA-2009 inventory data.	SO-C
W90	Advection	No	No change.	UP
W91	Diffusion	No	No change.	UP
W92	Matrix Diffusion	No	No change.	UP
W93	Soret Effect	No	New thermal values added for aluminum corrosion.	SO-C
W94	Electrochemical Effects	No	No change.	SO-C
W95	Galvanic Coupling (Outside the Repository)	No	No change.	SO-P
W96	Electrophoresis	No	No change.	SO-C
W97	Chemical Gradients	No	No change.	SO-C
W98	Osmotic Processes	No	No change.	SO-C
W99	Alpha Recoil	No	No change.	SO-C
W100	Enhanced Diffusion	No	No change.	SO-C
W101	Plant Uptake	No	No change.	SO-R (for section 191.13) SO-C (for section 191.15)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table 32-1. CRA-2009 FEPs Summary (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W102	Animal Uptake	No	No change.	SO-R (for section 191.13) SO-C (for section 191.15)
W103	Accumulation in Soils	No	No change.	SO-C Beneficial (for section 191.13) SO-C (for section 191.15)
W104	Ingestion	No	No change.	SO-R SO-C (for section 191.15)
W105	Inhalation	No	No change.	SO-R SO-C (for section 191.15)
W106	Irradiation	No	No change.	SO-R SO-C (for section 191.15)
W107	Dermal Sorption	No	No change.	SO-R SO-C (for section 191.15)
W108	Injection	No	No change.	SO-R SO-C (for section 191.15)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Those FEPs not separated by gridlines in the first column of Table 32-1 have been addressed by group, due to close similarity with other FEPs within that group.

32.6.2 40 CFR § 194.32(b)

The requirements of section 194.32(b) specify assumptions regarding the implementation of mining in PA calculations. The PA modeling system used for the mining scenario is similar to that developed for the undisturbed repository scenario, but with a modified Culebra transmissivity field in the controlled area to account for the mining effects. Minor changes were made in the way mining is implemented in PA due to comments by the EPA in their review of the CRA-2004 (Cotsworth 2004). These changes include redefining the mined area to include 0.8-kilometer- (0.5-mile [mi]) diameter exclusion zones around oil and gas wells (see Section 2.7 of Leigh et al. [2005]). The result of including the 0.8 kilometer- (0.5-mi) diameter exclusion zone around oil and gas wells was to increase travels times in the Culebra (Lowry 2004). Details regarding how mining processes are represented in PA models are described in Appendix PA-2009, Section PA-2.3.2.2.1 and Appendix MASS-2009, Section MASS-15.1. FEPs related to the presence of resources are described and considered in Appendix SCR-2009, Section SCR-5.0.

32.6.3 40 CFR § 194.32(c)

Section 194.32(c) provides specific time frames to evaluate activities that may affect the disposal system. This requirement focuses on activities that have occurred in the past, are occurring, or are expected to occur in the near future. The DOE classifies this time frame as HCN. Because section 194.32(e)(1) requires the evaluation of human-initiated EPs during the regulatory time period, the DOE also evaluates human-initiated FEPs for the period of time from closure of the repository to 10,000 years into the future (Future) (see human-initiated EPs in Table 32-1). Human-initiated EPs are described and screened for both the HCN and Future time frames in Appendix SCR-2009, Section SCR-5.0. Therefore, the DOE is in compliance with the requirements of section 194.32(c).

32.6.4 40 CFR § 194.32(d)

Low-probability events can be excluded on the basis of the criterion provided in 40 CFR § 194.32(d), which states, "performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years." In practice, for most SO-P FEPs, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative argument was used. SO-P FEPs are listed in Table 32-2.

32.6.5 40 CFR § 194.32(e)

The requirements in 40 CFR § 194.32(e) are met by the analyses of FEPs as documented in Appendix SCR-2009. Table 32-1 lists the CRA-2009 FEPs and summarizes any changes to screening decisions and arguments.

Section 194.32, "Scope of Performance Assessment" requires the identification, selection, screening, and incorporation of all significant processes and events into PA. The DOE has taken a comprehensive approach in meeting the requirements of the section as documented here and in Appendix SCR-2009 of this CRA. The process used is consistent with evaluations of WIPP FEPs in past compliance applications. Any new information that relates to WIPP FEPs is identified and incorporated into PA as appropriate. Therefore, the DOE has met the requirements of section 194.32.

Table 32-2. CRA-2009 FEPs Screened Out for Low Probability (SO-P)

FEP I.D.	FEP Name
N6	Salt Deformation
N7	Diapirism
N8	Formation of Fractures
N10	Formation of New Faults
N11	Fault Movement
N13	Volcanic Activity
N15	Metamorphic Activity
N18	Deep Dissolution
N20	Breccia Pipes
N21	Collapse Breccias
N29	Saline Intrusion (Hydrogeological Effects)
N30	Freshwater Intrusion (Hydrogeological Effects)
N32	Natural Gas Intrusion
N40	Impact of a Large Meteorite
N62	Glaciation
N63	Permafrost
W14	Nuclear Criticality: Heat
W24	Large Scale Rock Fracturing
W28	Nuclear Explosions
W65	Reduction-Oxidation Fronts
W95	Galvanic Coupling (Outside the Repository)

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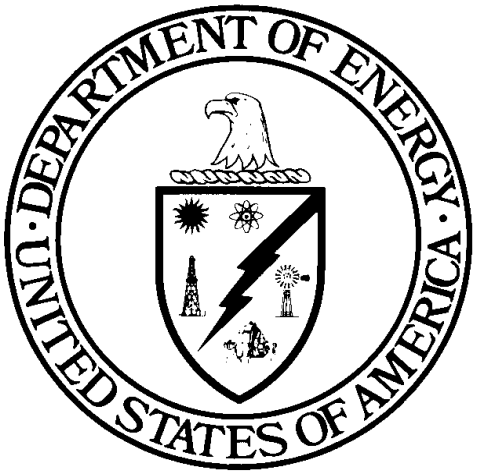
Consideration of Drilling Events in Performance Assessments (40 CFR § 194.33)



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Consideration of Drilling Events in Performance Assessments (40 CFR § 194.33)

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Acronyms and Abbreviations

%	percent
AIC	active institutional control
BLM	U.S. Bureau of Land Management
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
DBR	Direct Brine Release
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EPs	event and process
FEP	feature, event, and process
ft	feet
in.	inch
km^2	square kilometer
m	meter
m^3	cubic meters
md	millidarcy
mi	mile
mi^2	square mile
NMOCD	New Mexico Oil Conservation Division
PA	performance assessment
PAVT	Performance Assessment Verification Test
PIC	passive institutional control
WIPP	Waste Isolation Pilot Plant

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33.0 Consideration of Drilling Events in Performance Assessments (40 CFR § 194.33)

33.1 Requirements

§ 194.33 Consideration of Drilling Events in Performance Assessments

(a) Performance assessments shall examine deep drilling and shallow drilling that may potentially affect the disposal system during the regulatory time frame.

(b) The following assumptions and process shall be used in assessing the likelihood and consequences of drilling events, and the results of such process shall be documented in any compliance application:

(1) Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

(2) In performance assessments, drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame.

(3) The frequency of deep drilling shall be calculated in the following manner:

(i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared

(ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.

(4) The frequency of shallow drilling shall be calculated in the following manner:

(i) Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.

(ii) The total rate of shallow drilling shall be the sum of the rates of shallow drilling for each resource.

(iii) In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.

(c) Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:

(1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans.

(2) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.

(d) With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

33.2 Background

40 CFR § 194.33 (U.S. Environmental Protection Agency 1996) requires the U.S. Department of Energy (DOE) to make assumptions about future deep and shallow drilling in the Delaware Basin and the vicinity of the Waste Isolation Pilot Plant (WIPP). These assumptions pertain to the timing and duration of drilling, frequency of drilling, drilling practices and technology, and the effects of natural processes on boreholes.

Drilling in the near future within the Delaware Basin will most likely be for oil and gas exploration/exploitation, which constitutes a deep drilling event. Shallow drilling may occur for other resources (e.g., water), but has been screened out of this and past analyses due to lack of consequence on the disposal system (Compliance Certification Application [CCA], U.S. Department of Energy 1996, Chapter 6.0, Section 6.2.5.2; Compliance Recertification

Application of 2004 [CRA-2004], U.S. Department of Energy 2004, Appendix PA, Attachment SCR; Compliance Recertification Application of 2009 [CRA-2009], Appendix SCR-2009). Drilling is incorporated in the performance assessment (PA) as a single event or combinations of events based upon different scenarios. Deep and shallow drilling rates and related activities directly affect the cumulative potential for radionuclide releases to the surface or to subsurface geologic units around the WIPP.

Deep drilling is defined by the U.S. Environmental Protection Agency (1996) as events that terminate 655 meters (m) (2,150 feet [ft]) or more below ground surface, while shallow drilling events terminate no deeper than 655 m (2,150 ft) below ground surface. (Note that the repository level is 655 m (2,150 ft) below ground surface.)

33.3 1998 Certification Decision

33.3.1 40 CFR § 194.33(a) DOE Methodology and Conclusions

In the CCA, Chapter 6.0, Section 6.2.5, the DOE identified oil and gas exploration/exploitation and water and potash exploration as the principal human activities that must be considered within the PA. The remaining human initiated activities—such as exploration for geothermal energy, water supplies, and sulfur and brine extraction (solution mining)—were eliminated based upon low probability, low consequence, or for regulatory reasons.

33.3.1.1 Deep Drilling Methods

Descriptions of well drilling, plugging, and abandonment practices typically followed in the Delaware Basin are provided in the CCA, Appendix DEL, Section DEL.5 (the CCA, Appendix DEL, pp. DEL-26 through DEL-46). Chapter IX of the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) Final Report (New Mexico Bureau of Mines and Mineral Resources 1995, pp. IX-1 through IX-69) includes a discussion of drilling targets and practices, with typical casing designs presented in the CCA, Appendix DEL (Figure DEL-13). The typical operation sequence for well installation was presented in the CCA, Appendix DEL, Attachment 1 (Delaware Basin). Oil and gas exploration, exploitation, and production comprise 99% of the deep boreholes in the Delaware Basin, with the remainder being sulfur, potash, and stratigraphic test boreholes (the CCA, Appendix DEL, Table DEL-4).

The CCA also provides extensive information pertaining to the deep drilling process, from acquisition of leases to well completion and abandonment (the CCA, Appendix DEL, Section DEL.6.1). In the area near the WIPP site, deep drilling typically terminates between approximately 5,000 to 15,400 ft (1,524 to 4,695 m) below ground surface. The DOE stated that mud rotary drilling is the typical drilling method used in the Delaware Basin. A summary of deep drilling activities is provided in the CCA, Appendix DEL, Section DEL.5.1.

33.3.1.2 Shallow Drilling Methods

The CCA discusses shallow drilling methods in the CCA, Appendix DEL, Section DEL.5.2 (Potash Coreholes) and DEL.5.3 (Water Wells). Although shallow drilling for hydrocarbons, sulfur, and brine extraction (solution mining) also occur, the CCA did not explicitly discuss

drilling methods for hydrocarbons and brine extraction (solution mining) because they are comparable to those for deep drilling, while drilling methods for sulfur are comparable to those for potash drilling.

33.3.1.3 Evaluation of Borehole Properties

Typical borehole sizes and depths are evaluated in the CCA, Appendix DEL, Section DEL.5 (pp. DEL-26 through DEL-42). These borehole properties are described as having the potential to affect the disposal system through radionuclide migration and transport, as detailed below. The CCA, Chapter 6.0, Sections 6.5.3 and 6.5.5 provide the results of calculations showing that actinides expelled from the WIPP by these release mechanisms would not exceed EPA release limits. In addition, the CCA shows that the properties and degradation history of borehole plugging material are very important to the containment capabilities of the WIPP (the CCA, Chapter 6.0, Section 6.4.7.2, pp. 6-156 through 6-161).

33.3.1.4 Future Drilling Events Considered in the Performance Assessment

Future shallow drilling events were not considered in the PA because they were determined to be of low consequence to the PA calculations.

The CCA describes three different combinations of drilling events considered in PA, referred to as E1, E2, and E1E2:

- The E1 Scenario (the CCA, Chapter 6.0, Figure 6-11): one or more boreholes penetrate a Castile brine reservoir and also intersect a repository panel
- The E2 Scenario (the CCA, Chapter 6.0, Figure 6-10): one or more boreholes intersect a repository panel and do not penetrate a Castile brine reservoir
- The E1E2 Scenario (the CCA, Chapter 6.0, Figure 6-12): multiple penetrations of the same waste panel where at least one penetration must be of the E1 type

The following potential release mechanisms result from the intrusion scenarios listed above. Intrusions to the disposal system could affect radionuclide migration and transport via the following:

- Cuttings—material intersected by a rotary drilling bit
- Cavings—material eroded from a borehole wall during drilling
- Spallings—solid material carried into the borehole during rapid depressurization of the waste disposal region
- Direct Brine Releases (DBRs)—contaminated brine that may flow to the surface during drilling
- Long-Term Releases Following Drilling

Future drilling events are modeled through a random sampling procedure described in the CCA, Appendix CCDFGF, Sections 2 and 3. Uncertainty relative to the time and location of drilling is stochastic (i.e., derived from random processes, without knowledge about the future). Drilling is incorporated into the PA by repeatedly generating independent sequences of drilling-related events that could occur at the WIPP over the next 10,000 years. The defining parameters for the occurrence of future drilling events include not only the interval of time between drilling events and the location of drilling intrusions, but also the following four parameters:

- Activity of waste penetrated by each drilling intrusion (not related to deep or shallow drilling, but included for completeness)
- Plug configuration in the borehole
- Penetration of the Castile brine reservoir
- Occurrence of mining (not related to deep or shallow drilling, but included for completeness)

Random sampling from these distributions was used to calculate 10,000 different futures for the WIPP (the CCA, Chapter 6.0, Section 6.4.13.9).

33.3.2 40 CFR § 194.33(a) EPA Compliance Review

The EPA reviewed the information presented by the DOE in the CCA, Appendix DEL, Chapter DEL.6, Section 6.2, and Chapter IX of NMBMMR (New Mexico Bureau of Mines and Mineral Resources 1995) to determine how extensively deep and shallow drilling was considered and whether the information provided was sufficiently comprehensive, accurate, and correctly calculated. The EPA examined the list of references presented in the CCA relative to drilling and conducted a literature search to evaluate the fluid injection study (U.S. Environmental Protection Agency 1998a). The EPA determined that the DOE's scrutiny of resources to assess deep and shallow drilling practices and frequencies was comprehensive. The EPA also determined that the DOE's conclusions regarding representative drilling methods in the Delaware Basin are consistent with available data.

During the public comment period on the EPA's proposed certification, commenters raised the issue that both air and mud drilling might occur in the Delaware Basin and that releases from air drilling could be greater than from mud drilling, potentially causing the WIPP to fail the release limits of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993). The DOE did not include air drilling in the CCA because it was not a technique commonly used in the area near the WIPP. In response to issues raised by stakeholders, the DOE provided several reports (Dials 1998) that examined both the likelihood and consequence of drilling with air at and near the WIPP. Likewise, the EPA examined the air drilling issue from several perspectives and documented its findings in the Technical Support Document *EPA's Analysis of Air Drilling at WIPP* (U.S. Environmental Protection Agency 1998b) and in *Response to Comments*, Section 8 (U.S. Environmental Protection Agency 1998c). The results of the EPA's analysis showed that air drilling is not common practice in the Delaware Basin. In addition, even if air drilling were to occur, the volume of spalled material released is within the range presented in the CCA.

The EPA evaluated the drilling-related information in the CCA to determine how both deep and shallow drilling affect the WIPP disposal system, including but not limited to, pressurization of the WIPP, brine/fluid removal, and circulation of brine within the panels. The EPA concluded that the DOE appropriately excluded shallow drilling from PA based upon low consequence. The EPA also concluded that the DOE appropriately simplified the intrusion scenarios to include the three types of drilling occurrences that, alone or in combination, are representative of potential future intrusion events in the WIPP.

33.3.3 40 CFR § 194.33(b) DOE Methodology and Conclusions

The CCA presents an analysis of all known wells, including hydrocarbon borehole exploratory and development wells in the Delaware Basin, and determines that inadvertent and intermittent drilling is the most severe human intrusion scenario. The CCA, Appendix DEL (Section DEL.7.3) and Appendix PA, Attachment SCR, Section SCR.3 include the DOE's analyses of drilling events in the WIPP area. The CCA, Chapter 6.0 identifies scenarios for human intrusion and calculated cumulative radionuclide releases assuming different intrusion events and combinations of events.

The CCA, Appendix DEL, Table DEL-3 presents a listing of the types and number of boreholes encountered within the Delaware Basin. The hydrocarbon borehole category is broken down into seven individual types, including oil, gas, oil/gas, dry, abandoned, injection, and service. Both exploratory wells (boreholes drilled to locate hydrocarbons) and developmental wells (boreholes drilled to exploit known reserves) are included within each category listed in the table. For example, if a well was drilled to explore for natural gas or with the intent to extract more gas by secondary recovery method, both will be classified as gas wells.

By evaluating borehole types and standard well installation practices, the DOE determined that significant release of radionuclides from the disposal system can occur through only five drilling-related mechanisms (see CCA Chapter 6.0, Section 6.0.2.3, p. 6-5) for both exploratory and development wells.

33.3.4 40 CFR § 194.33(b)(1) EPA Compliance Review

The EPA evaluated resources considered by the DOE when developing human intrusion scenarios. The EPA examined resources identified by the DOE (the CCA, Chapter 2.0, Section 2.3.1, pp. 2-146 through 2-156, the CCA; Appendix GCR, and the CCA Appendix DEL, Section DEL.4) and compared them with potential resources available in the area. The EPA reviewed the DOE's data pertaining to wells associated with the exploration and development related to these resources (the CCA, Appendix DEL, Section DEL.7) and concluded that the DOE considered the full spectrum of inadvertent and intermittent human intrusion scenarios possible in the Delaware Basin and incorporated them into the PA.

The EPA found that the DOE adequately demonstrated that it had considered inadvertent and intermittent drilling into or through the repository as the most severe human intrusion scenario (Compliance Application Review Document [CARD] 33, U.S. Environmental Protection Agency 1998d). The EPA concluded that the DOE appropriately evaluated drilling in the Delaware Basin for inclusion in PA and adequately considered the drilling locations, depths, completion

intervals, practices, history, and occurrence of resources. Finally, the EPA concluded that exploratory and development wells were appropriately included in the DOE's analysis.

33.3.5 40 CFR § 194.33(b)(2) DOE Methodology and Conclusions

Based on the regulatory guidance and the historic rate of drilling in the Delaware Basin, the DOE calculated the rate of future drilling as 46.8 boreholes per square kilometer (km^2) per 10,000 years (the CCA, Chapter 6.0, Section 6.0.2.3, p. 6-5). In accordance with 40 CFR § 194.33(c)(1), the DOE assumes that current drilling practices will continue unchanged into the future.

The DOE discusses the drilling rate assumptions in the CCA, Chapter 6.0, Section 6.0.2.3, p. 6-5 and Appendix DEL, Section DEL.7, pp. 80–84. The DOE assumed random drilling events, with respect to both location and time, allocated among three time periods:

- A period when institutional controls are active (0 to 100 years), during which no intrusions will occur
- A period when passive institutional controls (PICs) are effective (100 to 700 years), for which the drilling rate is two orders of magnitude lower than the rate experienced during the uncontrolled period
- An uncontrolled period (700 to 10,000 years)

In the CCA, Chapter 6.0, Section 6.4.12.2, pp. 182–83, the DOE outlines the process by which the random drilling rate assumptions were implemented. The number and time of intrusions were represented using a Poisson process to calculate the time period that elapsed between intrusions based on historical drilling activity and assuming a rate of 46.8 boreholes/km^2 (for the 700 to 10,000 year period), and 0.486 boreholes/km^2 for the period when PICs are effective (100 to 700 years). Specifically, the DOE states in the CCA, Chapter 6.0, Section 6.4.12.2, p. 182, that both the number and time of intrusions are determined sequentially by sampling from a cumulative distribution function that describes the time elapsed between a given intrusion and the next intrusion. The potential time between intrusions varied from 0 to 9,900 years. Using this process, the DOE concluded that the most likely number of intrusions into a waste panel is 5, occurring with a probability of 0.1715. Zero intrusions occurred with a probability of 0.0041. The DOE found the largest number of intrusions that occurred is 14, with a probability of 0.0011 (the CCA, Chapter 6.0, Section 6.4.12.2, p. 183).

The DOE assigned drilling rates based on basin-wide borehole information. The drilling rate calculated for the basin was then applied to the area of the repository by the DOE randomly assigning intrusion borehole locations among 144 discrete regions in the repository. Each hypothetical intrusion was assumed to penetrate only 1 of the 144 blocks, and the probability of intersecting any given block was 1 in 144. Based on the ratio of excavated to undisturbed Salado in each grid block, the DOE concludes that a borehole has a 20% probability of encountering excavated Salado (i.e., waste-filled repository or experimental regions) and an 80% chance of encountering unexcavated Salado (the CCA, Chapter 6.0, Section 6.4.12.3, p. 184).

The DOE did not consider boreholes relevant to the potential for release outside the boundaries of the repository, and therefore only calculated locations that could potentially intrude the repository. Specific well locations in the remainder of the Delaware Basin were not calculated. The CCA, Appendix CCDFGF presents details regarding how the probability of borehole intrusion scenarios was implemented in the construction of future realizations.

33.3.6 40 CFR § 194.33(b)(2) EPA Compliance Review

The EPA reviewed the DOE's implementation of drilling rate and location assumptions, and concluded that the DOE used appropriate methods to derive drilling rates and locations. The EPA determined (U.S. Environmental Protection Agency 1998e) that the DOE adequately demonstrated that drilling events were assigned as occurring over random intervals of time and at random locations. The EPA also reviewed the DOE's implementation of drilling assumptions and determined that the method employed by the DOE in the calculations yields random drilling rate and location results. Use of Poisson distribution to project the time period that will elapse between intrusions was determined to be an acceptable approach. Division of the projected future into three distinct time periods was determined to be appropriately justified. The EPA disallowed PA credit for PICs. Nonetheless, the CCA Performance Assessment Verification Test (PAVT) calculations demonstrated that the effects of the proposed credits for active institutional controls (AICs) and PICs are insignificant, so that the PA results remain unaffected whether or not the credits are allowed (U.S. Department of Energy 1997a).

33.3.7 40 CFR § 194.33(b)(3) DOE Methodology and Conclusions

In the CCA, Appendix DEL, Sections DEL.7.3 and DEL.7.4, the DOE identifies deep drilling that has occurred during the past 100 years for each resource known to occur in the Delaware Basin (hydrocarbons, potash, and sulfur) and calculates the total rate of deep drilling as the sum of the rates for each resource (the CCA, Appendix DEL, Section DEL.4.2). The DOE obtained information on deep drilling from two industry sources, Petroleum Information and the Midland Map Company, based on original records compiled by the New Mexico Oil Conservation Division (NMOCD) and the Railroad Commission of Texas Oil and Gas Division. Approximately 99% of the deep boreholes in the Delaware Basin were related to hydrocarbon exploration and exploitation. Industry database information regarding the number of deep drilling events/resource and information sources is presented in the CCA, Appendix DEL, Tables DEL-3, DEL-4, DEL-6, and DEL-7.

The DOE stated that drilling for deep resources near the boundary of the WIPP site since 1974 has demonstrated that profitable quantities of oil and gas resources are present near, and likely beneath, the WIPP site. The CCA, Appendix DEL, Figure DEL-6 shows oil and gas wells in the area surrounding the WIPP site (the CCA, Appendix DEL, Section DEL.4.2.2.4).

The DOE stated that three hydrocarbon exploration/exploitation deep wells have been drilled in the WIPP land withdrawal area (the CCA, Appendix DEL, Section DEL.4.2.3, p. DEL-20). Of these, two were drilled prior to 1982 and were later plugged and abandoned. The third well, drilled in 1982, is currently producing natural gas from a sandstone reservoir of Pennsylvanian Atokan age. Condemnation actions 77-071-B and 77-776-B by the United States currently withdraws all of Section 31, which is approximately 3.2 km (2 miles) to the southwest of the

repository, from the surface to a depth of 1,829 m (6,000 ft) (the CCA, Appendix DEL, Section DEL.4.2.3). Leaseholders have mineral rights below 6,000 ft (1,829 m), which would be accessed by directional drilling from a surface location outside of Section 31.

The CCA, Appendix DEL, Section DEL.7.4, p. DEL-81, presents the DOE's calculated drilling rate in the Delaware Basin. The DOE calculated a rate of 46.8 deep holes per km^2 over 10,000 years and is shown below:

$$\text{Deep Drilling Rate} = \frac{(\text{Total \# of deep boreholes}) \times \text{Regulatory Period}}{\text{Area of the Delaware Basin}} \times \frac{1}{100 \text{ yrs}}$$

$$= \frac{(10{,}804)\ 10{,}000 \text{ yrs.}}{23102.1 \text{ km}^2} \times \frac{1}{100 \text{ yrs}}$$

$$= 46.765 \text{ deep boreholes per km}^2 \text{ per } 10{,}000 \text{ years}$$

The CCA contains tables that show the specific drilling rates for each type of well and for each type of resource (the CCA, Appendix DEL, pp. DEL-83 through DEL-84). The CCA, Chapter 6.0, Table 6-5 includes deep drilling events. The DOE used the drilling rates calculated from all available historical data as a basis for assigning future rates. These values and related calculation methods are shown in the CCA, Appendix DEL, Table DEL.6 and Table DEL.7. Reductions were made to these rates for AICs and PICs credit in the DOE analysis. As discussed in the CCA, Chapter 6.0, p. 6-181, AICs were credited for completely preventing inadvertent human intrusion for the first 100 years following repository closure. PICs were credited with reducing inadvertent intrusion to 1% of the calculated level for the period from 100 to 700 years after closure.

33.3.8 40 CFR § 194.33(b)(3) EPA Compliance Review

The EPA examined the CCA to determine the adequacy and accuracy of drilling rate calculations presented by the DOE, as well as supporting assumptions and determinations. The EPA examined the comprehensiveness and adequacy of deep drilling information and compared the DOE data to information on standard industry practice that had been collected for the Delaware Basin. The EPA checked the DOE's calculations regarding deep drilling frequency for accuracy and compared them with the EPA's calculations based upon an independently derived database (U.S. Environmental Protection Agency 1998a).

The EPA's review determined that the DOE appropriately identified deep drilling that occurred in the Delaware Basin. The CCA identified resources for which deep drilling is used and estimated the number of drilling events that occurred over the past 100 years as 46.8 boreholes/km^2. The EPA found that the DOE's method was sufficiently explained and that DOE adequately documented sources of supporting information. The EPA concluded that the DOE's results for the total rate of deep drilling are consistent with available data. The EPA disallowed credit for PICs. Therefore, the DOE did not take credit for PICs in the CCA PAVT calculations (U.S. Department of Energy 1997a and 1997b). The results of the PAVT were comparable to the

original CCA results, in which PICs credit was employed; therefore, the EPA concluded that the PICs credit was not significant to the WIPP's compliance with the disposal standards.

The EPA found that the DOE's sources of information on deep drilling were reliable and that the DOE's confidence in the industry database was appropriate, based on the EPA's independent review of industry activity in the area (U.S. Environmental Protection Agency 1998a). The DOE identified all resources relevant to deep drilling. Well databases are understood to contain all well types possible in the area, including both exploratory and development wells. Public comments on the proposed decision to certify the WIPP raised questions about the DOE's calculated deep drilling rate because commenters believed that the drilling rate used by the DOE was too low with respect to current drilling rates. The EPA concluded that the deep drilling rate used by the DOE was consistent with the requirements of 40 CFR Part 194.

33.3.9 40 CFR § 194.33(b)(4) DOE Methodology and Conclusions

The DOE examined the resources present within the Delaware Basin and determined that the shallow resources identified in the Delaware Basin are water, potash, sulfur, oil/gas, and brine wells (salt water "wells") (the CCA, Appendix DEL, Section DEL.4, Table DEL-5). Note: This table also presents stratigraphic and core test holes, but these apply to investigations associated with the five resources. The DOE examined these resources and determined that no shallow oil or gas is present in the controlled area or near the WIPP, and no minable sulfur reserves are present in the controlled area or near the WIPP (the CCA, Appendix DEL, p. DEL-81). The DOE also examined the possibility of brine extraction (solution mining) but excluded it from consideration in PA based upon low consequence. The DOE concluded that water and potash are potential resources within the controlled area, but nevertheless included drilling for oil/gas, brine extraction (solution mining), and stratigraphic test holes (exclusive of those installed as part of the WIPP site characterization program) in its shallow drilling rate calculations.

The DOE identifies a total of 5,536 shallow boreholes that have been installed in the Delaware Basin, including those for sulfur coreholes (495 coreholes) but excluding those boreholes installed as part of the WIPP site characterization program (the CCA, Appendix DEL, Table DEL-5, p. DEL-83).

The DOE's method for calculating the shallow drilling rate was first to collect comprehensive information on shallow drilling in the Delaware Basin, including drilling for hydrocarbons, sulfur, potash, stratigraphic tests, water, and brine extraction (solution mining) wells (the CCA, Appendix DEL, Table DEL-5). The DOE stated that information regarding shallow drilling in the Delaware Basin was obtained from commercial and government sources. The DOE collected water well data from a commercial database developed by Whitestar Corporation of Englewood, Colorado; potash well data from Bureau of Land Management (BLM) records; and sulfur corehole data from a database developed jointly by Whitestar Corporation and Petroleum Information Corporation of Denver, Colorado (the CCA, Appendix DEL, Tables DEL-3, DEL-4, and DEL-7). Sources used to determine the type and quality of resources include those used to determine the drilling rate.

The DOE calculated the total rate of shallow drilling as the sum of the rates for shallow drilling of resources in the Delaware Basin of the type and quality similar to those in the WIPP-

controlled area. DOE excluded consideration of the 495 sulfur drill holes when calculating the drilling rate, since no economically extractible sulfur is located within the WIPP land withdrawal area (the CCA, Appendix DEL, pp. DEL-25 and DEL-81; New Mexico Bureau of Mines and Mineral Resources 1995). Also, following EPA guidance, the DOE excluded consideration of shallow drill holes created as part of the WIPP site characterization efforts (the CCA, Appendix DEL, p. DEL-81). However, the DOE included drilling for oil/gas and brine solution mining in its rate calculations, even though the DOE indicated that it was not necessary to do so. The DOE calculated a shallow drilling rate over the past 100 years of 21.8 shallow holes per km^2 per 10,000 years (the CCA, Appendix DEL, Section DEL.7.4, p. DEL-81).

The DOE presents the shallow drilling rate for each resource in the CCA, Appendix DEL, Table DEL-5, p. DEL-83. The DOE indicated in a footnote to the CCA, Appendix DEL, Table DEL-5, p. DEL-83 that the number of shallow holes per km^2 is calculated as follows:

$$\text{Drilling Rate} = \frac{(\text{Total \# of boreholes - Sulfur coreholes}) \times \text{Regulatory Period}}{\text{Area of the Delaware Basin}} \times \frac{1}{100 \text{ yrs}}$$

$$= \frac{(5536\text{-}495)\ 10{,}000 \text{ yrs.}}{23102.1 \text{ km}^2} \times \frac{1}{100 \text{ yrs}}$$

$$= 21.821 \text{ shallow holes per km}^2 \text{ per } 10{,}000 \text{ years}$$

The DOE concludes in the CCA, Appendix SCR that shallow drilling (Section SCR.3.2, Table SCR-3) could be screened from PA based on low consequence. As a result, the DOE did not include shallow drilling in its PA drilling rate calculations and did not include any reduction in shallow drilling rates during the AIC and PIC periods.

33.3.10 40 CFR § 194.33(b)(4) EPA Compliance Review

The EPA reviewed the CCA, Appendices DEL, SCR, GCR, FAC, HYDRO, and other references (e.g., New Mexico Bureau of Mines and Mineral Resources 1995) and determined that the DOE appropriately identified shallow drilling resources and the number of drilling events for each resource over the past 100 years (U.S. Environmental Protection Agency 1998e). The EPA concluded that the DOE's exclusion of sulfur coreholes from drilling was consistent with geologic data indicating that sulfur resources are not present in the area. In addition, the DOE's exclusion of site-investigation coreholes is consistent with EPA guidance. The DOE adequately discussed the basis for and calculation of the frequency of shallow drilling. The EPA concluded that the DOE properly calculated both the frequency of shallow drilling (using the historical rate of shallow drilling) and the sum of shallow drilling for all resources (whichever are used in the area, such as potash and water only).

The EPA reviewed information in the CCA, Chapter 6.0 and Appendix DEL, but did not collect an independent database for comparison with the DOE's data because the EPA concurred with the DOE's screening of shallow drilling from PA calculations (as presented in the CCA, Appendix SCR, Section SCR.3, and summarized in Table SCR-3). The DOE states that since shallow boreholes would not penetrate the repository, the effects of boreholes on repository

performance, including hydraulic effects of drilling-induced flow (e.g., the CCA, Appendix SCR, Section SCR.3.3.1.1.3, pp. SCR-113-14), could be excluded due to low consequence. This exclusion precluded the need for a detailed evaluation of data used by the DOE to determine shallow drilling rates including whether the DOE's rates included exploratory and development wells (although assessments included both). The DOE states, "The effects of future shallow drilling within the controlled area have been eliminated from PA calculations on the basis of low consequence" (the CCA, Chapter 6.0, Section 6.2.5.2, p. 6-61). As such, the shallow drilling rate was not added to the deep drilling rate to obtain the total drilling rate used in the PA.

The EPA noted that the DOE took a combined approach relative to resources in the controlled area. That is, the DOE considered all the resources present in the area in shallow drilling rate calculations. Only drilling for potash and water wells fall in the shallow category (less than 655 m [2,150 ft] from the surface); thus, only these two resources were used in the calculation of shallow drilling rate for the controlled area. The EPA concluded that the DOE adequately discussed resources within the controlled area for those resources included, and justified the exclusion of other resources from consideration.

33.3.11 40 CFR § 194.33(c)(1) DOE Methodology and Conclusions

In the CCA, Appendix DEL, Section DEL.5.1, p. 26, the DOE states that modern rotary drilling techniques, with a variety of mud systems, have been used for well completions in the vicinity of the WIPP. The DOE indicated that drilling depths range from 1,219 m (4,000 ft) to more than 4,267 m (14,000 ft), depending on the hydrocarbon producing formation targeted. As stated in the CCA, Appendix DEL, Section DEL.4.2, the DOE took information regarding the depths of wells and probable resources primarily from Chapter IX of New Mexico Bureau of Mines and Mineral Resources (1995). The DOE stated that wells designed to penetrate the deeper Atokan natural gas plays (over 4,267 m [14,000 ft] below ground surface) tend to start at the surface with larger bits and conductor casings, and are completed with a long production string of 4 ½- to 5½-in casing. In such wells, the larger casing string present through the lower salt sections tends to be 8 in., 9 in., or larger in diameter.

The DOE indicated that wells intended for completion in the relatively shallower (approximately 1,524 m to 2,438 m [5,000 to 8,000 ft] deep) Delaware Group are drilled with similar technology and mud systems through the salt sections. Long string casing present across the Bell Canyon varies from 4 ½ to 13 in. Completions may use 2- or 3-in. tubing strings. Standard completion technology for both the Delaware Group and Atokan wells includes perforation of the long string casing with a hydraulic fracture treatment using a variety of gelled fluids to emplace sand proppant into the fractures. The DOE indicates that acid treatments and acid fracture treatments are frequently used, especially for Brushy Canyon completions (the CCA, Appendix DEL, Section DEL.5.1.9, p. DEL-40).

The DOE assumed that all oil and gas related boreholes in the area will be plugged according to current applicable regulations. The DOE based this assumption on records for wells drilled on federal lands, for which the NMOCD data showed that all wells were either plugged or scheduled to be plugged in accordance with regulatory requirements. A DOE study, provided in the CCA, Appendix MASS, Attachment 16-1, indicated that 100% of wells drilled and

abandoned since 1988 were, or are in the process of being, plugged per applicable BLM or NMOCD regulatory standards pertaining to technical requirements.

33.3.12 40 CFR § 194.33(c)(1) EPA Compliance Review

Based on review of data presented in the CCA, Chapter 6.0, Section 6.4.7.2 and Appendices DEL and MASS, the EPA found that the DOE has assumed that future drilling practices and technology will remain consistent with current practices in the Delaware Basin. In addition, the EPA determined that the DOE performed appropriate assessments of future drilling practices and technologies—including the types/amounts of drilling fluids and borehole dimensions—and that the assessments were consistent with data presented in the above-referenced CCA appendices. The EPA's evaluation of state files, private database records, and independent industry practice information confirmed the DOE's assumptions regarding future drilling practices and technologies, including the types/amounts of drilling fluids, and borehole dimensions (U.S. Environmental Protection Agency 1998a).

During the public comment period for the proposed certification decision, the EPA received comments that stated air drilling is current practice in the Delaware Basin. As a result of these questions, the EPA performed additional analyses of air drilling to determine whether it is common practice in the Delaware Basin. See the EPA's Analysis of Air Drilling at the WIPP (U.S. Environmental Protection Agency 1998b) and Response to Comments, Section 8 (U.S. Environmental Protection Agency 1998c). Based on this analysis, the EPA again determined that the use of mud as the drilling fluid is the current practice for drilling through the salt section (the Salado and Castile Formations) and that air drilling through the salt section is not consistent with current drilling practices in the Delaware Basin. Thus, the DOE properly excluded air drilling through the salt section from consideration in the WIPP PA.

The EPA informed the DOE in a letter dated December 19, 1996, that the DOE was required to provide detailed information about the large number (7,428) of unaccounted boreholes (the CCA, Appendix DEL, Table DEL-2) and about the inclusion of the effects of unplugged boreholes in the PA (Nichols 1996). The EPA required this information because the unplugged/abandoned borehole issue was not clearly presented in the CCA. The DOE's response to this comment is presented in three subparts (Dials 1997, Enclosure 2):

- The total number of boreholes listed in the CCA, Appendix DEL, Table DEL-2 is not consistent with the record keeping system of NMOCD (data source) because the categorization of data does not take into consideration the temporarily abandoned boreholes, service wells, injection wells, and dry wells. In addition, data came from different sources and different assumptions were made.

- The current regulatory process was designed, in part, to address the issue of unplugged boreholes. The EPA believes that the DOE appropriately identified that there are no unaccounted wells within the land withdrawal area. Wells in the land withdrawal area are either shallow or deep research boreholes drilled by the DOE, or several abandoned but plugged wells (see the CCA, Appendix DEL, Figure DEL-6). The DOE plans to follow State of New Mexico requirements in plugging boreholes drilled into the disposal system.

- The DOE stated that considering the degradation in plug properties to those of silty sand over time accounted for the issue of unplugged holes. The changes in properties were included in PA. The EPA agrees that boreholes will degrade, but the EPA believes that the permeability range should be different than that selected by the DOE (see below).

The EPA found the DOE's discussion to be technically adequate, because the boreholes in question are outside of the land withdrawal area and are not expected to affect the disposal system's capability to contain radionuclides. The EPA concluded that the DOE appropriately screened out abandoned boreholes drilled just meters away from the waste because of the limited communication through the low-permeability halite between the waste and the boreholes (U. S. Environmental Protection Agency 1998f).

The DOE included in the PA boreholes drilled into the waste areas. The DOE assumed that abandoned boreholes would have the permeability of silty sand. The EPA agreed that the upper limit of permeability assumed by the DOE was appropriate. However, the EPA believes that it is possible for abandoned boreholes to have low permeability, similar to a recently plugged borehole (U.S. Environmental Protection Agency 1998g). The EPA therefore required the DOE to include a larger range of long-term concrete plug permeability values in the CCA PAVT (Trovato 1997). This range in borehole permeability values is from 5×10^{-17} to 1×10^{-11} m^2, which the EPA believes covers the behavior of plugs in the Delaware Basin. The PAVT findings indicated that even with these changes in the borehole permeability, the releases did not violate the containment requirements.

33.3.13 40 CFR § 194.33(c)(2) DOE Methodology and Conclusions

The CCA, Appendix DEL, Attachment 7 (Inadvertent Intrusion Borehole Permeability) addressed borehole permeability variation. The CCA, Appendix DEL used published literature, plugging field tests, and oil and gas companies' experience to assess borehole permeability. The CCA, Appendix DEL also addressed wells that were plugged since 1988, when the State of New Mexico adopted new drilling and plugging regulations. Boreholes existing prior to 1988 are extremely limited in number within the WIPP land withdrawal area. The DOE accounted for the risk and uncertainties associated with boreholes drilled prior to 1988 in the PA by using various behaviors of plugs in the Delaware Basin. Borehole plug life for a two-plug configuration was considered in PA calculations to be 200 years; beyond that period, permeability was equivalent to marine silty sand and was held constant for the remainder of the regulatory period. The DOE assumed that processes that affect boreholes include steel casing corrosion and concrete plug alteration.

The DOE described different portions of the borehole over which degradation would act by first assigning plugging configurations for deep drilling in the Delaware Basin to one of three categories: a two-plug configuration, a three-plug configuration, and a continuous cement plug. The DOE evaluated the frequency of plug configurations based on those of 188 Delaware Basin wells installed since 1988. This provides an adequate database for analysis. Based on this study, the DOE assigns the following frequencies for each configuration (the CCA, Chapter 6.0, Section 6.4.12.7, p. 6-198):

- One continuous plug through the evaporite sequence: probability of 0.02.

- Two plugs—one in the Bell Canyon (below the potential brine reservoirs) and one in the Rustler Formation (between the Culebra of the Rustler Formation (hereafter referred to as Culebra) aquifer and the repository): probability of 0.68.

- Three plugs—two as described for the two-plug form and a third plug in the Salado: probability of 0.30.

The DOE estimated that this plug system was expected to have an initial permeability of 5×10^{-17} m^2. The DOE assumed that casings would corrode due to the saline groundwater environment (the CCA, Appendix DEL, Attachment 7, Appendix B) and that concrete plugs would degrade when sufficient water entered a plug to cause matrix degradation (the CCA, Appendix DEL, Attachment 7, Appendix C). The DOE also assumed that shallower casing and cement plugs will degrade in 200 years, allowing for more potential fluid flow earlier in the regulatory period in shallower horizons compared to deeper casing, which was assumed to fail approximately 5000 years after installation. The DOE assumes that the "corroded casing and degraded plug will fill the hole with material with a permeability approximating that of silty sand (10^{-11} to 10^{-14} m^2), and over time any of this material below the repository will compress through creep closure of the borehole to a permeability about one order of magnitude lower" (the CCA, Appendix DEL, Attachment 7, p. 19). Plug configurations do not apply explicitly to shallow drilling, except that abandoned shallow boreholes typically are continuously cemented and "are expected to have no effect on the performance of the WIPP" (the CCA, Appendix DEL, Section DEL.5.2, p. DEL-41).

The DOE concludes in the CCA, Appendix DEL, Section DEL.7.4, that permeability for each of the three types of plug systems never exceeded that of silty sand (10–11 to 10–14 m^2) over the 10,000-year regulatory period. The DOE offers the following borehole permeability changes over time, with the higher permeabilities the result of natural borehole degradation that would also potentially allow for increased fluid flow:

- One plug: 5×10^{-17} m^2 for 10,000 years

- Two plugs:
  - Between the repository and the surface
    - 5×10^{-17} m^2 for 200 years
    - 10^{-14} to 10^{-11} m^2 after 200 years
  - Between the Castile and the repository
    - "very high" permeability to 200 years (10^{-9} m^2)
    - 10^{-14} to 10^{-11} m^2 up to 1,200 years
    - 10^{-15} to 10^{-12} m^2 after 1,200 years

- Three plugs:
  - Between the intermediate plug and the surface
    - 5×10^{-17} m^2 for 200 years
    - 10^{-14} to 10^{-11} m^2 after 200 years
  - Intermediate plug
    - 5×10^{-17} m^2 for a median time of 5,000 years
  - Borehole between the Castile and the repository
    - 10^{-14} to 10^{-11} m^2 for 1,000 years (after 5,000 years)
    - 10^{-15} to 10^{-12} m^2 after 6,000 years.

Dimensions of cement plugs for the scenarios above were assumed by the DOE to be

- One plug: 3,000 ft (900 m), 50 tons of concrete (20 cubic meters [m^3]), and
- Other plugs: 150 ft (45.73 m), 2.5 tons of concrete (1 m^3).

The DOE assumed that plug system permeability will change over time in 98% of the configurations and will not change in 2% of the configurations. The DOE assumed that permeability change with time behaved according to the following relationship:

$$\Delta k = k_i \left(10^{7.39\Delta\eta - 1}\right)$$

where

Δk = change in permeability
k_i = initial hydraulic conductivity
$\Delta\eta$ = change in porosity from mineral alterations.

The DOE assumed that the permeability of plug systems is never greater than 10^{-11} m^2. Assumptions made by the DOE regarding borehole plug permeability and casing corrosion are presented in the CCA, Appendix DEL, Attachment 7.

33.3.14 40 CFR § 194.33(c)(2) EPA Compliance Review

The EPA reviewed the CCA, Appendices DEL and MASS and determined that the DOE sufficiently identified natural borehole degradation mechanisms that will affect boreholes over time. The EPA also examined the plug configurations presented by the DOE and compared these generalized configurations with those for oil/gas and potash resource boreholes in the WIPP vicinity, as evidenced by the resources targeted and necessary plugging techniques. The EPA determined that the DOE's plug configurations (which directly impact the portions of the

borehole over which degradation processes are expected to act) and plug probabilities are adequate representations of the plugs in the WIPP area (U.S. Environmental Protection Agency 1998g).

The EPA evaluated the effects that natural degradation of long-term borehole plugs would have on the plug system and the potential for increased transmissivity of abandoned well plugs due to such degradation. The EPA disagreed with the DOE's lower limit for borehole plug permeability. Although the DOE's permeabilities assigned for the various plug configurations were based on plausible data, the EPA believed the DOE assumed a low-end permeability that was too high. For further discussion of EPA's analysis of borehole permeabilities, see the Parameter Justification Report (U.S. Environmental Protection Agency 1998g).

If degraded boreholes are assumed to be filled with materials analogous to unconsolidated silt or silty sand, the permeabilities of 1×10^{-14} to 1×10^{-11} m^2 used by the DOE are not unreasonable estimates of values per industry standards (Freeze and Cherry 1979). (For purposes of comparison, the permeability range reported for shale and unweathered marine clay varies from 10^{-21} to 10^{-17} m^2. See the CCA, Appendix MASS, Attachment 16-3) (Thompson et al. 1996). However, as discussed below, the EPA investigated this assumption and found that permeability values could be lower than the DOE assumed. Lower values allow for greater gas pressurization of the WIPP and a subsequent increase in releases due to mechanisms such as spallings (U.S. Environmental Protection Agency 1998g, Section 5.17).

The EPA began by investigating the permeability of borehole materials and drilling fluids in the petroleum industry. Literature values for permeability of cement used in borehole applications can range from 9×10^{-21} to 1×10^{-16} m^2; these values are also cited in some of the publications referenced in the CCA. The EPA also investigated drilling muds. Filter cake and compacted clay-based drilling muds can yield permeabilities of less than 9.9×10^{-22} m^2 from field data for 11 pounds per gallon mud (U.S. Environmental Protection Agency 1998g, Section 5.17).

The EPA concludes that drilling mud circulated in Delaware Basin boreholes may not have the degree of clay-based solids loading typically experienced elsewhere (as discussed in the CCA, Appendix MASS, Attachment 16-3; Annex C); however, natural cuttings could contribute to lower borehole permeability than that postulated by the DOE. Lower initial permeabilities, more effective plug segments, mixed layers between plug components that would take time to degrade, and lower fluid velocities than the DOE assumed in its calculations could significantly retard plug degradation and could maintain the effective seal of the plug sequences for hundreds or thousands of years beyond that assumed by the DOE in the CCA, Appendix MASS, Attachment 16-3.

The DOE provided a variety of plausible mechanisms to increase plug permeability, and the EPA believes that this high range of permeability may be attained. However, the EPA also believes there is a limited probability that the lower borehole permeability (over several hundred vertical feet of borehole) would reach the relatively large permeabilities estimated by the DOE. Since permeability through any given borehole will actually be controlled by the permeabilities of all zones through which fluids must pass, the effective average permeability could be dominated by small sections of remaining competent plug or other low permeability material. If complete degradation does not occur throughout a well, or if natural materials and mud provide additional

layers with sealing properties, it is possible that the effective average permeability over several hundred feet of abandoned borehole could remain in the range of 9×10^{-21} to 1×10^{-16} m^2 over a period of hundreds, if not thousands, of years.

The EPA concludes that the borehole permeabilities assigned in the CCA (Appendix MASS, Attachment 16-3) were consistent with the broad range of available permeability data, but the DOE did not adequately consider the total range of permeability conditions that could exist in boreholes. Permeabilities assigned by the DOE may therefore overestimate the degree to which plugs would lose effectiveness. The EPA concluded that an alternative case could be made in which many of the plugs would retain a larger degree of effectiveness. As such, a lower maximum permeability value of approximately 1×10^{-17} m^2 (1×10^{-2} millidarcy) is quite possible (particularly for long-term conditions) and may have an impact on PA results. As a result, the EPA included both long- and short-term plug permeability changes in the CCA PAVT. The EPA required that PA simulations be conducted with lower permeabilities (concrete element of the borehole plug has a maximum of 10^{-19} m^2; silty sand element of the borehole plug has a maximum of 5×10^{-17} m^2) to account for possible cases in which complete degradation does not occur throughout a well, or natural materials and mud provide additional layers with sealing properties. Results of the CCA PAVT indicate that lower borehole permeability allows greater pressure buildup in the repository and, hence, greater release potential from mechanisms such as spallings. However, releases predicted by the CCA PAVT were still well below the EPA's release limits (U.S. Department of Energy 1997a 1997b).

In summary, the EPA agreed that the high permeabilities assumed by the DOE were generally appropriate; however, the EPA believed it is also possible for abandoned boreholes to have a lower permeability, similar to that of a recently plugged borehole (U.S. Environmental Protection Agency 1998g). Therefore, the EPA required the DOE to include larger ranges of undegraded concrete plug and long-term borehole filling permeability values in the CCA PAVT (Trovato 1997). The range of 1×10^{-17} to 1×10^{-19} m^2 was used in the CCA PAVT for an undegraded concrete plug, and the range of 1×10^{-11} to 5×10^{-17} m^2 was used in the CCA PAVT for a degraded borehole filling. The EPA found that these ranges adequately cover the behavior of plugs in the Delaware Basin. The results of the CCA PAVT indicated that even with these changes in the range of permeabilities for degraded borehole plugs, releases did not violate the EPA's containment requirements.

The EPA believes that its detailed review of the DOE's borehole plugging assumptions provided an adequate basis for the EPA's conclusion that the DOE's assumptions were acceptable. Although the EPA originally questioned many of those assumptions, further investigations substantiated many of the DOE's assumptions, and the use of modified permeability ranges in the CCA PAVT did not cause releases to exceed regulatory limits.

33.3.15 40 CFR § 194.33(d) DOE Methodology and Conclusions

The DOE assumed that future drilling practices will be the same as current practice in terms of the type and rate of drilling, emplacement of casing in boreholes, and procedures for plugging and abandonment. The DOE did not include the impact of resource recovery subsequent to future drilling of boreholes on the basis of low consequence. The DOE did not include the effects of resource recovery techniques in the PA analysis of future human intrusion. In

addition, in the deep drilling disturbed performance scenario, the DOE examined three drilling-only scenarios, but these did not incorporate resource recovery techniques. The DOE states in the CCA, Chapter 6.0, p. 6-60 that the PA did not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

33.3.16 40 CFR § 194.33(d) EPA Compliance Review

The EPA determined that the DOE was in accordance with the provisions of 40 CFR § 194.33(d) as the PA did not analyze the effects of resource recovery techniques in future drilling events (U.S. Environmental Protection Agency 1998e).

33.4 Changes in the CRA-2004

Table 33-1 presents changes in the CRA-2004 PA that relate to drilling for resources. This represents the migration of the PA baseline from the CCA to the CRA-2004. As noted below, most changes result from adopting the CCA PAVT parameters as directed by the EPA. Also, unless noted below, all other aspects of compliance with section 194.33 are consistent with that presented in the CCA, and do not represent changed or updated information.

Table 33-1. WIPP Project Changes and Cross References

WIPP Project Change	CRA-2004 Cross Reference
Incorporation of 1997 CCA PAVT Parameters	
Probability of Encountering a Brine Reservoir	6.0.2.3.8, 6.4.8, 6.4.12.6
Brine Reservoir Rock Compressibility	6.4.8
Brine Reservoir Porosity	6.4.8
Drill String Angular Velocity	Appendix PA, Attachment MASS (Section 16) and Attachment PAR
Long-term Borehole Permeability	6.4.7.2
Borehole Plug Permeability	6.4.7.2
Waste Shear Strength and Erodability	Appendix PA, Attachment MASS (Section 16)
Operational Changes	
Spallings Model	6.0.2.3.2; Appendix PA (Section 4.6) and Attachment MASS-16
Drilling Rate	6.0.2.3, 6.2.5.2; Appendix DATA (Section 2 and Attachment A)
Borehole Plugs Configuration Probability	6.4.7.2

33.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed the DOE's CRA-2004 documentation of continuing compliance with section 194.33 and concurred that little had changed since the CCA for the consideration of drilling events. The DOE adopted the EPA's PAVT parameter values and updated a few parameters based on the data collected from the Delaware Basin Monitoring Program. The EPA also concurred that the features, events, and processes (FEPs) had changed little for the CRA-2004.

The EPA found the DOE adequately demonstrated that it had considered inadvertent and intermittent drilling into the repository as the most severe human intrusion scenario for the CRA-2004 PA. The EPA concludes that exploratory and development wells were appropriately included in the DOE's CRA-2004 analysis (CARD 23, U.S. Environmental Protection Agency 2006).

Since the original CCA, the EPA has annually inspected the DOE's site monitoring program, in particular, the Delaware Basin drilling surveillance program. Each year, the EPA found the DOE's monitoring program to be adequate. The EPA found the DOE's compliance with the requirements of 40 CFR § 194.33(b)(4) related to shallow drilling to be adequate. The EPA found the DOE's documentation adequate to support their conclusion that drilling practices have not changed since the original CCA, that the DOE's basin surveillance program is sufficient to evaluate and capture any changes in activities in the basin.

The EPA agreed that borehole plugging techniques used in the CCA and CRA-2004 PA calculations have not changed, and therefore the way these are incorporated into the PA calculations is appropriate. The EPA also agreed that the minor change in the occurrence probability of plug configurations is appropriate and of no consequence to PA results.

Public comments expressed concern that the drilling rate was underestimated in the CRA-2004 PA given the amount of drilling currently taking place throughout the Delaware Basin. Comments suggested that the drilling rate be doubled to demonstrate compliance. Although the EPA determined that the DOE appropriately calculated and implemented a drilling rate of 52.2 boreholes/km^2/year in compliance with 40 CFR § 194.33(b) for recertification, the EPA requested that the DOE calculate the impacts of doubling the current drilling rate to respond to stakeholder concerns.

The DOE performed the calculations for this analysis with the drilling rate increased to 105 boreholes/km^2/year for 10,000 years. The results of computer modeling showed that doubling the drilling rate would increase releases from the repository. However, this increase is relatively small and still well below the EPA's regulatory release limits (CARD 23, U.S. Environmental Protection Agency 2006).

33.6 Changes or New Information Since the 2004 Recertification

There are two changes in the CRA-2009 that relate to the consideration of drilling in PA. First, the drilling rate has been updated based on drilling activities in the Delaware Basin since the CRA-2004 in accordance with 40 CFR § 194.33(b)(3) (see Appendix PA-2009, Section PA-3.3). Second, the duration of DBR has been modified to reflect current industry practice, in accordance with section 194.33(c)(1) (see Appendix PA-2009, Section PA-4.7.8). Furthermore, because recertification applications are expected to include any relevant updated activities and information since the most recent application, these changes are considered necessary to comply with the provisions of 40 CFR § 194.15(a)(4).

The following sections describe how these two changes relate to a demonstration of compliance with the provisions of section 194.33. Unless noted below, all other aspects of compliance with

section 194.33 are consistent with that presented in the CRA-2004, and do not represent changed or updated information.

33.6.1 New Information Related to 40 CFR § 194.33(a)

Potentially disruptive events and processes (EPs) that could affect the disposal system are identified, classified, and screened in the CRA-2004, Appendix PA, Attachment SCR. EPs that are screened into PA calculations are then incorporated into the appropriate scenarios and conceptual models. For the CRA-2009, there are no changes in the EPs screened into PA, or the scenarios and conceptual models that represent them. Therefore, the DOE continues to comply with 40 CFR § 194.33(a).

33.6.2 New Information Related to 40 CFR § 194.33(b)

There is no change in the implementation of the inadvertent human intrusion scenarios for this CRA-2009. PA continues to represent inadvertent and intermittent intrusion by drilling for resources as the most severe human intrusion scenario. Therefore, the DOE continues to comply with 40 CFR § 194.33(b)(1).

There is no change in the implementation of the location and timing of the intrusion borehole in the WIPP PA. Such events are assumed to occur randomly in space and time, as directed by the above criterion. These specific PA assumptions are implemented in the code CCDFGF, and described in the CCA, Chapter 6.0, Section 6.4.12. Additional details on the implementation of these assumptions are found in Appendix PA-2009, Section PA.3.2. Therefore, the DOE continues to comply with 40 CFR § 194.33(b)(2).

The method for determining the deep drilling rate for the WIPP PA has not changed. However, the drilling rate for this CRA-2009 is different from that used in the CRA-2004. This is due to the addition of recently drilled wells since the last recertification application. Derivation of the drilling rate used in PA is found in the Delaware Basin Monitoring Report for 2007 (U.S. Department of Energy 2007). For this CRA, the drilling rate is 58.5 boreholes/km^2. Therefore, the DOE continues to comply with section 194.33(b)(3).

The method for determining the shallow drilling rate for the WIPP has not changed since CRA-2004. The current rate of shallow drilling is 22.87 boreholes/km^2 and is based on information provided by Hughes (2008). The current shallow drilling rate is determined as follows:

$$\text{Drilling Rate} = \frac{\text{Total shallow boreholes} \times \text{Regulatory Period}}{\text{Area of the Delaware Basin}} \times \frac{1}{100 \text{ yrs}}$$

$$\text{Drilling Rate} = \frac{5{,}284[1] \times 10{,}000 \text{ yrs.}}{23102.1 \text{ km}^2} \times \frac{1}{100 \text{ yrs}}$$

$$= 22.87 \text{ shallow holes per km}^2 \text{ per } 10{,}000 \text{ years}$$

[1] The total shallow borehole count is derived by taking the total shallow count (6,179) as reported in U.S. Department of Energy, Table 4 (1997), and removing Sulfer holes (502), WIPP wells (199), and those holes currently being drilled or pending paperwork (194).

However, shallow drilling continues to be screened out of PA calculations for the CRA-2009 because of low consequence. Therefore, there are no changes with regard to compliance with this part of the compliance criteria and the DOE continues to comply with section 194.33(b)(4).

33.6.3 New Information Related to 40 CFR § 194.33(c)

The Delaware Basin Monitoring Annual Report for 2007 states that drilling practices have not changed since previous reports (see U.S. Department of Energy 2007, Section 4). However, one change has been made to the WIPP PA system since the CRA-2004 that relates to analyzing drilling-related events: The maximum time a DBR can occur has been changed from 11 days to 4.5 days. The maximum DBR duration is represented in PA by the parameter MAXFLOW and used in the code BRAGFLO. Kirkes (2007) documents that this change is in keeping with current drilling practices within the Delaware Basin and the previous assumption of 11 days was incorrect. Kirkes and Clayton (2008) document the impacts of reducing the maximum duration of DBR and show that this change has a very minor impact upon performance predictions. Appendix PA-2009, Section PA.9.3 discusses the contribution of DBR to total releases for the CRA-2009 performance calculations. Therefore, the DOE continues to comply with 40 CFR § 194.33(c).

33.6.4 New Information Related to 40 CFR § 194.33(d)

No changes have occurred with respect to the WIPP's approach to compliance with this requirement. As in previous applications, certain EPs that relate to the extraction and production of resources can be screened out of PA calculations. Appendix SCR-2009 states that the human-related FEPs H19, "Explosions for Resource Recovery," H25, "Oil and Gas Extraction," and H26, "Groundwater Extraction," are screened out according to the exclusion afforded by the provision of section 194.33(d), as these processes directly relate to the recovery of resources subsequent to drilling. Three new FEPs for the CRA-2009 are also screened out according to the criteria of section 194.33(d): H60, "Liquid Waste Disposal–inside the WIPP boundary (IB)," H61, "Enhanced Oil and Gas Production–IB," and a "Hydrocarbon Storage–IB," are screened out for the future time frame using this regulatory provision. Therefore, the DOE continues to comply with section 194.33(d).

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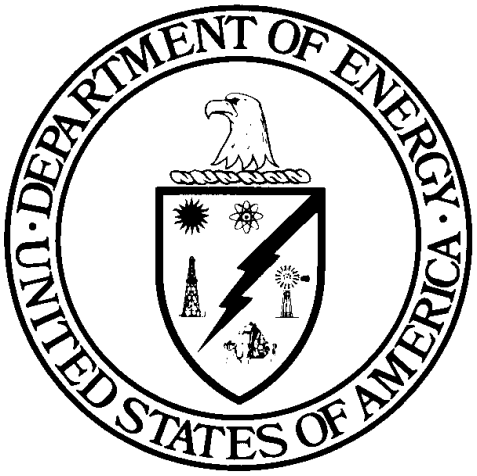
Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Results of Performance Assessments
(40 CFR § 194.34)



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Results of Performance Assessments
(40 CFR § 194.34)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CPR	cellulose, plastic, and rubber
CRA	Compliance Recertification Application
DBR	direct brine release
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
LHS	Latin hypercube sampling
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
WIPP	Waste Isolation Pilot Plant

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34.0 Results of Performance Assessments (40 CFR § 194.34)

34.1 Requirements

§ 194.34 Results of Performance Assessments

(a) The results of performance assessments shall be assembled into complementary, cumulative distribution functions (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

(b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application.

(c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application.

(d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability. Values of cumulative release shall be calculated according to Note 6 of Table 1, Appendix A of Part 191 of this chapter.

(e) Any compliance application shall display the full range of CCDFs generated.

(f) Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of 40 CFR 191.13.

34.2 40 CFR § 194.34(a)

34.2.1 Background

The radioactive waste disposal regulations of 40 CFR Part 191 Subparts B and C (U.S. Environmental Protection Agency 1993) include containment requirements for radionuclides. The containment requirements of 40 CFR § 191.13 specify that releases from a disposal system to the accessible environment must not exceed the release limits set forth in Part 191 Appendix A, Table 1. Assessment of the likelihood that the Waste Isolation Pilot Plant (WIPP) will meet the release limits is conducted through a process known as a performance assessment (PA). The WIPP PA consists of a series of computer simulations that model the physical attributes of the repository (site, geology, waste forms and quantities, engineered features) in a manner that captures the expected behaviors and interactions among its various components over the 10,000-year regulatory time frame.

The PA must consider all significant processes and events that may affect the disposal system (see Section 32 of this application), and it must be structured and conducted in a way that (1) demonstrates an adequate understanding of the physical conditions at the disposal system and its surroundings and (2) shows that the future performance of the system can be predicted with reasonable assurance. In addition, it must include simulations for both undisturbed conditions and human intrusion scenarios. The results of the PA are used to demonstrate compliance with the containment requirements of section 191.13.

The containment requirements place limits on the likelihood of radionuclide releases from a disposal system. A radionuclide release to the accessible environment is defined in terms of the location of the release and its magnitude. Any release of radionuclides to the ground surface,

atmosphere, or surface water is considered a release to the accessible environment. In addition, any subsurface transport of radionuclides beyond the boundary of the WIPP controlled area is also considered a release to the accessible environment.

The results of the WIPP PA are required to be expressed as complementary cumulative distribution functions (CCDFs). A CCDF indicates the probability of exceeding various levels of cumulative release. The CCDFs must be generated using random sampling techniques that draw upon the full range of values established for each uncertain parameter.

34.2.2 1998 Certification Decision

To meet the requirements of 40 CFR § 194.34(a) (U.S. Environmental Protection Agency 1996), the U.S. Environmental Protection Agency (EPA) expected the U.S. Department of Energy (DOE) to demonstrate that

1. The results of the PA were assembled into CCDFs.

2. The CCDFs represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

3. All significant processes and events that may affect the repository during the 10,000-year period after closure have been incorporated into the CCDFs presented.

The EPA reviewed the features, events, and processes for WIPP and the construction of the CCDFs for the Compliance Certification Application (CCA) (U.S. Department of Energy 1996). The EPA concluded that the DOE appropriately captured the significant processes and events that could occur during the regulatory period in the CCDFs and thus complied with the requirements of section 194.34(a).

A complete description of the EPA's 1998 Certification Decision for section 194.34(a) can be obtained from Compliance Application Review Document (CARD) 34, Section 34.A.6 (U.S. Environmental Protection Agency 1998a).

34.2.3 Changes in the CRA-2004

The DOE developed CCDFs for the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004) using the same methodology as used for the CCA and the CCA Performance Assessment Verification Test (PAVT); the only changes were in the values of some parameters and modeling assumptions. See the CRA-2004, Chapter 6.0, Table 6-1.

The DOE used selected computer codes and input parameters to generate estimates of radionuclides for a large number of scenarios. In total, 300 CCDFs (100 for each of the 3 replicates) were constructed and presented in the CRA-2004 Performance Assessment Baseline Calculation (PABC) Report (Leigh et al. 2005) for total normalized releases. Three hundred realizations were needed to satisfy the criteria of 40 CFR § 194.34(d). Normalized release results for 10,000 simulations of possible futures were used to calculate each of the 300 CCDF curves. In addition, the DOE provided CCDFs for individual pathways.

34.2.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA's analysis concluded that the DOE adequately presented the PA results in CCDFs, which show the probability of exceeding various levels of cumulative releases (U.S. Environmental Protection Agency 2006a, Section 12.0).

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.34(a) (see CARD 34, Section Recertification Decision [194.34(a)], U.S. Environmental Protection Agency 2006b).

34.2.5 Changes or New Information Since the 2004 Recertification

There are changes in the CRA-2009 related to parameter updates, error corrections, and code improvements made since the CRA-2004 decision (see Appendix PA-2009, Section PA-2.1.1 for more details). The DOE developed CCDFs for the CRA-2009 using the same sampling process and CCDF computational technique as in the CCA and the CRA-2004 (see the CCA, Chapter 6.0, Section 6.1).

In total, 300 CCDFs (100 for each of the 3 replicates) for total normalized releases were constructed and presented in Appendix PA-2009 (Figure 34-1). All of the 300 CCDFs lie below the limit of cumulative releases as defined in the containment requirements of section 191.13. Thus, the DOE continues to demonstrate compliance with the provisions of section 194.34(a).

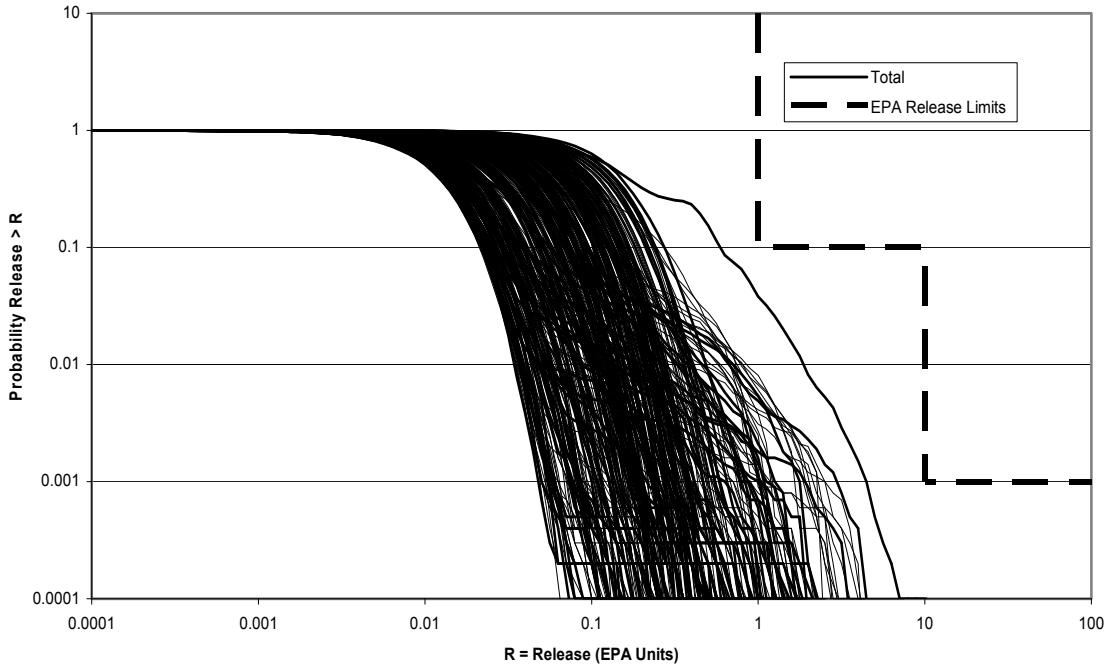

Figure 34-1. 300 CCDFs for Total Normalized Releases: CRA-2009 PA (from Figure 6-6 in Clayton et al. [2008])

34.3 40 CFR § 194.34(b)

34.3.1 Background

There is uncertainty associated with many of the parameters used in PA. 40 CFR § 194.34(b) addresses the need for the uncertain parameters to be sampled from a probability distribution (e.g., uniform, normal, etc.) that has been appropriately documented and justified.

34.3.2 1998 Certification Decision

To meet the criteria in section 194.34(b), the EPA expected the DOE to

1. Discuss the sources used and the methods by which each of the probability distributions was developed (e.g., experimental data, field data, etc.)

2. Identify the functional form of the probability distribution (e.g., uniform, lognormal) used for the sampled parameters

3. Describe the statistics of each probability distribution, including the values for lower and upper ranges, mean (geometric mean when appropriate), and median

4. Identify the importance of the sampled parameters to the final releases

5. Demonstrate that the data used to develop the input parameter probability distribution were qualified and controlled in accordance with 40 CFR § 194.22

Upon reviewing the DOE's parameters, the EPA found that the DOE adequately documented the probability distributions in the CCA, Appendix PAR. In addition, the DOE discussed the data and method used to create the probability distribution of each of the 57 sampled variables. The DOE provided general information on probability distributions, data sources for parameter distribution, forms of distributions, bounds, and importance of parameters to releases. The EPA identified inconsistencies with some of the parameter values and probability distributions, but these were resolved for the CCA PAVT the EPA required the DOE to conduct (U.S. Environmental Protection Agency 1998b, Section 5.0).

A complete description of the EPA's 1998 Certification Decision for section 194.34(b) can be obtained from the CARD 34, Section 34.B.5 (U.S. Environmental Protection Agency 1998a).

34.3.3 Changes in the CRA-2004

There were some changes in parameter values and probability distributions in the CRA-2004 PA from the CCA PAVT. Many of these changes are related to inventory changes, but some are related to modeling assumption changes (see Leigh et al. 2005, Section 2.0). However, the basic process the DOE used to develop the parameter information and sample the parameters did not change from the CCA methodology.

The DOE documented its selection of parameters and probability distributions for the key parameters in the CRA-2004, Chapter 6.0 and Appendix PA, Attachment PAR; the CRA-2004

PABC report (Leigh et al. 2005); and associated references. The CRA-2004 PABC sampled 56 parameters whose values were obtained through random sampling in the PA (Kirchner 2005). There were changes to several of the parameters from the CRA-2004 PA for the CRA-2004 PABC (Leigh et al. 2005). The ultimate goal of parameter sampling was to capture uncertainties in the parameters and show their effects on the CCDFs, which the DOE discussed in the CRA-2004, Chapter 6.0, Sections 6.4 and 6.5 and in the CRA-2004 PABC report (see Leigh et al. 2005, Section 2.9).

34.3.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed the DOE's parameter selection and probability distributions in several technical support documents related to computer codes (U.S. Environmental Protection Agency 2006c and 2006d), parameters (U.S. Environmental Protection Agency 2006e, 2006f, and 2006g), and chemistry (U.S. Environmental Protection Agency 2006a, 2006f, and 2006g). The EPA found that the DOE adequately documented the probability distributions. In addition, the DOE discussed the data and method used to create the probability distribution of each sampled variable.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.34(b) (see CARD 34, Section Recertification Decision [194.34(b)]; U.S. Environmental Protection Agency 2006b).

34.3.5 Changes or New Information Since the 2004 Recertification

Although 15 parameters were modified and 90 were added (Fox 2008, Table 6), the process that the DOE used to develop the parameter information and sample the parameters did not change from the EPA-approved CCA methodology (see Fox 2008 for parameter sample distribution information). Thus, the DOE continues to demonstrate compliance with provision of section 194.34(b).

34.4 40 CFR § 194.34(c)

34.4.1 Background

The intent of 40 CFR § 194.34(c) is to ensure that the sampled parameters were appropriately selected for use in PA.

34.4.2 1998 Certification Decision

To demonstrate compliance with section 194.34(c), the EPA expected the DOE to do the following:

1. Discuss the computational techniques used for random sampling

2. Demonstrate that sampling occurred across the entire range of each parameter

The EPA agreed it was appropriate to use the Latin hypercube sampling (LHS) method for the 57 sampled parameters described in the CCA, Appendix PAR. The CCDFGF code also sampled stochastic variables with Monte Carlo sampling for each realization. The EPA concluded that the DOE adequately discussed the computational techniques and sampling ranges.

A complete description of the EPA's 1998 Certification Decision for section 194.34(c) can be obtained from CARD 34, Section 34.C.5; (U.S. Environmental Protection Agency 1998a).

34.4.3 Changes in the CRA-2004

In the CRA-2004, the DOE used the same LHS methodology for sampling uncertain parameters as in the CCA. There was no change in the methodology.

34.4.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA determined during the CCA review that the LHS method ensures parameter values will be selected from the entire range of the probability distributions because LHS stratifies the probability distributions into a number (100, in this case) of equal-probability regions and then samples one value from each region. The EPA noted that the LHS method is appropriate for generating random samples (CARD 34, Section 34.C.5; U.S. Environmental Protection Agency 1998a). The DOE used the same approach in the CRA-2004.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the criteria for section 194.34(c) (see CARD 34, Section Recertification Decision [194.34(c)]; U.S. Environmental Protection Agency 2006b).

34.4.5 Changes or New Information Since the 2004 Recertification

In the CRA-2009, the DOE uses the same LHS methodology for sampling uncertain parameters as in the CCA and CRA-2004. There is no change in the methodology. Thus, the DOE continues to demonstrate compliance with provisions of section 194.34(c).

34.5 40 CFR § 194.34(d)

34.5.1 Background

The intent of 40 CFR § 194.34(d) is to ensure that PA modeling appropriately sampled uncertain parameters and that future scenarios were appropriately used in PA.

34.5.2 1998 Certification Decision

To demonstrate compliance with section 194.34(d), the EPA expected the DOE to do the following:

1. Identify the number of CCDFs generated

2. Discuss how the DOE determined the number of CCDFs to be generated

3. List the probabilities of exceeding cumulative releases of 1 and 10 for each CCDF generated

4. Demonstrate that the maximum CCDF generated, at cumulative normalized releases of 1 and 10, exceeds the 99th percentile with at least a 0.95 probability, including examples of calculations

The EPA found the analysis presented in the CCA, Chapter 8.0, sufficient to show that 298 CCDF curves would satisfy the statistical criterion. The EPA's independent analysis also verified that the 300 CCDF curves computed and presented in the CCA were sufficient (CARD 34, Section 34.D.5; U.S. Environmental Protection Agency 1998a). The DOE correctly interpreted the definition of the 99th percentile value, and applied standard mathematical expressions for deriving the probability of an outcome of multiple events (i.e., the generation of multiple CCDF curves). The probabilistic analysis was found to be appropriate for sampling with the LHS method, which achieves better coverage than nonstratified random sampling of parameter ranges.

A complete description of the EPA's 1998 Certification Decision for section 194.34(d) can be obtained from the CARD 34, Section 34.D.5 (U.S. Environmental Protection Agency 1998a).

34.5.3 Changes in the CRA-2004

In the CRA-2004, the DOE used the same methodology as in the CCA to generate 300 CCDFs in three sets (replicates) of 100. There was no change in the methodology.

34.5.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA noted that the DOE generated 3 sets of 100 CCDFs each and discussed the statistical confidence levels based on the entire set of CCDFs. Based on the analysis in the CCA and the fact that the DOE used the same approach in the CRA-2004, the EPA concurred with the DOE's CRA-2004 analyses.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.34(d) (see CARD 34, Section Recertification Decision [194.34(d)]; U.S. Environmental Protection Agency 2006b).

34.5.5 Changes or New Information Since the 2004 Recertification

In the CRA-2009, the DOE is using the same methodology as in the CCA and CRA-2004 to generate 300 CCDFs in 3 sets (replicates) of 100. There is no change in the methodology. Thus, the DOE continues to demonstrate compliance with provisions of section 194.34(d).

34.6 40 CFR § 194.34(e)

34.6.1 Background

The intent of 40 CFR § 194.34(e) is to show the full range of CCDFs in order to provide an indication of the nature of the releases.

34.6.2 1998 Certification Decision

To demonstrate compliance with section 194.34(e), the EPA expected the DOE to do the following:

1. Display the full range of CCDFs generated

2. Present appropriate information to allow the EPA to confirm the DOE's PA analysis, including the steps used to arrive at the result and the data values that are represented by the CCDFs

3. Include descriptive statistics such as the range, mean, median, etc., for the estimated CCDFs at cumulative releases of 1 and 10

The DOE employed LHS to create 3 independent replicates of 100 realizations each, yielding 300 CCDF curves. The DOE concluded that the requirement of section 194.34(e) was met. The EPA concurred with this conclusion.

A complete description of the EPA's 1998 Certification Decision for section 194.34(e) can be obtained from CARD 34, Section 34.E.5 (U.S. Environmental Protection Agency 1998a).

34.6.3 Changes in the CRA-2004

There were no changes to the approach used by the DOE with regards to section 194.34(e) in the CRA-2004. The DOE presented and discussed the results of the PA analysis in the CRA-2004, Chapter 6.0 and the CRA-2004 PABC report (see Chapter 6 in Leigh et al. 2005), which display the full range of CCDFs generated. Furthermore, appropriate information needed to confirm the analysis and descriptive statistics for the estimated CCDFs were shown.

34.6.4 EPA's Evaluation of Compliance for the 2004 Recertification

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.34(e) (see CARD 34, Section Recertification Decision [194.34(e)]; U.S. Environmental Protection Agency 2006b).

34.6.5 Changes or New Information Since the 2004 Recertification

There are no changes to the approach used by the DOE with regards to section 194.34(e) in the CRA-2009. The full range of CCDFs generated for the CRA-2009 PA is shown in Figure 34-1. Thus, the DOE continues to demonstrate compliance with provisions of section 194.34(e).

34.7 40 CFR § 194.34(f)

34.7.1 Background

Because of the unique nature of the WIPP, the EPA wanted to ensure that the PA results could be used to adequately support a certification decision. To this end, the EPA required the DOE to demonstrate compliance with a high statistical confidence. For 40 CFR § 194.34(f), the DOE must show, in effect, that the mean of its 300 CCDF curves, and the 95th percentile upper confidence limit of the population mean, meet the containment requirements of section 191.13 for the cumulative releases at 1 and 10 times the quantities in Part 191 Appendix A, Table 1.

34.7.2 1998 Certification Decision

To demonstrate compliance with section 194.34(f), the EPA expected the DOE to do the following:

1. Present appropriate information, including steps used to arrive at the result and the data used in the analysis, allowing the EPA to confirm that the mean of the CCDF population meets the containment requirements of section 191.13 with a 95% statistical confidence level

2. Identify the mean of the sample of CCDFs generated for the cumulative releases at 1 and 10 times the quantities in Part 191 Appendix A, Table 1

3. Identify the CCDF values associated with a 95% statistical confidence level of the population mean for the cumulative releases at 1 and 10 times the quantities in Part 191 Appendix A, Table 1

Upon analysis of the CCA PA, the EPA identified inconsistencies with some of the parameter values and probability distributions, and so the EPA required the DOE to conduct the CCA PAVT, which resolved the issues (U.S. Environmental Protection Agency 1998b, Section 5.0). The Certification Decision was based on the CCA PAVT results. The CCA PAVT results demonstrated that the mean of the CCDFs met the section 191.13 containment requirements and that the level of statistical confidence is significantly greater than 95%. Therefore, the EPA concluded that the final result of the CCA PAVT was in compliance with the containment requirements of section 191.13 and that the results were presented in accordance with section 194.34(f) (see CARD 34, Section 34.F.5, U.S. Environmental Protection Agency 1998a).

34.7.3 Changes in the CRA-2004

In the CRA-2004, the DOE used the same general approach for calculating the statistical confidence for release limits as was used in the CCA. The DOE provided the CCDFs and uncertainty information in the CRA-2004 documentation.

34.7.4 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA's and the DOE's review of the CRA-2004 identified several errors that may have affected the CRA-2004 PA's compliance with section 194.34(f) (Cotsworth 2005). Incorrect LHS transfer files were used as input to PRECCDFGF for Replicates 2 and 3; thus, some of the same parameter inputs were used multiple times instead of being appropriately sampled for each replicate. A spallings release calculation for the volume fraction of contact-handled transuranic waste was omitted from CCDFGF, and an error in the input control file for the computer code SUMMARIZE affected spallings results. Finally, only 50 vectors for DRSPALL calculations were run for the CRA-2004 PA, instead of a full set of 100 vectors for each of the three replicates, thus potentially reducing the range of spallings releases.

Because of these problems, the EPA required the DOE to run a full set of DRSPALL vectors and correct the problem with LHS transfer files in the CRA-2004 PABC. The results of the CRA-2004 PABC are provided in the DOE's CRA-2004 PABC report (Leigh et al. 2005). In its review of the CRA-2004 PABC, the EPA concurred that the errors were corrected (CARD 34, U.S. Environmental Protection Agency 2006b).

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements for section 194.34(f) (CARD 34, Section Recertification Decision [194.34(f)], U.S. Environmental Protection Agency 2006b).

34.7.5 Changes or New Information Since the 2004 Recertification

For the CRA-2009, the DOE is using the same approach to calculate the statistical confidence for evaluation against the release limits. The mean of the 300 CCDFs, along with the 95% confidence levels about the overall mean for the total normalized releases of the CRA-2009 PA, are shown in Figure 34-2. Table 34-1 lists the overall mean total normalized release CCDF values of the CRA-2009 PA at the compliance probabilities of 0.1 and 0.001, along with the values of the upper and lower 95% confidence limit CCDFs at the same probabilities. More details on the normalized release results of the CRA-2009 PA are discussed in Appendix PA-2009, Section PA-9.0. As seen in Figure 34-2 and Table 34-1, the results of the PA demonstrate a greater than 95% level of statistical confidence that the overall mean of the population of CCDFs is in compliance with the containment requirements of section 191.13, and thus the DOE continues to comply with provisions of section 194.34(f).

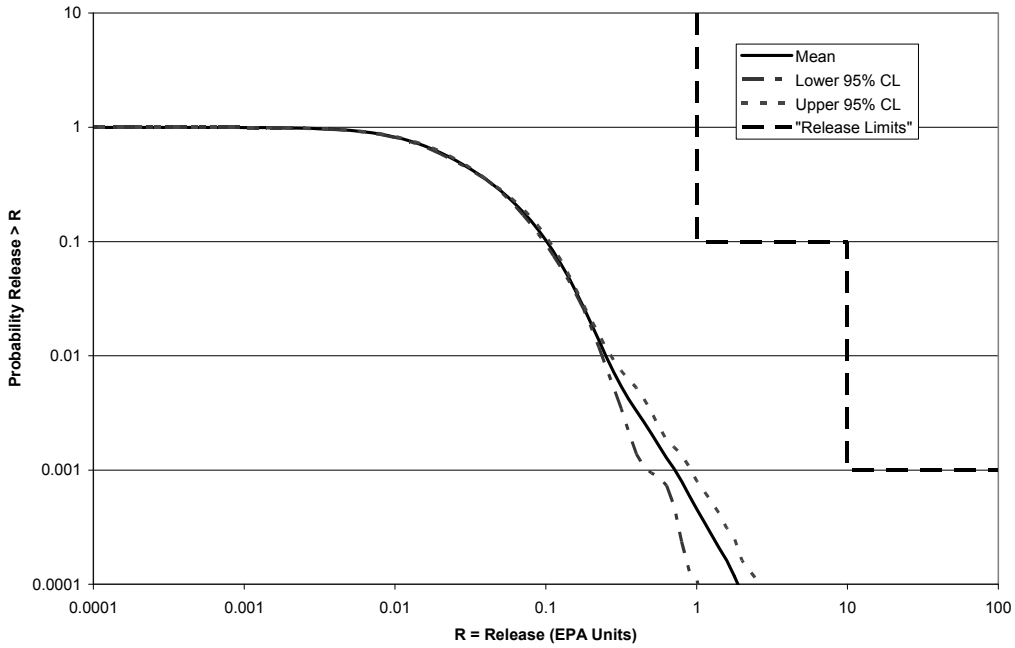

Figure 34-2. Mean and Confidence Interval CCDFs for Total Normalized Releases: CRA-2009 PA (from Figure 6-7 in Clayton et al. [2008])

Table 34-1. CRA-2009 PA Statistics on the Overall Mean for Total Normalized Releases at Probabilities of 0.1 and 0.001, All Replicates Pooled Compared with Release Limits (from Table 6-1 in Clayton et al. [2008])

Probability	Mean Total Release	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Regulatory[a] Limit
0.1	0.10	0.10	0.11	1
0.001	0.72	0.48	0.92	10

[a] Releases divided by the release limits in Part 191 Appendix A, Table 1.

The DOE believes that the information presented in this section and additional information in Appendix PA-2009 demonstrates continued compliance with section 194.34.

34.8 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Active Institutional Controls
(40 CFR § 194.41)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Active Institutional Controls
(40 CFR § 194.41)

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Acronyms and Abbreviations

AIC	active institutional control
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
PA	performance assessment
WIPP	Waste Isolation Pilot Plant

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41.1 Requirements

> § 194.41 Active Institutional Controls
>
> (a) Any compliance application shall include detailed descriptions of proposed active institutional controls, the controls' location, and the period of time the controls are proposed to remain active. Assumptions pertaining to active institutional controls and their effectiveness in terms of preventing or reducing radionuclide releases shall be supported by such descriptions.
>
> (b) Performance assessments shall not consider any contributions from active institutional controls for more than 100 years after disposal.

41.2 Background

One of the six assurance requirements is found in 40 CFR § 194.41 (U.S. Environmental Protection Agency 1996) which contains the compliance criteria. Assurance requirements are included in the disposal regulations to compensate in a qualitative manner for the inherent uncertainties in projecting the behavior of natural and engineered components of the Waste Isolation Pilot Plant (WIPP) for many thousands of years (U.S. Environmental Protection Agency 1985, p. 38072, and Compliance Application Review Document [CARD] 41, U.S. Environmental Protection Agency 1998a, Section 41.A.1). Section 194.41 is one of the six assurance requirements in the Compliance Criteria. Active institutional controls (AICs) are defined in 40 CFR § 191.12 (U.S. Environmental Protection Agency 1993) as "controlling access to a disposal site by any means other than passive institutional controls, performing maintenance operations or remedial actions at a site, controlling or cleaning up releases from a site, or monitoring parameters related to disposal system performance." Section 194.41 requires AICs to be maintained for as long a period of time as practicable after disposal; however, contributions from AICs for reducing the rate of human intrusion in the performance assessment (PA) may not be considered for more than 100 years after disposal.

41.3 1998 Certification Decision

To meet the requirements for section 194.41, the U.S. Environmental Protection Agency (EPA) expected the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) to describe in detail the proposed AICs and their location and function and to identify the period of time they are expected to remain active. The EPA also expected the U.S. Department of Energy (DOE) to provide detailed information regarding implementation of the controls, any assumptions pertaining to the effectiveness of active controls, a justification for any credit for the AICs used in the PA, and the method for determining the credit. The EPA specified that the PA could not assume that the AICs would be effective for a period longer than 100 years after disposal.

In the CCA, Chapter 7.0 and Appendix AIC, the DOE describes its plan for the AICs, including constructing a fence and roadway around the surface footprint of the repository, posting warning signs, and performing routine patrols and surveillance. The DOE states that the AICs will be maintained for 100 years after closure of the WIPP facility and would effectively prevent human intrusion during that time.

The EPA reviewed the DOE's proposed plans for the AICs in connection with the types of activities (U.S. Environmental Protection Agency 1998a, Section 41.A.3) that may be expected to occur in the vicinity of the WIPP site during the first 100 years after disposal (i.e., ranching, farming, hunting, scientific activities, utilities and transportation, groundwater pumping, surface excavation, potash exploration, construction, and hostile or illegal activities). The EPA also examined the assumptions made by the DOE to justify the assertion that the AICs will be completely effective for 100 years.

The EPA found that the DOE adequately described the proposed AICs and the basis for their assumed effectiveness and did not assume in the PA that the AICs would be effective for more than 100 years, and thus found the DOE to be in compliance with section 194.41.

A complete description of the EPA's 1998 Certification Decision for section 194.41 can be found in U.S. Environmental Protection Agency (1998b).

41.4 Changes in the CRA-2004

The 2004 Compliance Recertification Application (CRA-2004), Chapter 7.0 contains the changes related to AICs since 1998. The DOE reported that the CCA, Appendix AIC was unchanged since 1998; however, the following changes were included in CRA-2004:

- A new timeline for implementation of AICs
- DOE's approach to maintaining and replacing AICs
- Minimum standards to apply during construction and maintenance of AICs

41.5 EPA's Evaluation of Compliance for the 2004 Recertification

Based on the EPA's review of the activities and conditions in and around the WIPP site, the EPA did not identify any significant changes in the planning and execution of the DOE's AICs plan since the 1998 Certification Decision (U.S. Environmental Protection Agency 2006a, p. 41-2, paragraph 2 and paragraph 4).

The EPA concluded that the CRA-2004 adequately describes, in detail, the proposed AICs and their location and function, and identifies the basis for the DOE's assumed effectiveness. The EPA confirmed that the DOE's CRA-2004 Performance Assessment Baseline Calculations used the maximum allowable credit for the AICs against human intrusion (100 years). The EPA found reasonable the DOE's assertion that the AICs will completely prevent human intrusion for 100 years.

The EPA approved the removal of Appendix LMP from recertification applications. The EPA found that information from Appendix LMP was not used as a basis for the EPA's 1998 Compliance Decision on section 194.41 (U.S. Environmental Protection Agency 1998b). Because it does not directly support compliance demonstrations for the EPA's disposal regulations, its removal from the CRA-2004 was not significant; nor did it affect the EPA's evaluation of continued compliance.

During its review of the CRA-2004, the EPA received no public comments on the DOE's continued compliance with the AICs requirements of section 194.41. The EPA found (U.S. Environmental Protection Agency 2006c) the DOE to be in continued compliance with the requirements of section 194.41.

41.6 Changes or New Information Since the 2004 Recertification

In the 2009 CRA (CRA-2009), the DOE is not proposing any changes to the AICs program for the WIPP. Information pertaining to the program as provided in the CCA and the CRA-2004 remains unchanged. The DOE believes it has demonstrated continued compliance with the provisions of section 194.41.

41.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Monitoring
(40 CFR § 194.42)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Monitoring
(40 CFR § 194.42)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CMP	Compliance Monitoring Program
COMP	Compliance Monitoring Parameter
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
SNL	Sandia National Laboratories
WIPP	Waste Isolation Pilot Plant

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42.0 Monitoring (40 CFR § 194.42)

42.1 Requirements

§ 194.42 Monitoring

(a) The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system and shall include the results of such analysis in any compliance application. The results of the analysis shall be used in developing plans for pre-closure and post-closure monitoring required pursuant to paragraphs (c) and (d) of this section. The disposal system parameters analyzed shall include, at a minimum:

1. Properties of backfilled material, including porosity, permeability, and degree of compaction and reconsolidation;
2. Stresses and extent of deformation of the surrounding roof, walls, and floor of the waste disposal room;
3. Initiation or displacement of major brittle deformation features in the roof or surrounding rock;
4. Ground water flow and other effects of human intrusion in the vicinity of the disposal system;
5. Brine quantity, flux, composition, and spatial distribution;
6. Gas quantity and composition; and
7. Temperature distribution.

(b) For all disposal system parameters analyzed pursuant to paragraph (a) of this section, any compliance application shall document and substantiate the decision not to monitor a particular disposal system parameter because that parameter is considered to be insignificant to the containment of waste in the disposal system or to the verification of predictions about the future performance of the disposal system.

(c) Pre-closure monitoring. To the extent practicable, pre-closure monitoring shall be conducted of significant disposal system parameter(s) as identified by the analysis conducted pursuant to paragraph (a) of this section. A disposal system parameter shall be considered significant if it affects the system's ability to contain waste or the ability to verify predictions about the future performance of the disposal system. Such monitoring shall begin as soon as practicable; however, in no case shall waste be emplaced in the disposal system prior to the implementation of pre-closure monitoring. Pre-closure monitoring shall end at the time at which the shafts of the disposal system are backfilled and sealed.

(d) Post-closure monitoring. The disposal system shall, to the extent practicable, be monitored as soon as practicable after the shafts of the disposal system are backfilled and sealed to detect substantial and detrimental deviations from expected performance and shall end when the Department can demonstrate to the satisfaction of the Administrator that there are no significant concerns to be addressed by further monitoring. Post-closure monitoring shall be complementary to monitoring required pursuant to applicable federal hazardous waste regulations at parts 264, 265, 268, and 270 of this chapter and shall be conducted with techniques that do not jeopardize the containment of waste in the disposal system.

(e) Any compliance application shall include detailed pre-closure and post-closure monitoring plans for monitoring the performance of the disposal system. At a minimum, such plans shall:

(1) Identify the parameters that will be monitored and how baseline values will be determined;

(2) Indicate how each parameter will be used to evaluate any deviations from the expected performance of the disposal system; and

(3) Discuss the length of time over which each parameter will be monitored to detect deviations from expected performance.

42.2 Background

In 40 CFR §194.42 (U.S. Environmental Protection Agency 1996), the U.S. Environmental Protection Agency (EPA) provides criteria to demonstrate compliance with the assurance requirement at 40 CFR §191.14(b) (U.S. Environmental Protection Agency 1993) to monitor the disposal system. The purpose of this monitoring is "to detect substantial and detrimental deviations from expected performance," with the expected performance predicted by performance assessment (PA). The criteria also require both a preclosure and postclosure

monitoring program using techniques that do not jeopardize the containment of waste in the disposal system. Ten monitoring parameters were identified in an analysis performed to fulfill the section 194.42 requirement during the original certification process. More detailed information describing the section 194.42 monitoring program is located in the U.S. Department of Energy (DOE) Compliance Monitoring Implementation Plan (U.S. Department of Energy 2005); the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), Chapter 7.0, Section 7.2; and Appendix MON-2009.

The 10 parameters, their associated monitoring programs, the frequency of data collection and reporting, related PA parameters, and related screening decisions used to support the PA are listed in Appendix MON-2009, Table MON-1. These parameters are periodically evaluated to determine if there is an impact on the PA-related parameters, conceptual models, or features, events, and processes screening decisions (Wagner 2008a).

42.3 1998 Certification Decision

Based on information in the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) and supplemental monitoring-related information for the CCA submitted to the EPA in response to their request for additional information regarding the methodology of the MONPAR analysis, the EPA determined that DOE was in compliance with the criteria of section 194.42 (U.S. Environmental Protection Agency 1998a, Section VIII.D.2, Monitoring). Additional details of the EPA's evaluation of compliance can be found in the Compliance Application Review Document (CARD) 42, Monitoring (U.S. Environmental Protection Agency 1998b).

42.4 Changes in the CRA-2004

Since 1998, the DOE has monitored and evaluated the 10 monitoring parameters listed in Appendix MON-2004, Table MON-1. For the CRA-2004, the DOE reassessed the CCA monitoring parameter analysis in light of changes in the monitoring program. This reassessment is documented in Kirkes and Wagner (2003), and described in the CRA-2004, Chapter 7.0, Section 7.2. It was determined that the CCA, Appendix MON, Attachment MONPAR monitoring parameter analysis performed to comply with section 194.42 requirements was adequate and did not need to be redone for the CRA-2004. The 10 monitoring parameters identified in the CCA were still sufficient to be included in the Compliance Monitoring Program (CMP) to detect substantial deviations from performance expectations and to comply with the requirements of section 194.42. Supplemental information was submitted to the EPA in response to their request for compliance monitoring annual reports and monitoring data references (Response C-42-1 through C-42-4; Detwiler [2004a], Response C-42-5 and C-42-6 Detwiler [2004b]). Since the CCA, the DOE found four monitoring parameters that either did not fall within the set trigger values or indicated a change from values used in the CCA. These parameters include

- Changes in the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra) water level that may impact Culebra groundwater flow direction and/or composition
- A change in the probability of encountering a Castle brine reservoir

- A change in the drilling rate because of continued oil and gas drilling in the Delaware Basin
- Changes in the waste activity caused by changes in the waste inventory

The impacts of these changes were considered in the CRA-2004, Appendix PA and the EPA-mandated CRA-2004 Performance Assessment Baseline Calculation (PABC) to assess their impact on compliance; see CARD 23, Models and Computer Codes (U.S. Environmental Protection Agency 2006a), which documents EPA's review of these impacts and their determination of continued compliance with the disposal standards.

42.5 EPA's Evaluation of Compliance for the 2004 Recertification

In the EPA's CARD 42, the EPA stated that through their annual monitoring and waste emplacement inspections they had determined that the DOE meets the requirements of section 194.42 (U.S. Environmental Protection Agency 2006b). The results of these inspections are documented in CARD 21, Tables CARD 21-1 and 21-2 (U.S. Environmental Protection Agency 2006c).

42.6 Changes or New Information since the 2004 Recertification

The CMP outlined in Section 42.2 was developed to implement the requirements of section 194.42; the program continues to monitor the WIPP to detect substantial and detrimental deviations from expected performance. This program has not indicated such a condition. No changes have been made to this program from that described in the CRA-2004, Chapter 7.0, Section 7.2, and Attachment MON-2004. New information that supplements the information in the CRA-2004, Chapter 7.0, Section 7.2 includes the following:

1. Results of the CMP since 2004 (Appendix DATA-2009 contains these reports)
2. Assessment of the impact of changes on the CMP (Wagner 2008b)

The annual Compliance Monitoring Parameters (COMPs) report presents monitoring results and determines whether the results are within PA expectations, whether they impact the assumptions or parameters used in PA, or whether they impact the monitoring program. A review of the conclusions in the last four annual COMPs reports (Wagner 2008b) shows the following:

- The results of the COMPs assessments concluded that there were no reportable conditions or events.
- Water levels in the Culebra continue to rise across the monitored region. DOE continues their investigation of these events. These investigations led to the inclusion of updated water-level information during the CRA-2004 PABC (see preface to Appendix TFIELD-2009). The CRA-2009 PA uses the CRA-2004 PABC transmissivity fields.
- The CMP is investigating sample collection and analytical laboratory techniques to reduce uncertainties in water chemistry results.

- No changes to the COMPs or CMP were recommended.

The results of the COMPs reports validate the need to monitor groundwater and demonstrate the importance of continued monitoring and the need to incorporate results into the PA (Sandia National Laboratories 2004).

The CCA, Appendix MON, Attachment MONPAR documents an analysis that is used to determine which monitoring parameters should be included in the CMP. A reassessment of this analysis, documented in Wagner (2008b), determines whether changes to elements of the WIPP program since the last certification affect the conclusions in the CCA, Appendix MON, Attachment MONPAR analysis. The reassessment first determined which changes should be considered, and then determined the impact of these changes on the conclusions drawn in the CCA, Appendix MON, Attachment MONPAR analysis. Changes to the following disposal system elements were evaluated:

1. Monitoring results
2. Experimental activities
3. PA changes: methodology, parameters, and implementation
4. WIPP operational changes
5. Proposed changes to activities and conditions approved by the EPA

Based on the review of operational activities, conditions, monitoring data, the PA, and experimental programs that occurred since the CRA-2004, the reassessment concludes, "the conclusions of the MONPAR analysis remain valid and its conclusions continue to be adequate for inclusion in the CRA-2009" (Wagner 2008b).

The DOE believes the information presented in the CRA-2004, Chapter 7.0, Section 7.2; the CRA-2004, Attachment MON-2004; Appendix MON-2009; and the supplemental information provided in this section continue to demonstrate compliance with the provisions of section 194.42.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Passive Institutional Controls
(40 CFR § 194.43)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Passive Institutional Controls
(40 CFR § 194.43)

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Acronyms and Abbreviations

CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
PIC	passive institutional control
WIPP	Waste Isolation Pilot Plant

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43.0 Passive Institutional Controls (40 CFR § 194.43)

43.1 Requirements

§ 194.43 Passive Institutional Controls

(a) Any compliance application shall include detailed descriptions of the measures that will be employed to preserve knowledge about the location, design, and contents of the disposal system. Such measures shall include:

(1) Identification of the controlled area by markers that have been designed and will be fabricated and emplaced to be as permanent as practicable;

(2) Placement of records in the archives and land record systems of local, State, and Federal governments, and international archives, that would likely be consulted by individuals in search of unexploited resources. Such records shall identify:

(i) The location of the controlled area and the disposal system;

(ii) The design of the disposal system;

(iii) The nature and hazard of the waste;

(iv) Geologic, geochemical, hydrologic, and other site data pertinent to the containment of waste in the disposal system, or the location of such information; and

(v) The results of tests, experiments, and other analyses relating to backfill of excavated areas, shaft sealing, waste interaction with the disposal system, and other tests, experiments, or analyses pertinent to the containment of waste in the disposal system, or the location of such information.

(3) Other passive institutional controls practicable to indicate the dangers of the waste and its location.

(b) Any compliance application shall include the period of time passive institutional controls are expected to endure and be understood.

(c) The Administrator may allow the Department to assume passive institutional control credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates in the compliance application that such credit is justified because the passive institutional controls are expected to endure and be understood by potential intruders for the time period approved by the Administrator. Such credit, or a smaller credit as determined by the Administrator, cannot be used for more than several hundred years and may decrease over time. In no case, however, shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely.

43.2 Background

Regulations in 40 CFR Part 191 Subparts B and C (U.S. Environmental Protection Agency 1993) state that disposal systems shall be designed and built such that they provide a reasonable expectation that for 10,000 years (1) the undisturbed performance of the system will not result in an annual committed effective dose to any member of the public in excess of 15 millirem, (2) the levels of radioactive contamination in groundwater will not exceed limits specified by the standard in 40 CFR § 191.24, and (3) the probability of releases from all significant processes and events acting on the disposal system will not exceed the specifications in 40 CFR § 191.13(a).

40 CFR Part 191 Appendix C states "that inadvertent and intermittent intrusion by exploratory drilling for resources can be the most severe intrusion scenario assumed by the DOE." Subsequent to Part 191 requirements, 40 CFR § 194.32 (U.S. Environmental Protection Agency 1996) also requires that performance assessments include the effects of drilling. A goal of passive institutional controls (PICs) is to minimize the likelihood of inadvertent human activities that affect repository performance (U.S. Department of Energy 1996, Compliance Certification Application [CCA], Appendix PIC).

43.3 1998 Certification Decision

To meet the requirements for 40 CFR § 194.43, the U.S. Environmental Protection Agency (EPA) expected the U.S. Department of Energy (DOE) to describe the markers that would be placed at the Waste Isolation Pilot Plant (WIPP) site to warn future generations about the disposal system's design and contents, including the presence and hazards of radioactive waste. The markers were to be as permanent as practicable using current technology. The DOE also needed to describe individual markers in detail, including information demonstrating that the markers were as permanent as practicable. Permanence refers to the markers' ability to withstand both natural and human-initiated forces that could reasonably be expected to occur at the site. Markers did not need to be designed to withstand catastrophic, low-probability events, such as nuclear war or a comet strike, since any attempt to do so would undoubtedly strain the practicability of the design. Practicability refers to the DOE's ability to emplace markers using currently available resources and technology.

In addition to describing markers that would be fabricated and emplaced, the DOE was also expected to provide a timeline for implementing the markers. Finally, the DOE was permitted to propose a credit for PICs in the performance assessment. A credit must be based on the proposed effectiveness of PICs over time, and would take the form of reduced likelihood in the performance assessment of human intrusion over several hundred years.

The CCA, Chapter 7.0, Section 7.3.3.1.1 and Section 7.3.3.3; the CCA, Appendices PIC and EPIC; and supplemental information requested by the EPA contains the information supporting the DOE's compliance with this requirement.

The EPA determined that the DOE complied with the requirements of section 194.43 because the measures proposed in the CCA are comprehensive, practicable, and likely to endure and be understood for long periods of time. The EPA denied the DOE's request for credit for a 99% reduction in the likelihood of human intrusion into the WIPP during the first 700 years after closure. The EPA denied the credit because the DOE did not use an expert judgment elicitation to derive the credit. The EPA also established as a condition of the 1998 Certification Decision (U.S. Environmental Protection Agency 1998) that the DOE submit additional information concerning the schedule for completing PICs, fabrication of granite markers, and commitments by various recipients to accept WIPP records no later than the final recertification application.

A complete description of the EPA's 1998 Certification Decision for section 194.43 can be found in U.S. Environmental Protection Agency (1998).

43.4 EPA's Changes in the CRA-2004

In the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), Chapter 7.0, Section 7.3.1 (Requirements for PICs), the DOE added language discussing Condition 4 of the EPA's 1998 Certification Decision. This condition requires the DOE to submit the following items prior to the final recertification application, which will be submitted before closure of the disposal system:

- A schedule for implementing PICs, which also describes the testing of all aspects of the conceptual design
- Documentation regarding the granite pieces for the proposed monuments
- Documentation regarding the archives and record centers maintaining the WIPP docket documents
- Documentation of a plan to ensure that the recipients of WIPP information continue to have access to docket documents and supplementary information

New information pertaining to the permanent markers portion of the PICs program and additional amendments to the planning process were also included in the CRA-2004, Chapter 7.0, Section 7.3.3 (Implementation of the PICs Program), which is documented in *Permanent Markers Testing Program Plan* (U.S. Department of Energy 2000).

The CRA-2004, Chapter 7.0, Section 7.3.3.1.1 assured the EPA that the permanent markers will be constructed of materials selected through an evaluation process; the berm design, including the materials of construction, will be refined; and the final design specifications will be provided to the EPA for approval prior to construction.

Examples of the types of files to be archived were added in the CRA-2004, Chapter 7.0, Section 7.3.3.1.2 (Records).

The CRA-2004, Chapter 7.0, Section 7.3.3.3 (PICs Timelines) discusses a new and revised schedule under which the DOE will implement its PICs program. The DOE referenced a letter sent to the EPA (Triay 2002) and the EPA's subsequent approval (Marcinowski 2002) of this revised timeline.

The DOE claimed no credit for the effectiveness of PICs for the 2004 Performance Assessment Baseline Calculation (U.S. Environmental Protection Agency 2006a). As indicated previously by the EPA, the DOE has the right to claim such credit in future recertification applications.

43.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA concluded that the DOE adequately described changes that had been made in the PICs program and continued to comply with the requirements of section 194.43 (U.S. Environmental Protection Agency 2006b).

43.6 Changes or New Information Since the 2004 Recertification

In a letter dated January 11, 2007 (Moody 2007), the DOE requested an extension to start testing PICs 10 years before closure as identified in the DOE's letter of May 16, 2002 (Triay 2002), and agreed to in the EPA's letter of November 7, 2002 (Marcinowski 2002). This request for schedule extension by the DOE was to allow the maximum amount of time to determine the most updated design and materials technologies for implementation of PICs based upon projected closure dates. The EPA responded to the DOE's schedule extension request in a letter dated

March 7, 2008 (Reyes 2008). The EPA agreed to a modified schedule based on activities and current projections of the anticipated WIPP closure date. Table 43-1 is the revised list of approved schedule changes for PICs Testing.

Table 43-1. Approved Schedule Changes for PICs Testing[a]

Activity	Original Time Frame	November 2002 Time Frame	New (December 2007) Time Frame
Identification of suitable source material	1999–2004	2007	2014, but with an annual progress report
Submit plans for test marker system to EPA	2003	2007	2016, but with an annual progress report
Construction of berm and begin testing of berm and markers	2004–2009	2008	2018
Monitor performance of test berm and test markers	2007–2083	2009–closure	2019–closure
Develop final design of markers	2083–2090	2033 (anticipated)	2033 (anticipated)
Finalize messages	n/a	2033 (anticipated)	2033 (anticipated)

[a] Source: Reyes 2008.

In this application the DOE is not proposing any changes to the PICs program for the WIPP. Information pertaining to the program as provided for the CCA and the CRA-2004 remains unchanged, with the exception of the PICs testing schedule. The DOE believes it has demonstrated continued compliance with the provisions of section 194.43.

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Title 40 CFR Part 191
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for the
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Engineered Barriers
(40 CFR § 194.44)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Engineered Barriers
(40 CFR § 194.44)

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Acronyms and Abbreviations

AMWTP	Advanced Mixed Waste Treatment Project
An	actinide
CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
CPR	cellulose, plastic, and rubber
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	feet
gal	gallon
in	inch
INL	Idaho National Laboratory
L	liter
m	meter
NMED	New Mexico Environment Department
OSE	New Mexico Office of the State Engineer
PA	performance assessment
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions, LLC

Elements and Chemical Compounds

CO_2	carbon dioxide
MgO	magnesium oxide

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44.0 Engineered Barriers (40 CFR § 194.44)

44.1 Requirements

§ 194.44 Engineered Barriers

(a) Disposal systems shall incorporate engineered barrier(s) designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment.

(b) In selecting any engineered barrier(s) for the disposal system, DOE shall evaluate the benefit and detriment of engineered barrier alternatives, including but not limited to: cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placements in the disposal system, and alternative disposal system dimensions. The results of this evaluation shall be included in any compliance application and shall be used to justify the selection and rejection of each engineered barrier evaluated.

(c)(1) In conducting the evaluation of engineered barrier alternatives, the following shall be considered, to the extent practicable:

(i) The ability of the engineered barrier to prevent or substantially delay the movement of water or waste toward the accessible environment;

(ii) The impact on worker exposure to radiation both during and after incorporation of engineered barriers;

(iii) The increased ease or difficulty of removing the waste from the disposal system;

(iv) The increased or reduced risk of transporting the waste to the disposal system;

(v) The increased or reduced uncertainty in compliance assessment;

(vi) Public comments requesting specific engineered barriers;

(vii) The increased or reduced total system costs;

(viii) The impact, if any, on other waste disposal programs from the incorporation of engineered barriers (e.g., the extent to which the incorporation of engineered barriers affects the volume of waste);

(ix) The effects on mitigating the consequences of human intrusion.

(2) If, after consideration of one or more of the factors in paragraph (c)(1) of this section, DOE concludes that an engineered barrier considered within the scope of the evaluation should be rejected without evaluating the remaining factors in paragraph (c)(1) of this section, then any compliance application shall provide a justification for this rejection explaining why the evaluation of the remaining factors would not alter the conclusion.

(d) In considering the ability of engineered barriers to prevent or substantially delay the movement of water or radionuclides toward the accessible environment, the benefit and detriment of engineered barriers for existing waste already packaged, existing waste not yet packaged, existing waste in need of repackaging, and to-be-generated waste shall be considered separately and described.

(e) The evaluation described in paragraphs (b), (c) and (d) of this section shall consider engineered barriers alone and in combination.

44.2 Background

Assurance requirements are included in the disposal standard to provide the confidence needed for long-term compliance with the requirements of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993). 40 CFR § 194.44 (U.S. Environmental Protection Agency 1996) is one of the six assurance requirements in the Compliance Criteria. Section 194.44 implements the assurance requirement of 40 CFR § 191.14(d) (U.S. Environmental Protection Agency 1993) to incorporate one or more engineered barriers at radioactive waste disposal facilities. The disposal regulations at 40 CFR § 191.12(d) define a barrier as "any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment." Section 194.44 requires the U.S. Department of Energy (DOE) to conduct a study of available options for engineered barriers at the Waste Isolation Pilot Plant (WIPP) and submit this study and evidence of its use with the compliance application. Consistent with the

containment requirement at section 191.13, the DOE analyzed the performance of the complete disposal system, including the engineered barrier(s).

44.3 1998 Certification Decision

The analysis of potential engineered barriers, including a comparison of the benefits and detriments of each was documented in the DOE's Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Appendix EBS. In the CCA, the DOE proposed multiple barriers, including shaft seals, the panel closure system, magnesium oxide (MgO) backfill, and borehole plugs.

The U.S. Environmental Protection Agency (EPA) evaluated the information regarding engineered barriers provided by the DOE in the CCA, Chapter 3.0, pp. 3-14 through 3-45, Chapter 6.0, pp. 6-105 through 6-114, and Chapter 7.0, pp. 7-89 through 7-96, as well as in the CCA, Appendices BACK; EBS; SEAL; PCS; SOTERM, Section SOTERM-2.2; and WCA, Section WCA.4.1. The DOE also provided supplemental information in the report "Implementation of Chemical Controls Through a Backfill System for the Waste Isolation Pilot Plant (WIPP)" (Sandia National Laboratories 1996).

The DOE specified the proposed method of incorporating the engineered barrier (MgO backfill) into the disposal system in the CCA, Chapter 3.0, Section 3.3.3 and Appendix BACK. The DOE identified MgO as an engineered barrier and provided the rationale for selecting the physical form of MgO to be used, the approximate grain size of the MgO to be emplaced, and the type and size of packages to be used to transport and emplace the MgO. The CCA also described how the MgO minisacks and supersacks would be arranged around waste containers in the disposal rooms and stated that the MgO backfill could be emplaced in the same manner and with the same equipment as the waste containers.

The EPA found that the DOE conducted the requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or substantially delay the movement of water or radionuclides toward the accessible environment. In the 1998 Certification Decision (U.S. Environmental Protection Agency 1998), the EPA specified that only the MgO backfill met the regulatory definition of an engineered barrier. The EPA determined that the DOE provided sufficient documentation to show that MgO can effectively reduce actinide (An) solubility in the disposal system.

A complete description of the EPA's 1998 Certification Decision for section 194.44 can be found in U.S. Environmental Protection Agency 1998.

44.4 Changes in the CRA-2004

In the CRA-2004, the DOE did not report any significant changes to the information on which the EPA based the 1998 Certification Decision. The DOE submitted two planned change requests and one planned change notice after the original certification decision. The DOE's requests included a request to eliminate the MgO minisacks, the notification of a new MgO vendor, and a request to emplace compressed waste from Idaho National Laboratory (INL; formerly Idaho National Engineering and Environmental Laboratory). These changes were

approved by the EPA prior to the 2004 submission of the Compliance Recertification Application (CRA-2004, U.S. Department of Energy 2004). Details of these submissions are documented in Section 44.5. These changes are discussed in detail in Appendix MgO-2009 (see Section MgO-2.1.2 for the minisack elimination change, Section MgO-2.2 for the vendor change, and Section MgO-2.1.3 for the compressed waste change).

Since the final engineered barrier was selected by the DOE using the results of the section 194.44 analysis in the CCA, Appendix EBS, the DOE did not conduct a new analysis to evaluate the benefit and detriment of engineered alternatives (originally required by 40 CFR §§ 194.44(b) through (e)). The CRA-2004 reflected the EPA's determination that only the MgO backfill met the EPA's requirements for an engineered barrier.

44.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA did not identify any significant changes in the implementation of the requirement for engineered barriers based on their review of the activities and conditions in and around the WIPP site. The CRA-2004 did not reflect any changes to the analysis of engineered barrier documented in the CCA, Appendix EBS. The CRA-2004 accurately reflected the 1998 Certification Decision and its conclusion that the MgO backfill is the only engineered barrier that met the EPA's requirements (U.S. Environmental Protection Agency 1998).

44.6 Changes or New Information since the 2004 Recertification

There are no significant changes in the factors on which the EPA based the determination of compliance with section 194.44. The DOE did not change the engineered barrier type, form, or function and therefore did not conduct a new analysis to evaluate the benefit and detriment of engineered alternatives (originally required by sections 194.44(b) through (e)). The CRA-2009 follows the EPA's determination that only the MgO backfill met the EPA's requirements for an engineered barrier at section 191.14(d).

The DOE had proposed shaft seals, borehole plugs, and panel closures as engineered barriers in the CCA. Changes to the approved engineered barrier that have occurred since the last recertification and changes to other disposal system design features originally proposed as engineered barriers (termed disposal system barriers) will be discussed in the following subsections for completeness.

44.6.1 Engineered Barrier

MgO is used in the WIPP to meet the requirements for multiple natural and engineered barriers. MgO acts as an engineered barrier by decreasing An solubilities through the consumption of essentially all carbon dioxide (CO_2) possibly produced by microbial activity. Since microbial activity is an uncertain process, the MgO engineered barrier reduces uncertainty in the repository chemical conditions by ensuring low CO_2 fugacity and by controlling pH (see Appendix MgO-2009, Section MgO-5.0 and Appendix SOTERM-2009, Section SOTERM-2.3).

The description of the supersacks and their placement in the disposal system is described in the CRA-2004, Chapter 3.0, Section 3.3.1. Minor emplacement changes were made as a result of an

EPA-approved planned change for disposal of compressed waste (Marcinowski 2004). This change was approved prior to the submittal of the CRA-2004, but was not described in that application. This change will be discussed in Section 44.6.1.2. The representation of the engineered barrier in performance assessment (PA) is described in the CRA-2004, Chapter 6.0, Section 6.4.6.4 (with minor editing in response to the EPA Comment C-23-5 [Detwiler 2004]), and Appendix PA-2009, Appendix MgO-2009 and Appendix SOTERM-2009. The edits correct the stated MgO excess factor to the EPA-approved 1.67 value. A detailed history of the MgO engineered barrier is presented in Appendix MgO-2009 and describes the placement, function, and experimental activities associated with the barrier since it was first proposed. This document (Appendix MgO-2009) describes in greater detail the changes that have occurred since the CRA-2004.

The developments associated with the MgO engineered barrier that have occurred since the EPA's Recertification Decision include information from additional analyses and the DOE's planned change requests. These developments include the following:

1. A change in MgO vendor
2. The EPA's approval of the DOE's planned change request to dispose of compressed waste
3. The EPA's approval of the DOE's planned change request to change the MgO excess factor from 1.67 to 1.20
4. Results of ongoing MgO experimental investigations

The following sections provide detail for these items.

44.6.1.1 Change in MgO Vendors

National Magnesia Chemicals of Moss Landing, CA, was the first vendor to provide MgO for the WIPP. National Magnesia supplied MgO from the opening of the WIPP in March 1999 (Panel 1, Room 7) through mid-April 2000, at which time National Magnesia stopped producing MgO. Based on cost and the results of a technical evaluation, the DOE selected Premier Chemicals of Gabbs, NV, as the MgO supplier (see Section 44.5, above). Premier Chemicals supplied MgO from mid-April 2000 (Panel 1, Room 7) through 2004 (Panel 2, Room 2). In 2004, Premier Chemicals informed WTS that it would soon be unable to provide MgO that met the requirement for the minimum concentration of MgO in the DOE's specification (Washington TRU Solutions [WTS] 2003). The DOE selected Martin Marietta Magnesia Specialties LLC, which has supplied the MgO emplaced since January 2005 (Panel 2, Room 2). The DOE selected Martin Marietta's MgO based on cost and a technical evaluation of its suitability by Wall (2005). The results of this study and additional characterization of Martin Marietta's MgO are described in more detail in Appendix MgO-2009, Section MgO-4.3.

44.6.1.2 Change to Allow Compressed Waste from the Advanced Mixed Waste Treatment Project

In March 2004, the EPA approved the emplacement in the WIPP of compressed (supercompacted) waste from the Advanced Mixed Waste Treatment Project (AMWTP) at the

INL (Marcinowski 2004, Trinity Engineering Associates 2004, U.S. Environmental Protection Agency 2004). However, the EPA specified that the DOE must maintain an MgO excess factor (see Section 44.5) of 1.67. The AMWTP waste contains concentrations of CPR materials that are higher than the average concentration of CPR materials in transuranic (TRU) waste, necessitating the emplacement of additional MgO. Therefore, in addition to the one supersack per stack configuration, the DOE has emplaced additional MgO supersacks on racks placed among the waste containers. These additional supersacks are emplaced as required to meet the excess factor. Each rack contains five supersacks identical to those placed on top of the waste containers, and spans the same vertical distance normally occupied by three 7-packs of 55-gallon (208-liter) drums, 3 Standard Waste Boxes, or various combinations of these and other waste containers. Thus, emplacement of additional MgO in the repository has used space normally occupied by contact-handled (CH) transuranic (TRU) (CH-TRU) waste.

44.6.1.3 Change in Excess Factor from 1.67 to 1.20

In April 2006, the DOE requested that the EPA approve a reduction in the MgO excess factor from 1.67 to 1.2 (Moody 2006a). To justify its request, the DOE used reasoned arguments regarding health-related transportation risks to the public, the cost of emplacing MgO, and the uncertainties inherent in predicting the extent of microbial consumption of CPR materials during the 10,000-year WIPP regulatory period. The EPA responded by requesting that the DOE address the uncertainties related to MgO effectiveness, the size of the uncertainties, and the potential impact of the uncertainties on long-term performance. In particular, the EPA instructed the DOE to (1) identify all uncertainties related to the calculation of the MgO excess factor, and (2) quantify these uncertainties, if possible (Gitlin 2006). The DOE responded to this request with a detailed uncertainty analysis (Moody 2006b). In February 2008, the EPA approved the reduction of the MgO excess factor to 1.2 (Reyes 2008, Langmuir 2007, Cohen and Associates 2008, U.S. Environmental Protection Agency 2008).

44.6.1.4 MgO Investigations

MgO investigations include characterization of the current vendor's (Martin Marietta) MgO, hydration and carbonation experimental updates, and independent reviews of the use of MgO as an engineered barrier at the WIPP. Deng et al. (2006) and Deng, Xiong, and Nemer (2007) investigated the characteristics and properties of a sample of Martin-Marietta-supplied MgO identical to that emplaced in the WIPP. The analysis looked at the particle size and morphology; the weight percentage of magnesium, calcium, aluminum, iron, and silica of the sample; and the loss on ignition and gravimetric analysis of hydrated MgO. The investigation also included a qualitative analysis using scanning electron microscope imaging and the associated energy dispersive spectrum of the as-received MgO. The results of these investigations helped to confirm that the MgO backfill will perform as expected in the WIPP environment (see Appendix MgO-2009, Section MgO-3.0 and Section MgO-4.0, for a summary of these investigations and their results).

44.6.2 Disposal System Barriers

The following sections discuss changes to other disposal system design features that were also proposed as engineered barriers in the CCA: shaft seals, panel closures, and borehole plugs.

While shaft seals, panel closures, and borehole plugs are not considered engineered barriers by the EPA, they are important physical elements of the WIPP disposal system. It is within this context that they are discussed below.

44.6.2.1 Shaft Seals

No changes have been proposed by the DOE to the shaft seal information presented in the CRA-2004, Chapter 3.0, Section 3.3.2. Material specifications and construction techniques for the shaft seal system are given in the CRA-2004, Appendix BARRIERS, Section BARRIERS-3.2.2 and the CCA, Appendix SEAL, Section SEAL 5.0 and Section 6.0. Appendix PA-2009, Section PA-4.2.7 summarizes the representation of the shafts in PA. Fox (2008, Table 19) provides parameter values used in the modeling of shaft seals.

44.6.2.2 Panel Closures

The baseline panel closure design is termed "Option D." The Option D panel closure design presented in the CRA-2004, Chapter 3.0, Section 3.3.3 and the CRA-2004, Appendix BARRIERS, Section BARRIERS-3.2.1 has not been modified since the last recertification. Representation of the panel closures in PA is described in Appendix PA-2009, Section PA-4.2.8; parameters relevant to the panel closures are provided in Fox (2008, Table 20).

The DOE submitted a planned change request to modify the panel closure design in 2002, prior to submittal of the CRA-2004 (Triay 2002). Because the EPA determined the change would require a rulemaking, they deferred their review until after the certification decision (Marcinowski 2002). In January 2007, the DOE renewed their request for EPA approval of the 2002 panel closure planned change request (Moody 2007a). This letter also requested a delay in permanent closure of panels to allow gas monitoring, through a substantial barrier, with the installation of the permanent closure depending on the results of the monitoring. The proposed monitoring was intended to develop an understanding of flammable gas generation rates in filled panels of waste in order to optimize the final panel closure design. The DOE also requested that the EPA modify Condition 1 of the original certification decision to acknowledge that the New Mexico Environment Department (NMED) is responsible for regulating the design and construction of the panel closure system, provided that the DOE demonstrates there are no long-term impacts on performance. In their letter, the DOE provided a detailed justification for this request and stated that the closure is an operational period requirement (Moody 2007a). The purpose of the closure system is to control volatile organic compound emissions during operations and protect the health and safety of the workers. The EPA responded in a subsequent letter agreeing with the request to delay closure for gas monitoring, but denying the request to modify Condition 1 of the certification decision (Reyes 2007). The EPA stated that the panel closure design was a condition of the EPA's 1998 certification decision and that a change in the design is a significant departure from the most recent compliance application. The EPA also stated that under 40 CFR §194.65, the EPA is required to address changes to the panel closure design through a formal rulemaking process (Reyes 2007). Following a June 2007 panel closure meeting between the NMED, the EPA, and the DOE, the DOE withdrew the request to modify the panel closure design pending results of the gas monitoring and development of a final closure design (Moody 2007b). Option D continues to be the WIPP baseline panel closure design.

44.6.2.3 Borehole Plugs

Over the life of the WIPP project, many exploratory, monitoring, and characterization-related boreholes have been drilled by the DOE and its predecessors in the vicinity of the WIPP. In addition to the DOE-drilled wells, water wells have been drilled for livestock and homesteads, and wells have been drilled by oil, gas, and potash companies in their efforts to exploit resources in the Delaware basin. Figure 44-1 identifies existing unplugged boreholes that lie within the WIPP site boundary. Of these boreholes, two are deep boreholes that exceed the depth of the repository (WIPP-13 and ERDA-9), and the remainder are shallow boreholes that do not reach the repository horizon. There were two additional boreholes deeper than the repository that have been plugged (DOE-1 and WIPP-12).

To mitigate the potential for contaminants to migrate toward the accessible environment, the DOE uses established borehole plugging practices (Christensen and Peterson 1981) to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones, and to limit the hypothetical volume of contaminated brine released from the repository to the accessible environment. The governing regulations for plugging and/or abandonment of boreholes are summarized in Table 44-1.

The CRA-2009 monitoring period was from 10/1/2002 through 9/30/2007. Appendix DATA-2009, Attachment A lists the operational monitoring wells within the WIPP vicinity. During the monitoring period, 19 new wells were drilled and put into service: 3 were for the shallow water program and 16 were for the groundwater program. The shallow water wells were all less than 23.5 meters (m) (77 feet [ft]) in depth. The groundwater-monitoring wells varied from 68.3 m to 414.5 m (224 to 1,360 ft) in depth. There were 16 groundwater-monitoring wells plugged during the monitoring period, and all were plugged solid with cement. During this monitoring period, two monitoring wells were plugged back, converted to water wells, and turned over to local ranchers for their use. In addition, one former potash borehole was converted to a groundwater-monitoring well. See Appendix DATA-2009, Attachment A for a description of the wells in the WIPP monitoring system.

Four deep wells (greater than 655.3 m [2,150 ft] in depth), DOE 1, ERDA 9, WIPP 12, and WIPP 13 are required to be plugged in accordance with the State of New Mexico, Oil Conservation Division, Order No. R-111-P. The key provisions of Order No. R-111-P are as follows:

- A salt protection string of casing must be installed at least 100 ft (30 m) below and not more than 600 ft (183 m) below the base of the salt section. Cementing requirements for both shallow wells (above 5,000 ft [1,524 m]) and deep wells (below 5,000 ft [1,524 m]) above or below the Delaware Mountain Group are specified.

- All oil and gas wells drilled within the potash area must provide a solid cement plug through the salt section and any water bearing horizon and prevent liquids or gases from entering the hole above or below the salt section.

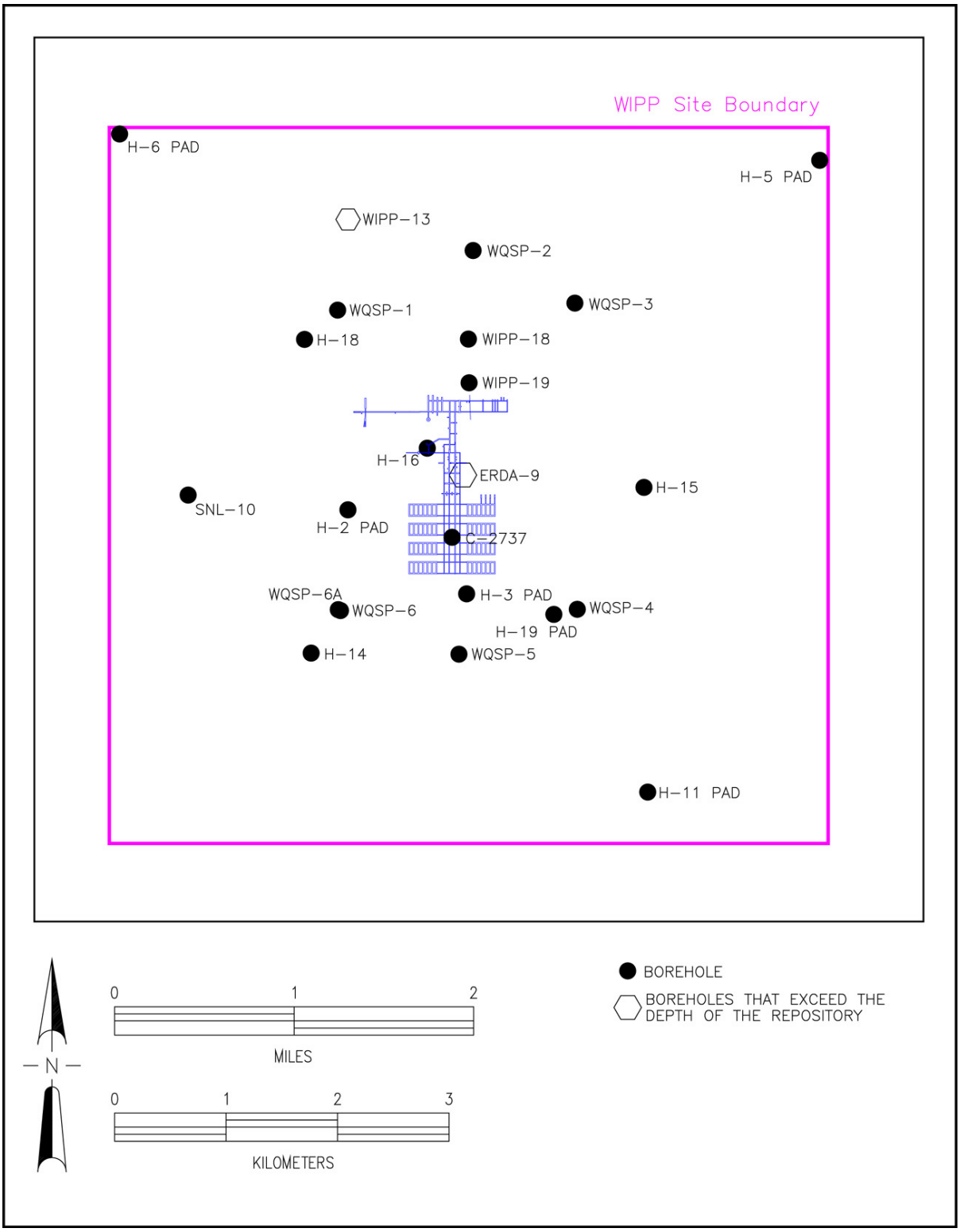

Figure 44-1. Approximate Locations of Unplugged Boreholes[1]

[1] Modified from the CRA-2004, Chapter 3.0, Figure 3-10.

Table 44-1. Governing Regulations for Borehole Abandonment

Federal or State Land	Type of Well or Borehole	Governing Regulation	Summary of Requirements
Both	Groundwater Wells	Well Driller Licensing; Construction, Repair and Plugging of Wells (State of New Mexico 2005, Article 4-140	Any specific plugging requirements and provisions made by the state engineer shall be set forth in the permit.
Federal	Oil and Gas Wells	Onshore Oil and Gas Operations (43 CFR 3160) (U.S. Department of the Interior 1983, p. 36583), Well Abandonment (43 CFR 3162.3-4) (U.S. Department of the Interior 1988a, p. 47765)	The operator shall promptly plug and abandon, in accordance with a plan first approved in writing or prescribed by the authorized officer.
Federal	Potash	Solid Minerals (Other than Coal) Exploration and Mining (43 CFR 3590) (U.S. Department of the Interior 1988b, p. 39461), Core or Test Hole Cores, Samples, Cuttings (43 CFR 3593.1) (U.S. Department of the Interior 1988c, p. 39461)	(b) Surface boreholes for development or holes for prospecting shall be abandoned to the satisfaction of the authorizing officer by cementing and/or casing or by other methods approved in advance by the authorized officer. The holes shall also be abandoned in a manner to protect the surface and not endanger any present or future underground operation, any deposit of oil, gas, or other mineral substances, or any aquifer.
State	Potash	Well Driller Licensing; Construction, Repair and Plugging of Wells (State of New Mexico 2005, Article 4-20.2)	In the event that the test or exploratory well is to be abandoned, the state engineer shall be notified. Such wells shall be plugged in accordance with Article 4-19.1 so that the fluids will be permanently confined to the specific strata in which they were originally encountered.
State	Oil and Gas Well Outside the Oil-Potash Area	Plugging and Permanent Abandonment (State of New Mexico 1996, Rule 202)	B. Plugging (1) Before an operator abandons a well, the operator shall plug the well in a manner that permanently confines all oil, gas and water in the separate strata in which they are originally found. The operator may accomplish this by using mud-laden fluid, cement and plugs singly or in combination as approved by the division on the notice of intention to plug. (2) The operator shall mark the exact location of plugged and abandoned wells with a steel marker not less than 10.2 centimeters (4 inches) in diameter set in cement and extending at least 1.2 m (4 ft) above mean ground level. The operator name, lease name and well number and location, including unit letter, section, township and range, shall be welded, stamped or otherwise permanently engraved into the marker's metal.

Table 44-1. Governing Regulations for Borehole Abandonment (Continued)

Federal or State Land	Type of Well or Borehole	Governing Regulation	Summary of Requirements
State	Oil and Gas Wells Inside the Oil-Potash Area	Order No. R-111-P (State of New Mexico 1988)	F. Plugging and Abandonment of Wells (1) All existing and future wells that are drilled within the potash area shall be plugged in accordance with the general rules established by the Division. A solid cement plug shall be provided through the salt section and any water-bearing horizon to prevent liquids or gases from entering the hole above or below the salt selection. It shall have suitable proportions—but no greater than three percent of calcium chloride by weight—of cement considered to be the desired mixture when possible.

- The fluid used to mix the (plugging) cement must be saturated with salts common to the salt section penetrated, but not more than 3% of calcium chloride by weight of cement wherever possible.

Two of the four deep wells (WIPP-12 and DOE-1) were plugged and abandoned. The New Mexico Office of the State Engineer (OSE) regulates the drilling, operation, and abandonment of groundwater wells. This agency has regulatory oversight of wells in the controlled area. Although WIPP-12 was plugged with standard cement slurry (no salt), the OSE subsequently agreed that the use of standard cement slurry was acceptable for this instance. DOE-1 was plugged using a salt-saturated cement through the salt section, and a standard cement slurry through the rest of the borehole.

The boreholes not used for monitoring will be plugged at decommissioning. See the CRA-2004, Appendix BARRIERS, Chapter BARRIERS-3.0, Section BARRIERS-3.2.3 for a detailed discussion of borehole plugs (excluding Section BARRIERS-3.2.3.2). Appendix PA-2009, Section PA-4.2.9 summarizes the representation of the borehole plugs in PA. Fox (2008, Tables 13 through 17) provides parameter values used in the PA modeling. A listing of all wells drilled in support of the WIPP and other boreholes located within the 16-section Land Withdrawal Area was first included as the CCA, Appendix BH. The CRA-2004, Appendix DATA, Attachment G provides updates on all of the monitoring wells used in the CCA, Appendix BH and the new monitoring wells drilled since the initial certification (U.S. Department of Energy 2004). Appendix DATA-2009, Attachment A lists updates to the borehole information since the CRA-2004. A detailed discussion of the boreholes used in the groundwater monitoring at WIPP is in Appendix HYDRO-2009, Section HYDRO-5.0.

44.6.3 Compliance Summary

The information provided in this section demonstrates continued compliance with the section 194.44 criteria.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Consideration of the Presence of Resources
(40 CFR § 194.45)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Consideration of the Presence of Resources (40 CFR § 194.45)

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Acronyms and Abbreviations

CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEP	feature, event, and process
PA	performance assessment
WIPP	Waste Isolation Pilot Plant

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45.0 Consideration of the Presence of Resources (40 CFR § 194.45)

45.1 Requirements

> § 194.45 Consideration of the Presence of Resources
> Any compliance application shall include information that demonstrates that the favorable characteristics of the disposal system compensate for the presence of resources in the vicinity of the disposal system and the likelihood of the disposal system being disturbed as a result of the presence of those resources. If performance assessments predict that the disposal system meets the containment requirements of §191.13 of this chapter, then the Agency will assume that the requirements of this section and §191.14(e) of this chapter have been fulfilled.

45.2 Background

40 CFR § 194.45 (2004) implements the assurance requirement that the disposal system be sited so that the benefits of the disposal system's natural barriers compensate for the increased probability of disruptions to the disposal system resulting from exploring and developing existing resources. In promulgating this requirement, the U.S. Environmental Protection Agency (EPA) determined that performance assessment (PA) provides a rigorous analytical methodology to determine whether the Waste Isolation Pilot Plant (WIPP) site has compensating features that outweigh the presence of resources (U.S. Environmental Protection Agency 1996). In accordance with the compliance criteria, the U.S. Department of Energy (DOE) must demonstrate that the PA has incorporated the potential effects of human activities near the WIPP prior to disposal, and of drilling and excavation mining over the regulatory time frame.

45.3 1998 Certification Decision

In the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Chapter 7.0, Section 7.5, the DOE describes the measures taken to comply with the requirements of section 194.45. The CCA, Chapter 7.0, Section 7.5 states that the results of the PA, taking into account the potential for resource exploration, met the containment requirements of the EPA as dictated by the disposal regulations and compliance criteria. The CCA, Chapter 7.0, Section 7.5.2 states that the DOE concluded that the favorable characteristics of the WIPP compensate for any possible disturbance.

The EPA found that the information contained in the CCA, Chapter 7.0, Section 7.5, and portions of the CCA cross-referenced in Chapter 7.0, Section 7.5 demonstrates that the DOE accounted for potential resource exploration and met the EPA's requirements based on the results of the PA. Furthermore, the DOE's Final Environmental Impact Statement for the WIPP indicates that resource considerations were taken into account during the disposal system's site selection process (U.S. Department of Energy 1980, Volume 1, Section 7.3.7). Based on these factors, the EPA concluded that the DOE complied with the requirements of section 194.45. A complete description of the EPA's 1998 Certification Decision for section 194.45 can be obtained from U.S. Environmental Protection Agency 1998a and 1998b.

45.4 Changes in the CRA-2004

The DOE did not report any significant changes to the information on which the EPA based the 1998 Certification Decision. The Compliance Recertification Application (CRA) of 2004 (CRA-2004) (U.S. Department of Energy 2004), Chapter 7.0, Section 7.5, contains all the changes related to resource considerations since 1998. The DOE made some minor changes to the list of features, events, and processes (FEPs) considered in the CRA-2004, but the changes did not affect the outcome of the PA. (See the CRA-2004, Appendix SCR, Table SCR-1.)

In the CRA-2004, Chapter 7.0, Section 7.5, the DOE demonstrates that:

- The effects of mining and drilling over the regulatory time frame have been incorporated into PAs according to the requirements of 40 CFR §§ 194.32, 194.33, and 194.43.

- The PA incorporates the effects on the disposal system of any activities that occur in the vicinity of the disposal system or are expected to occur in the vicinity of the disposal system during the 10,000 year regulatory period, according to the requirements of section 194.32.

- The results of PA demonstrate compliance with the containment requirements of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993).

The results of the recertification PA are documented in the CRA-2004, Chapter 6.0, Section 6.5, and in supplemental information on the CRA-2004 Performance Assessment Baseline Calculation (Leigh et al. 2005). In addition, the impacts of resource development outside the controlled area were considered in the development of the WIPP's conceptual models, as well as in the site selection process.

45.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA's review of the activities and conditions in and around the WIPP site did not identify any significant changes since the 1998 Certification Decision related to the presence of resources.

Based on a review and evaluation of the CRA-2004; supplemental information in the CCA, Appendices GCR, IRL, and DEL provided by the DOE in the CRA-2004; and an assessment of changes since 1998, the EPA determined that the DOE continued to comply with the requirements in section 194.45.

45.6 Changes or New Information Since the 2004 Recertification

Section 194.45 states, "If performance assessments predict that the disposal system meets the containment requirements of Section 191.13 of this chapter, then the Agency will assume that the requirements of this section and §191.14(e) of this chapter have been fulfilled." Therefore, provided that the PA appropriately incorporates processes relating to resource discovery and production, and predicts releases that are below limits established by the EPA, compliance with section 194.45 has been demonstrated. This conditional logic relies heavily upon whether or not the PA is structured to appropriately represent resource-related activities at the WIPP site. To

accomplish this, the DOE uses a structured methodology to identify and select FEPs that may have an impact on the disposal system. This process is documented in "Scope of Performance Assessment," Section 32, and Appendix SCR-2009. There have been no changes in screening decisions for resource related FEPs for the CRA-2009.

While there have been no screening changes for FEPs related to the presence of resources, there have been two changes relating to the implementation of the presence of resources in PA models. These changes include a new drilling rate (LAMBDAD) (see Appendix DATA-2009 and Appendix PA-2009, Section PA-2.1.1) and a change in the duration of direct brine releases through the PA parameter MAXFLOW (see Appendix PA-2009, Section PA-2.1.1). These changes are not significant, but have been made to incorporate the most recent information available relating to the exploitation of resources (see "Consideration of Drilling Events in Performance Assessment," Section 33). Besides these two drilling-related parameters, there have been no planned changes adopted by the DOE since the CRA-2004 that impact the previous position and bases for demonstrating compliance with this section. The PA calculations responsive to section 191.13 show predicted releases to be well within the regulated limits and demonstrate that the favorable characteristics and isolating capability of the WIPP outweigh the risks associated with the presence of resources at the site. Therefore, the requirements of section 194.45 are met.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Removal of Waste
(40 CFR § 194.46)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Removal of Waste
(40 CFR § 194.46)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
WIPP	Waste Isolation Pilot Plant

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46.0 Removal of Waste (40 CFR § 194.46)

46.1 Requirements

> § 194.46 Removal of Waste
> Any compliance application shall include documentation which demonstrates that removal of waste from the disposal system is feasible for a reasonable period of time after disposal. Such documentation shall include an analysis of the technological feasibility of mining the sealed disposal system, given technology levels at the time a compliance application is prepared.

46.2 Background

The U.S. Environmental Protection Agency's (EPA's) 40 CFR § 194.46, "Removal of Waste" (U.S. Environmental Protection Agency 1996a), is one of the six assurance requirements in the Compliance Criteria. The EPA states in the preamble to the 1985 promulgation of the disposal standards 40 CFR Part 191 (U.S. Environmental Protection Agency 1993) that the assurance requirements were included in the disposal standards to compensate in a qualitative manner for the inherent uncertainties in projecting the behavior of natural and engineered components of the Waste Isolation Pilot Plant (WIPP) for many thousands of years.

46.3 1998 Certification Decision

To meet the criteria of section 194.46, the EPA states in their Compliance Application Guidance that compliance with the section 194.46 criteria is demonstrated by an analysis that includes (1) procedures for removal of waste after disposal are complete, (2) descriptions of current technology that could be used in implementing these procedures, and (3) an estimate of when it will no longer be technologically feasible to remove the waste (U.S. Environmental Protection Agency 1996b).

The U.S. Department of Energy's (DOE's) demonstration of compliance with section 194.46 was included in the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Chapter 7.0 and Appendix WRAC. The DOE presented a five-phased approach to accomplish the removal of waste. This approach was supported by a discussion of techniques that could be used to remove the waste, given repository conditions at the time of removal. The EPA reviewed the material to assess the completeness of the strategy and the justification of the proposed technology for removing the waste. The EPA states in their 1998 Certification Decision (U.S. Environmental Protection Agency 1998a) for section 194.46 that the DOE has demonstrated it is possible to remove waste from the repository for a reasonable period of time after disposal; therefore, the EPA found the DOE in compliance with section 194.46. A complete description of the EPA's decision can be found in U.S. Environmental Protection Agency 1998a, Section VIII.D.6, and Compliance Application Review Document (CARD) 46 (U.S. Environmental Protection Agency 1998b).

46.4 Changes in the CRA-2004

The DOE did not report any changes in the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004) to the information on which the EPA based their 1998 Certification Decision (U.S. Environmental Protection Agency 1998a). The DOE maintained their original position on waste removal after closure, which was presented in the CCA, Chapter 7.0, Section 7.6. Only editorial changes were made to the original text in the CCA, Chapter 7.0, Section 7.6, pp. 7-90 through 7-91. The CRA-2004 included the CCA, Appendix WRAC by reference; no changes were made to Appendix WRAC.

46.5 EPA's Evaluation of Compliance for the 2004 Recertification

Based on the EPA's review of the activities and conditions in and around the WIPP site, the EPA did not identify any significant changes in the planning and execution of the DOE's strategy for removal of waste since the 1998 Certification Decision (U.S. Environmental Protection Agency 1998a). The CRA-2004 provides documentation that the removal of waste from the disposal system is feasible for a reasonable period of time after disposal (see the CRA-2004, Chapter 7.0, Section 7.6.2).

The EPA did not receive any public comments on the DOE's continued compliance with the removal-of-waste requirements of section 194.46 presented in the CRA-2004.

Based on a review and evaluation of the CRA-2004 and the CCA, Appendix WRAC, the EPA determined that the DOE continued to comply with the requirements of section 194.46 (U.S. Environmental Protection Agency 2006, Section V.E).

46.6 Changes or New Information Since the 2004 Recertification

The DOE has not changed its position on waste removal presented in the CCA, Chapter 7.0, Section 7.6. There have been no design changes or changes to the disposal system in waste emplacement within the disposal area since the CRA-2004. There have been no changes in the planning or execution of the DOE's strategy for removal of waste since the EPA's 1998 Certification Decision (U.S. Environmental Protection Agency 1998a). Thus, there is no new information to be provided as part of the CRA-2009, and the information presented in the CRA-2004, Chapter 7.0, Section 7.6, pp. 7-90 through 7-91 and the CCA, Appendix WRAC, continues to demonstrate compliance with the provisions of section 194.46.

46.7 References

U.S. Department of Energy (DOE). 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant* (October). 21 vols. DOE/CAO-1996-2184. Carlsbad, NM: Carlsbad Area Office.

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U.S. Environmental Protection Agency (EPA). 1996b. *Compliance Application Guidance for 40 CFR 194* (March 29). EPA 402-R-95-014. ERMS 239159. Washington, DC: Office of Radiation and Indoor Air.

U.S. Environmental Protection Agency (EPA). 1998a. "40 CFR Part 194: Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision; Final Rule." *Federal Register*, vol. 63 (May 18, 1998): 27353–406.

U.S. Environmental Protection Agency (EPA). 1998b. "CARD No. 46: Removal of Waste." *Compliance Application Review Documents for the Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR 191 Disposal Regulations: Final Certification Decision* (May) (pp. 46-1 through 46-4). Washington, DC: Office of Radiation and Indoor Air.

U.S. Environmental Protection Agency (EPA). 2006. "Recertification CARD No. 46: Removal of Waste." *Compliance Application Review Documents for the Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR 191 Disposal Regulations: Final Recertification Decision* (March) (pp. 46-1 through 46-2). Washington, DC: Office of Radiation and Indoor Air.

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Consideration of Protected Individual and Exposure Pathways (40 CFR §§ 194.51 and 194.52)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Consideration of Protected Individual and Exposure Pathways (40 CFR §§ 194.51 and 194.52)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
mrem	millirem
PA	performance assessment
pCi/L	picocuries per liter
USDW	underground source of drinking water
WIPP	Waste Isolation Pilot Plant

Elements and Chemical Compounds

Ra	radium

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51.0 Consideration of Protected Individual and Exposure Pathways (40 CFR §§ 194.51 and 194.52)

51.1 Requirements

> §194.51 Consideration of Protected Individual and Exposure Pathways
> Compliance assessments that analyze compliance with §191.15 of this chapter shall assume that an individual resides at the single geographic point on the surface of the accessible environment where that individual would be expected to receive the highest dose from radionuclide releases from the disposal system.
>
> §194.52 Consideration of Protected Individual and Exposure Pathways
> In compliance assessments that analyze compliance with §191.15 of this chapter, all potential exposure pathways from the disposal system to individuals shall be considered. Compliance assessments with part 191, subpart C and §191.15 of this chapter shall assume that individuals consume 2 liters per day of drinking water from any underground source of drinking water in the accessible environment.

51.2 Background

40 CFR §§ 194.51 and 194.52 (2004) of the Waste Isolation Pilot Plant (WIPP) certification criteria implement the individual protection requirements of 40 CFR § 191.15 (2000) and the groundwater protection standards of 40 CFR Part 191 Subpart C. Section 194.51 requires the U.S. Department of Energy (DOE) to assume in its compliance assessments that an individual resides at the point where the dose from radionuclide releases from the WIPP would be greatest. Section 194.52 requires the DOE to consider in its compliance assessments all the potential exposure pathways for radioactive contaminants from the WIPP. Compliance with sections 194.51 and 194.52 is addressed in this single section because the criteria are closely related.

Assessment of the likelihood that the WIPP will meet the individual dose limits and radionuclide concentration limits for groundwater is conducted through a process known as compliance assessment. Compliance assessment uses methods similar to those of the performance assessment (PA) for the containment requirements, but is required to address only undisturbed performance of the disposal system. That is, compliance assessment does not include human intrusion scenarios (i.e., drilling or mining for resources). Compliance assessment can be considered a "subset" of PA.

The U.S. Environmental Protection Agency (EPA) incorporated requirements in 40 CFR Part 191 for the protection of individuals and groundwater. The individual protection requirements of Part 191 limit annual committed effective doses of radiation to members of the public to no more than 15 millirem (mrem). This requirement is concerned with human exposure to radionuclides from disposal systems for 10,000 years. These criteria address the definition of a protected individual, the consideration of exposure pathways, the consideration of underground sources of drinking water (USDWs), the scope of compliance assessments, and the basis for determining compliance with the Individual Protection Standards (U.S. Environmental Protection Agency 1995, pp. 5780−81).

51.3 1998 Certification Decision

To obtain the EPA's 1998 certification decision, the DOE was required to demonstrate a reasonable expectation that the potential releases from the undisturbed repository will result in radiation doses lower than the dose limit of 15 mrem per year, as established by section 191.15. This demonstration incorporated the provisions of sections 194.51 and 194.52, which require the DOE to identify the location of maximum potential exposure for an individual on the surface, consider all potential exposure pathways, and assume that drinking water from any contaminated underground source is consumed at the rate of two liters per day.

To demonstrate a reasonable expectation that the undisturbed performance of the WIPP will not exceed 15 mrem per year, the DOE showed that even a highly improbable, conservative case will meet the regulatory requirements, thereby suggesting that any more probable case must also be in compliance. The DOE referred to this approach as a "bounding" dose calculation because it identified an upper bound to possible exposures. The DOE's analysis is presented in the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Chapter 8.0, Section 8.1.2.2. Supplemental analyses were also performed and are described in U.S. Department of Energy 1997.

In the DOE's analysis, an individual receives the highest dose if one assumes that the individual consumes drinking water directly from a well in the Salado Formation located at the land withdrawal boundary. The DOE assumed that an individual would receive the maximum estimated dose regardless of location on the surface and calculated the resultant doses accordingly. The EPA found this approach to be conservative and found the DOE in compliance with section 194.51.

To demonstrate compliance with section 194.52, the DOE had to assume that an individual consumes two liters per day of drinking water from any USDW from the Salado outside the WIPP area. The DOE considered three ingestion pathways and one inhalation pathway:

- An individual consumes drinking water directly from the Salado.
- An individual ingests plants irrigated with contaminated water.
- An individual ingests milk and beef from cattle whose stock pond contained contaminated water from the Salado.
- An individual inhales dust from soil irrigated with contaminated water from the Salado.

Intended to result in the maximum dose, the DOE's assumption that water is ingested directly from the Salado is conservative, because Salado water is highly saline and would have to be greatly diluted to function as drinking or irrigation water.

The EPA determined that the DOE complied with section 194.52 because the DOE considered all potential exposure pathways and assumed that an individual consumes two liters of Salado water per day, following dilution to make the water usable (U.S. Environmental Protection Agency 1998a).

A complete description of the EPA's 1998 Certification Decision for sections 194.51 and 194.52 is provided in the EPA's final certification decision (U.S. Environmental Protection Agency 1998a) and in U.S. EPA Compliance Application Review Document (CARD) 51/52 (U.S. Environmental Protection Agency 1998b).

51.4 Changes in the CRA-2004

In its 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), the DOE did not report any significant changes to the information on which the EPA based its 1998 certification decision of compliance with the requirements of sections 194.51 and 194.52.

The compliance assessment combines the results of the PA (for the undisturbed case) with the dose calculation. The DOE did not modify the CCA dose-bounding calculations for the compliance assessment in the CRA-2004. Releases predicted by the CRA-2004 PAs are less than or similar to those predicted by the CCA PA results; therefore, the EPA concurred that the CCA dose bounding calculations did not need to be reexecuted for the CRA-2004 compliance assessment.

51.5 EPA's Evaluation of Compliance for the 2004 Recertification

Based on the EPA's review of the activities and conditions in and around the WIPP site, the EPA did not identify any significant changes in the consideration of the protected individual and exposure pathways (see the CRA-2004, Chapter 8.0). The EPA concluded that the CRA-2004 adequately describes the location of the protected individual and the potential exposure pathways (CARD 51/52, U.S. Environmental Protection Agency 2006a).

During its review of the CRA-2004, the EPA received no public comments on the DOE's continued compliance with the certification criteria of sections 194.51 and 194.52.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements of sections 194.51 and 195.52 (U.S. Environmental Protection Agency 2006a and 2006b).

51.6 Changes or New Information Since the 2004 Recertification

In support of the CRA-2009, the DOE has reviewed and updated information provided in the CCA and the CRA-2004, Chapter 8.0, Individual and Groundwater Protection Requirements. The updated material is provided as Appendix IGP-2009. Changes or new information pertaining to the update are listed below.

1. The CRA-2009 evaluation shows that with undisturbed performance, only 1 of the 300 modeling system realizations results in radionuclide concentrations greater than zero reaching the accessible environment through the anhydrite interbeds in the Salado. The remaining 299 realizations show no radionuclides reaching the accessible environment during the 10,000-year period (Appendix PA-2009, Section PA-7.2). In the case of the single realization showing releases to the accessible environment, the resulting calculated dose is an

order of magnitude less than the value reported in the CCA (Appendix IGP-2009, Section IGP-2.1). Accordingly, the CCA calculations bound the CRA-2009 results and demonstrate continued compliance with the 40 CFR § 191.15(a) individual protection standard (see Appendix IGP-2009, Section IGP-1.0).

2. To update the evaluation of the presence of any USDW at or near the WIPP, information pertaining to several new boreholes is presented in Appendix IGP-2009. Relevant data pertaining to total dissolved solids concentration and water pumping rates are provided. Evaluating the data from the new boreholes has resulted in no new or changed conclusions regarding the presence of USDWs in the WIPP vicinity (see Appendix IGP-2009, Section IGP 3.2).

3. An updated evaluation of maximum potential radium-226 (^{226}Ra) and ^{228}Ra concentrations is provided in Appendix IGP-2009. The results of this evaluation indicate that the maximum concentration at the accessible environment boundary would be well below the 5-picocurie-per-liter (pCi/L) regulatory limit; therefore, continued compliance with the 40 CFR § 141.15(a) (2003) groundwater protection standard is demonstrated (see Appendix IGP-2009, Section IGP-3.3.2).

4. For the CRA-2009 evaluation, the gross alpha particle activity, including ^{226}Ra and excluding radon and uranium at the boundary of the accessible environment, is expected to be essentially 0.07 pCi/L (equivalent to the concentration calculated for the CRA-2004). This compares with the standard defined in 40 CFR § 141.15(b) of 15 pCi/L. Continued compliance with the section 141.15(b) groundwater protection standard is demonstrated (see Appendix IGP-2009, Section IGP-3.3.3).

5. For the CRA-2009 evaluation, the maximum radionuclide concentration in the accessible environment is one order of magnitude less than the maximum bounding CCA value (Appendix IGP-2009, Section IGP-2.1). As such, resulting doses for the CRA-2009 case would be correspondingly lower and continued compliance with the 40 CFR § 141.16(a) annual dose equivalent standard is demonstrated (see Appendix IGP-2009, Section IGP-3.3.4).

6. The CCA compliance assessments assumed that an individual resides at the single geographic point on the surface of the accessible environment where that individual would be expected to receive the highest dose of radionuclide releases from the disposal system. Potential releases calculated for the CRA-2009 compliance assessment are less than those calculated for the CCA. Therefore the CCA dose calculation is bounding, and a new dose calculation is unnecessary for the CRA-2009 (see Appendix IGP-2009, Section IGP 4.0).

7. The CCA and CRA-2009 compliance assessments evaluate all potential exposure pathways from the disposal system to individuals. The assessments also include an assumption that individuals consume two liters per day of drinking water from any USDW in the accessible environment (see Appendix IGP-2009, Section IGP-2.2.2).

The DOE continues to comply with the provisions of sections 194.51 and 194.52 (see Appendix IGP-2009, Section IGP-4.0).

51.7 References

U.S. Department of Energy (DOE). 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant* (October). 21 vols. DOE/CAO-1996-2184. Carlsbad, NM: Carlsbad Area Office.

U.S. Department of Energy (DOE). 1997. *Analysis Report for Estimating Dose from Cattle, Vegetable Consumption, and Inhalation Pathways Utilizing Contaminated Water from the Top of the Salado, Culebra, and Selected Marker Beds for an Undisturbed Case Supporting Review of the Compliance Certification Application* (Version 1.01). ERMS 243298. Albuquerque: Sandia National Laboratories.

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U.S. Environmental Protection Agency (EPA). 1998a. "40 CFR Part 194: Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision; Final Rule." *Federal Register*, vol. 63 (May 18, 1998): 27353–406.

U.S. Environmental Protection Agency (EPA). 1998b. "CARD No. 51/52: Consideration of Protected Individual/Exposure Pathways." *Compliance Application Review Documents for the Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR 191 Disposal Regulations: Final Certification Decision* (May) (pp. 51-1 through 51-11). Washington, DC: Office of Radiation and Indoor Air.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Consideration of Underground
Sources of Drinking Water
(40 CFR § 194.53)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Consideration of Underground Sources of Drinking Water (40 CFR § 194.53)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
gpm	gallons per minute
l	liters
MCL	maximum contamination level
mg/L	milligrams per liter
ppm	parts per million
TDS	total dissolved solids
USDW	Underground Source of Drinking Water
WIPP	Waste Isolation Pilot Plant

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53.0 Consideration of Underground Sources of Drinking Water (40 CFR § 194.53)

53.1 Requirements

> §194.53 Consideration of Underground Sources of Drinking Water
> In compliance assessments that analyze compliance with part 191, subpart C of this chapter, all underground sources of drinking water in the accessible environment that are expected to be affected by the disposal system over the regulatory time frame shall be considered. In determining whether underground sources of drinking water are expected to be affected by the disposal system, underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water shall be considered.

53.2 Background

40 CFR § 194.53 (U.S. Environmental Protection Agency 1996) requires the U.S. Department of Energy (DOE) to consider, in compliance assessments, underground sources of drinking water (USDWs) near the Waste Isolation Pilot Plant (WIPP) and their interconnections. A USDW is defined in 40 CFR §191.22 (2000) as "an aquifer or its portion that supplies a public water system, or contains a sufficient quantity of ground water to do so and (i) currently supplies drinking water for human consumption or (ii) contains fewer than 10,000 milligrams per liter (mg/L) of total dissolved solids." The groundwater protection requirements limit releases to the maximum contamination level (MCL) established in the Safe Drinking Water Act Regulations at 40 CFR Part 141 (2003) as they existed on January 19, 1994.

53.3 1998 Certification Decision

The Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Chapter 8.0, discusses the assumptions and approaches used to consider USDWs and the uncertainty associated with the analyses. The DOE provided detailed information on the location and nature of the USDWs, indicated the estimated concentrations of radionuclides in a hypothetical USDW in the accessible environment, and showed that the MCLs for radionuclides will not be exceeded during the regulatory time period.

In the CCA, the DOE presented an evaluation of the USDWs near the WIPP that could potentially be affected by the disposal system over the regulatory time frame. This information was included in the CCA, Chapter 8.0, Section 8.2, and Appendix USDW, Section USDW.3. Based on the definitions in section 191.22, the DOE identified three subcriteria to determine whether a water-bearing horizon located within the WIPP-controlled area would qualify as a USDW:

1. A minimum pumping rate of five gallons per minute (gpm)
2. A supply of water at a rate of five gpm for a 40-year period
3. A maximum of 10,000 mg/L (10,000 parts per million [ppm]) of total dissolved solids (TDS)

These requirements characterize the capacity and quality of a public water system. A public water system is defined in section 191.22 as a system providing piped water for human consumption to 25 individuals, or one that has at least 15 service connections.

Applying these criteria, the DOE identified the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra), the Dewey Lake Formation, and the Santa Rosa Formation as potential USDWs. The DOE conducted a bounding analysis of the contaminants' concentrations to assess compliance with 40 CFR Part 191, Subpart C. In this analysis, the DOE assumed 10,000 ppm TDS, which is much less than the observed concentration of brine derived from the Salado anhydrite marker beds. A USDW was also assumed to be present at and beyond the WIPP Land Withdrawal Boundary. The DOE indicated in the CCA, Chapter 8.0, Section 8.3, that the bounding analysis showed that the resulting radionuclide concentrations in the USDWs would be less than half the maximum limit specified in Part 141 (the U.S. Environmental Protection Agency's [EPA's] National Primary Drinking Water Standards), and the dose to a receptor drinking from the USDW would be a factor of 10 less than the individual protection standard.

The DOE believed the assumption that all contaminants reaching the accessible environment are directly available to the receptor is not realistic but conservative, because this results in overestimating potential doses to an individual. The DOE's findings indicated that even with this conservative approach, the estimated potential dose to an individual was below the Part 191 requirements. The CCA analysis also assumed that all contaminants reaching the accessible environment were directly available to the receptor so that the interconnections of surface, ground, and underground drinking water were all considered and treated as a single source.

The EPA examined the DOE's approach and assumptions associated with the USDW determination in the CCA. The EPA found the analyses to be well supported and accurate, including the uncertainty associated with these analyses. In addition, the EPA assessed all possible aquifers to determine how USDWs were identified and discussed in the CCA. The EPA also examined whether the flow rates and directions were included in the description. The modeling assumptions and specifications for the bounding analysis were examined to assess reliability and assurance of safety. The EPA reviewed the estimated concentrations of radionuclides to determine if they complied with the groundwater protection standard (see the CCA Compliance Application Review Document [CARD] 53, U.S. Environmental Protection Agency 1998, for details of the EPA's CCA review).

The EPA found that the DOE's determination of the USDWs was in accordance with definitions contained in section 191.22 and with the compliance criteria in section 194.53. The bounding analysis was performed with conservative assumptions for a hypothetical USDW to estimate contamination and potential doses to a receptor.

A complete description of the EPA's 1998 Certification Decision for section 194.53 is provided in EPA CARD 53 (U.S. Environmental Protection Agency 1998).

53.4 Changes in the CRA-2004

In the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), Chapter 8.0, the DOE updated some aspects of the USDW analysis. The DOE updated the data for groundwater quantity determination to define a USDW. In the CCA, the DOE used 1990 census data to determine the average water usage per person per day of 282 gallons (1067 L). In the CRA-2004, the DOE used 2000 census data to determine that the average water usage per person per day had increased to 305 gallons (1154 L). The DOE did not believe it was necessary to change the subcriterion of a 5 gpm rate of production from a well to define a USDW (see the CRA-2004, Chapter 8.0, Section 8.2.1.1).

The DOE monitored and evaluated new wells drilled in the area since the completion of the CCA. A new well, C-2737, was drilled to replace H-1 in 2001. Water sampled from the Dewey Lake Formation showed 2,590 ppm TDS. Additional wells were drilled at the WIPP site to investigate the extent of groundwater at the contact of the Santa Rosa and Dewey Lake Formations. The groundwater samples indicate TDS at both below and above 10,000 ppm TDS. The DOE was unable to pump water from any one of these boreholes at a rate of 5 gpm or more.

The updates and changes made by the DOE in the CRA-2004 did not significantly impact the conclusions regarding USDWs in the CCA. In the CRA-2004, the DOE continued to identify the Culebra, Dewey Lake, and Santa Rosa as the only potential USDWs. The DOE stated that the conservative bounding analysis used for the 1998 Certification Decision compliance assessment was still applicable (see the CRA-2004, Chapter 8.0, Section 8.2.1.1).

53.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA evaluated the information on the USDWs contained in the CRA-2004, Chapter 8.0 and examined data from the new wells drilled within the study area since the 1998 Certification Decision. The EPA determined that the DOE applied adequately conservative assumptions to the data for a hypothetical USDW to determine compliance with section 194.53.

Because of the lack of significant changes to the parameters for the protected individual, the potential exposure pathways, and the USDWs, the EPA agreed that the bounding analysis performed for the dose calculation in the CCA still applied. See CRA-2004 CARD 55 (U.S. Environmental Protection Agency 2006) for more information on the results of the compliance assessment.

The EPA received no public comments on the DOE's continued compliance with the consideration of USDW requirements in section 194.53.

Based on a review and evaluation of the CRA-2004 and supplemental information provided by the DOE, the EPA determined that the DOE continued to comply with the requirements of section 194.53.

53.6 Changes or New Information Since the 2004 Recertification

In support of the CRA-2009, the DOE has reviewed and updated information provided in the CCA and the CRA-2004, Chapter 8.0, Individual and Groundwater Protection Requirements. The updated material is provided as Appendix IGP-2009. Changes or new information pertaining to the update are as follows:

1. Updated information regarding average household water consumption in communities near the WIPP has been obtained from the New Mexico Office of the State Engineer to assess the continued appropriateness of criteria for making USDW determinations. The updated information is included in Appendix IGP-2009, Section IGP-3.1.1. A review of these new data indicates that no change in the criteria for making USDW determinations is warranted.

2. Several new boreholes have been drilled near the WIPP since the CRA-2004. These include wells to further characterize flow characteristics in the Culebra and to better understand shallow groundwater flow near the WIPP salt storage piles. Detail regarding these new wells is included in Appendix IGP-2009, Section IGP-3.2. Data from these wells indicate that no changes to the previous USDW determinations are warranted.

3. Based on the review of available data in support of the CRA-2009, the DOE concludes that no modification of the USDW determinations reported in the CCA, Chapter 8.0 and Appendix USDW is warranted (see Appendix IGP-2009, Section IGP-3.2). The DOE continues to conclude that USDWs are present in the Culebra, and potential USDWs are present in the Dewey Lake and the Santa Rosa. Based on this, the DOE concludes that all USDWs in the accessible environment expected to be affected by the disposal system over the regulatory time frame have been considered. In addition, the DOE approach ensures that underground interconnections among bodies of surface water, groundwater, and USDWs are considered.

Based on these considerations, the DOE believes that continued compliance with the provisions of section 194.53 is demonstrated.

53.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Scope of Compliance Assessments
(40 CFR § 194.54)

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Scope of Compliance Assessments (40 CFR § 194.54)

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEP	feature, event, and process
PA	performance assessment
WIPP	Waste Isolation Pilot Plant

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54.0 Scope of Compliance Assessments (40 CFR § 194.54)

54.1 Requirements

§ 194.54 Scope of Compliance Assessments

(a) Any compliance application shall contain compliance assessments required pursuant to this part. Compliance assessments shall include information which:

(1) Identifies potential processes, events, or sequences of processes and events that may occur over the regulatory time frame;

(2) Identifies the processes, events, or sequences of processes and events included in compliance assessment results provided in any compliance application; and

(3) Documents why any processes, events, or sequences of processes and events identified pursuant to paragraph (a)(1) of this section were not included in compliance assessment results provided in any compliance application.

(b) Compliance assessments of undisturbed performance shall include the effects on the disposal system of:

(1) Existing boreholes in the vicinity of the disposal system, with attention to the pathways they provide for migration of radionuclides from the site; and

(2) Any activities that occur in the vicinity of the disposal system prior to or soon after disposal. Such activities shall include, but shall not be limited to: Existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

54.2 Background

The individual and groundwater protection requirements (40 CFR § 191.15 and 40 CFR Part 191 Subpart C [U.S. Environmental Protection Agency 1993]) place limitations on both the potential radiation exposure of individuals and the possible levels of radioactive contamination of groundwater resulting from disposal of waste in the WIPP. The individual protection criteria of 40 CFR § 194.54 (U.S. Environmental Protection Agency 1996) focuses on the annual radiation dose of a maximally exposed hypothetical person living on the surface just outside the boundary to the accessible environment.

In contrast to the containment requirements, the individual and groundwater protection requirements apply to the potential doses received by an individual over a human lifespan. Moreover, compliance assessments utilized to demonstrate compliance with the individual and groundwater protection requirements consider performance of the repository in the "undisturbed scenario," that is, without any human intrusion.

As with performance assessments (PAs), compliance assessments must consider features, events, and processes (FEPs) and the uncertainties associated with those FEPs. PAs are used to demonstrate compliance with the containment requirements of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993). Compliance assessments may be regarded as a "subset" of PAs, inasmuch as the latter incorporates FEPs related to undisturbed conditions that are necessary for the compliance assessment. The results of the PA are used as input values to the compliance assessments. Section 194.54 contains the criteria for assessments of WIPP's compliance with the individual dose and groundwater protection requirements.

54.3 1998 Certification Decision

Per 40 CFR § 194.54(a), the DOE includes in the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) a comprehensive list of FEPs evaluated through the compliance assessment. The U.S. Environmental Protection Agency (EPA) reviewed the DOE's initial FEP list to determine whether it was comprehensive in the CCA. The EPA examined information sources used by the DOE to compile FEP lists for technical accuracy. The EPA also examined FEP listings to determine whether the DOE's rationale for reducing the number of FEPs was appropriately documented and technically sufficient. The EPA concluded that the DOE adequately identified and considered any natural processes or events that may occur within the regulatory time frame in the WIPP area.

The EPA reviewed the CCA, Appendix SCR; numerous references; and FEP screening record packages. To evaluate compliance with 40 CFR § 194.54(b), the EPA reviewed the DOE's arguments concerning natural flow through abandoned boreholes within the Land Withdrawal Boundary, including natural fluid head conditions, abandonment techniques, and number and location of abandoned boreholes. The EPA concluded that the DOE's screening arguments and documentation were reasonable.

In accordance with section 194.54(b), the EPA's detailed review of the CCA indicated that the DOE appropriately screened the FEPs, although the limited justification of some FEPs required additional evaluation. The EPA ultimately concluded that the DOE appropriately identified and screened FEPs pertaining to undisturbed performance. The EPA concluded that criteria for screening FEPs were adequately described and implemented. Also, the EPA concluded that the DOE appropriately identified and discussed the effects of the sequences and combinations of FEPs that resulted in modeled scenarios.

In the CCA, the DOE screened out the possibility that oil and gas extraction would affect the WIPP based upon low consequence. The EPA concurred with the DOE's decision and concluded that the FEP screening appropriately considered the possibility of both subsidence and pressure gradients due to oil and gas extraction. The EPA concludes that the DOE considered the appropriate issues, and that the technical conclusions reached by the DOE regarding current and near-future screening of oil and gas extraction activities were valid. (See *Technical Support Document for* 40 CFR § *194.32: Fluid Injection Analysis*, U.S. Environmental Protection Agency 1998a, for detailed results of EPA's analysis. See Compliance Application Review Document [CARD] 32, U.S. Environmental Protection Agency 1998b, for a discussion of the EPA's analysis of fluid injection.) A complete description of the EPA's 1998 Certification Decision for section 194.54 can be found in U.S. Environmental Protection Agency 1998c.

Also in regard to section 194.54(b) for the CCA, the DOE screened out induced system changes due to hydrocarbon storage operations that have occurred thus far in the vicinity of the WIPP site, based on low consequence. The EPA concluded that this screening was appropriate. Although the DOE did not specify oil and gas field lifetimes in detail for each field near the WIPP in the CCA, Appendix DEL, the EPA found that it was possible to derive the expected active lifetimes of oil and gas fields from information presented in that appendix. The EPA agreed that the lease life estimation values presented in the CCA were reasonable, although the EPA asked the DOE to consider the effects of longer injection periods (Trovato 1997). In

response, the DOE performed a second analysis applying more conservative assumptions including longer injection periods. The second analysis supported the conclusion of the earlier screening evaluations.

54.4 Changes in the CRA-2004

The 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004) did not report significant changes related to the section 194.54 criteria. In the CCA, the DOE screened in 67 undisturbed performance FEPs. The DOE added three FEPs as a result of its CRA-2004 FEPs reevaluation (see the CRA-2004, Appendix PA, Attachment SCR). The DOE added Organic Complexation (W68), Organic Ligands (W69), and Surface Disruptions (H41). FEPs W68 and W69 were added because information acquired since the CCA indicates that organic ligands may increase actinide solubilities and should be included in assessments at the WIPP (see the CRA-2004, Appendix PA, Attachment SCR, Section SCR-6.5.6.1.3). FEP H41 was added because surface activities may impact infiltration, requiring its inclusion in assessments (see the CRA-2004, Appendix PA, Attachment SCR, Section SCR-5.3.1.2.3). All other undisturbed performance FEPs were unchanged in the CRA-2004; therefore, except for FEPs W68, W69, and H41, the DOE did not change the process, screening arguments, or final decisions related to 67 FEPs in the CCA.

The CRA-2004, Chapter 8.0, Section 8.1.1 documents that the DOE considered existing boreholes and potential boreholes as required by 40 CFR §§ 194.52(b)(1) and 194.52(b)(2) (U.S. Environmental Protection Agency 1996). In the CRA-2004, the DOE confirmed that the most plausible undisturbed transport pathway is through the anhydrite marker beds as assumed in the CCA. Therefore, the DOE's approach had not changed since the CCA.

In the CRA-2004, the DOE did not change its dose calculation methodology. The DOE continued to assume an existing borehole (see the CRA-2004, Chapter 8.0, Section 8.1.2.1) and continued to use a bounding analysis (see the CRA-2004, Chapter 8.0, Section 8.1.2.2) if needed. The DOE determined that the maximum release concentrations predicted for undisturbed performance were lower than the CCA predictions; therefore, the new bounding dose calculations were not needed for the CRA-2004. The DOE reconsidered some parameters, such as average water usage and its water quality determination, based on information acquired since the CCA (see the CRA-2004, Chapter 8.0, Sections 8.2.1 and 8.2.2). These parameter changes did not change the DOE's analysis.

54.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed DOE compliance with the section 194.54 criteria (CARD 54, U.S. Environmental Protection Agency 1998c). The EPA verified that the DOE's FEP development process has not changed since the CCA. The DOE reevaluated CCA FEPs in the CRA-2004, and the EPA found the CRA-2004 process to be reasonable and adequately documented. The EPA found that the DOE adequately identified FEPs that may occur over the regulatory time frame (see the CRA-2004, Chapter 6.0, Section 6.3.1), identified FEPs included in the compliance assessment (see the CRA-2004, Chapter 6.0, Section 6.3.1), and adequately documented why FEPs were not selected (see the CRA-2004, Appendix PA, Attachment SCR). The EPA also

found that the DOE adequately considered existing wells and activities that may occur in the vicinity of the WIPP (see the CRA-2004, Chapter 8.0, Section 8.1.1).

The EPA received no public comments on the DOE's continued compliance with the scope of compliance assessments requirements of section 194.54.

54.6 Changes or New Information Since the 2004 Recertification

There are no significant changes related to the section 194.54 requirements since the CRA-2004.

The screening decisions for the undisturbed performance FEPs have not changed for the CRA-2009, but the justification for some screening decisions has changed (Appendix SCR-2009).

Appendix IGP-2009, Section IGP-2.1 demonstrates that the DOE continues to consider existing boreholes and potential boreholes as required by sections 194.54(b)(1) and (b)(2). The CRA-2009 PA analysis continues to confirm that the most plausible undisturbed transport pathway is through the anhydrite marker beds, as assumed in the CRA-2004 and the CCA (Appendix IGP, Section IGP-2.2.1). The DOE's approach has not changed.

The DOE has not changed its dose calculation methodology. The DOE continues to assume an existing borehole (Appendix IGP-2009, Section IGP-2.2.1) and still applies PA results in a bounding analysis (Appendix IGP-2009, Section IGP-2.2.2). The DOE continues to determine that the maximum release concentrations predicted for undisturbed performance are lower than the CCA predictions; therefore, new bounding dose calculations were not needed for the CRA-2009 (Appendix IGP-2009, Section IGP-2.3). The DOE has also reconsidered some parameters, such as average water usage and associated water-quantity determinations, based on acquired information since the CRA-2004 (Appendix IGP-2009, Sections IGP-3.1 and IGP-3.2). The new information provided by the DOE in this document does not warrant changes to the analyses.

Based on this information, the DOE believes continued compliance with the requirements of section 194.54 is demonstrated.

54.7 References

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Results of Compliance Assessments
(40 CFR § 194.55)

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Results of Compliance Assessments
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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
LHS	Latin Hypercube Sampling
mrem	millirem
PA	performance assessment
PAVT	Performance Assessment Verification Test
pCi/L	picocuries per liter
USDW	underground source of drinking water
WIPP	Waste Isolation Pilot Plant

Elements and Chemical Compounds

Pu	plutonium
Ra	radium
Rn	radon
U	uranium

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55.0 Results of Compliance Assessments (40 CFR § 194.55)

55.1 Requirements

§ 194.55 Results of Compliance Assessments

(a) Compliance assessments shall consider and document uncertainty in the performance of the disposal system.

(b) Probability distributions for uncertain disposal system parameter values used in compliance assessments shall be developed and documented in any compliance application.

(c) Computational techniques which draw random samples from across the entire range of values of each probability distribution developed pursuant to paragraph (b) of this section shall be used to generate a range of:

(1) Estimated committed effective doses received from all pathways pursuant to § 194.51 and § 194.52;

(2) Estimated radionuclide concentrations in USDWs pursuant to § 194.53; and

(3) Estimated dose equivalent received from USDWs pursuant to § 194.52 and § 194.53.

(d) The number of estimates generated pursuant to paragraph (c) of this section shall be large enough such that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates with at least a 0.95 probability.

(e) Any compliance application shall display:

(1) The full range of estimated radiation doses; and

(2) The full range of estimated radionuclide concentrations.

(f) Any compliance application shall document that there is at least a 95 percent level of statistical confidence that the mean and the median of the range of estimated radiation doses and the range of estimated radionuclide concentrations meet the requirements of § 191.15 and part 191, subpart C of this chapter, respectively.

55.2 Background

The individual and groundwater protection requirements of 40 CFR § 191.15 and 40 CFR Part 191 Subpart C (U.S. Environmental Protection Agency 1993) place limitations on both the potential radiation exposure of individuals and the possible levels of radioactive contamination of groundwater caused by disposal of waste in the Waste Isolation Pilot Plant (WIPP). The criteria for compliance are provided in 40 CFR §§ 194.51 through 194.55 (U.S. Environmental Protection Agency 1996). The individual protection requirement focuses on the annual radiation dose of a maximally exposed person living on the surface just outside the Land Withdrawal Act boundary. In particular, section 191.15 requires that the WIPP be constructed in such a manner as to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system will not cause the annual committed effective dose equivalent (hereafter simply called "dose") to exceed 15 millirems (mrem) (150 microsieverts) to any member of the public in the accessible environment. Part 191 Subpart C also requires that underground sources of drinking water (USDWs) be protected at least to the extent prescribed by the Safe Drinking Water Act regulations at 40 CFR Part 141 as they existed on January 19, 1994 (per 40 CFR § 191.24(a)(1)).

55.3 1998 Certification Decision

55.3.1 40 CFR § 194.55(a)

In the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the U.S. Environmental Protection Agency (EPA) found that the U.S. Department of Energy (DOE) considered uncertainty in two ways: (1) by assigning probability distributions to 57 of the key

parameters that describe the repository, and sampling from those distributions to carry out the performance assessment (PA) (see the CCA, Chapter 6.0, pp. 6-21 to 6-23 and 6-173 to 6-199; and the CCA, Appendix PAR) and (2) by translating from groundwater contaminant level to doses by means of the bounding analysis (see the CCA, Chapter 8.0 and Dials 1997).

The DOE's method of evaluation of uncertainty in the amounts of contaminants transported underground was essentially the same as that for the 300 scenarios involving human intrusion in the PA, as presented in the CCA, Chapter 6.0, Section 6.1.2, except that those uncertainties introduced by the borehole drilling process can be ignored. The EPA found this aspect of the treatment of uncertainties to be satisfactory.

The EPA reviewed the bounding calculation as presented in the CCA, Chapter 8.0 and supplementary information regarding models and computer codes, parameter values, dose calculations and related topics (Dials 1997) and reported the results of that evaluation in Compliance Application Review Document (CARD) 51/52 (U.S. Environmental Protection Agency 1998a). The EPA determined that the DOE's conceptual model and the use of the GENII-A computer code to calculate radiation doses were appropriate. The EPA found this bounding calculation to be acceptable in lieu of further uncertainty analysis (CARD 55, U.S. Environmental Protection Agency 1998b).

55.3.2 40 CFR § 194.55(b)

The probability distributions for uncertain disposal system parameter values used for demonstrating compliance with the individual dose and groundwater criteria of section 194.55 are identical to those used for the containment requirements in 40 CFR § 194.34 (U.S. Environmental Protection Agency 1996). The EPA concluded that the DOE provided general information in the CCA on probability distributions, data sources for parameter distribution, forms of distributions, bounds, and importance of parameters to releases.

The EPA initially raised concerns about the completeness of the list of PA parameters in the CCA, the descriptions and justifications that support the development of some code input parameters, and the traceability of data reduction and analysis of parameter records. The DOE improved the documentation regarding the basis of parameters, and also developed better "roadmaps" that link parameter documentation and parameter development. Upon subsequent review of records, the EPA determined that the DOE adequately provided the required information for probability distributions of code input parameters (CARD 55, U.S. Environmental Protection Agency 1998b).

55.3.3 40 CFR § 194.55(c)

The EPA examined the DOE's use of the Latin Hypercube Sampling (LHS) procedure and found that the LHS technique draws samples from the entire range of each sampled parameter, was appropriate for use in assessing the concentrations of radionuclides in groundwater, and was implemented correctly by the DOE.

The DOE's evaluation of individual doses and groundwater radionuclide contamination and assessment of USDWs were described in the CCA, Chapter 8.0. The EPA evaluated the

conceptual model that the DOE used to estimate a maximum individual exposure in its bounding calculation. The EPA determined that the DOE's conceptual model and the use of the GENII-A computer code to calculate the radiation doses were appropriate (CARD 55, U.S. Environmental Protection Agency 1998b).

55.3.4 40 CFR § 194.55(d)

Compliance with 40 CFR § 194.55(d) is described in detail in Appendix IGP-2009, Section IGP-2.4. A summary is provided here.

The number of estimates generated must be large enough that the probability is at least 0.95 that the maximum estimate exceeds the 99^{th} percentile of the population of estimates. If the 300 realizations were statistically independent, then the probability that the maximum estimate exceeded the 99^{th} percentile of the population of estimates would equal $1 - (0.99)^{300} = 0.951$, and the section 194.55(d) criterion would be satisfied. On that basis, the probability that the maximum estimate exceeds the 99^{th} percentile of the population of estimates exceeded 0.95, and the section 194.55(d) criterion was satisfied.

The determination of the groundwater concentration and individual dose was based on the PA analysis of releases to the Salado Formation interbeds. Therefore, the number of estimates of concentrations and doses caused by releases to the interbeds was the same as the number in the PA and was dependent on the same calculations. The EPA concluded that the assessment of 300 realizations of the modeling system meets the requirements of 194.55(d) (CARD 55, U.S. Environmental Protection Agency, 1998b).

55.3.5 40 CFR § 194.55(e)

40 CFR § 194.55(e) requires the DOE to display the full ranges of estimated doses and concentrations. The EPA found that:

- The estimated doses caused by ingesting water from the USDW were reported in the CCA, Chapter 8.0, Table 8-2. The maximum estimated dose rate from the other relevant pathways (0.46 mrem per year) was reported in the DOE response document (Dials 1997). The all-pathway individual doses were obtained by adding 0.46 mrem per year to those values. The maximum annual dose obtained in this fashion was less than 1 mrem per year (0.93 mrem per year).

- The CCA, Chapter 8.0, Section 8.2.3, pp. 8-15 to 8-16, states that the maximum estimated radium (Ra) concentration across the 9 non-zero realizations was 2.0 picocuries per liter (pCi/L).

- The CCA, Chapter 8.0, Table 8-1 contains the 300 estimated concentrations for the 5 radionuclides americium-241, plutonium-239 (^{239}Pu), plutonium-238 (^{238}Pu), uranium-234 (^{234}U), and thorium-230, of which only 9 were above the selection criteria. The 9 radium-226 (^{226}Ra) concentrations were not separately recorded, but the maximum gross alpha-particle concentration, including Ra and excluding radon (Rn) and U, was reported as 7.81 pCi/L. The confidence interval analysis described below under 40 CFR § 194.55(f) used a

more conservative approach that added the total radium concentration bound (2.0 pCi/L) to the total of the 5 radionuclide concentrations, including U.

- The USDW dose estimates were reported in the CCA, Chapter 8.0, Table 8-2.

The EPA found the DOE's calculations to be conservative and therefore acceptable (CARD 55, U.S. Environmental Protection Agency 1998b).

55.3.6 40 CFR § 194.55(f)

The EPA required the DOE to perform a Performance Assessment Verification Test (PAVT) using modifications to the parameters and codes used in PA. The DOE performed additional compliance assessment calculations of individual dose and radioactivity concentration as part of the CCA PAVT. The mean dose calculated in the CCA PAVT from all pathways was an order of magnitude below the limit of section 191.15. Because all radionuclides contributing to the dose were alpha-emitting, the CCA PAVT also demonstrated compliance with the annual dose equivalent to the total body or any internal organ from beta particle and photon radioactivity in USDWs. The mean radionuclide concentrations calculated in the CCA PAVT for alpha-emitting radionuclides (including Ra but excluding Rn and U) and for ^{226}Ra and ^{228}Ra were below the limits of 40 CFR Part 191 Subpart C (U.S. Department of Energy 1997a).

The DOE was required to demonstrate that there was at least a 95% level of statistical confidence that the mean and the median of the range of estimated radiation doses were less than 15 mrem per year, and that the range of estimated radionuclide concentrations was compatible (after dilution, as discussed above) with the regulations developed under the Safe Drinking Water Act. The DOE's bounding analysis indirectly verified these requirements by showing that the maximum estimated dose or concentration was always lower than the maximum allowable value.

As with the CCA, the CCA PAVT involved groundwater modeling simulations for the undisturbed repository. The results of this modeling projected nonzero groundwater concentrations for 13 of the 300 modeling simulations (as opposed to 9 in the CCA, Appendix PA). The projected groundwater concentrations from the CCA PAVT are found in *Summary of EPA-Mandated Performance Assessment Verification Test (Replicate 1) and Comparison with the Compliance Certification Application Calculations* (U.S. Department of Energy 1997b) and *Supplemental Summary of EPA-Mandated Performance Assessment Verification Test (All Replicates) and Comparison with the Compliance Certification Application Calculations* (U.S. Department of Energy 1997c). The EPA found that the mean and median radionuclide concentrations in groundwater calculated in the CCA PAVT complied with the requirements of Part 191, Subpart C both for gross alpha particle radioactivity (including Ra but excluding Rn and U) and for radioactivity concentration for ^{226}Ra and ^{228}Ra (U.S. Environmental Protection Agency 1998c).

Drinking-water and all-pathways doses corresponding to projected groundwater concentrations in the CCA PAVT were estimated using the modeling methodology established for the CCA. The DOE initially submitted results for the drinking-water pathway only, where the largest dose value was 3.2×10^{-2} mrem per year (U.S. Department of Energy 1997a, Table 3). Later, in its *Summary of the EPA-Mandated Performance Assessment Verification Test Results for Individual*

Protection Requirements, the DOE calculated 3.1×10^{-2} mrem per year for all other pathways combined (U.S. Department of Energy 1997d, Table 5). This calculation again resulted in a value two orders of magnitude less than the 15 mrem per year requirement. The EPA's calculation of the total body dose from the DOE's concentrations for the 13 nonzero realizations yielded a maximum value of 3.1×10^{-1} mrem per year (U.S. Environmental Protection Agency 1998d).

The DOE's PAVT analysis of beta, electron, and photon doses to the whole body and to individual internal organs is shown in its *Summary of the EPA Mandated Performance Assessment Verification Test Results for Individual Protection Requirements* (U.S. Department of Energy 1997d, Table 3). The DOE demonstrated that the largest organ dose is 2.9×10^{-4} mrem per year on the bone surface. The analysis also showed that the maximum effective dose from beta, electron, and photon emissions is 1.5×10^{-5} mrem per year.

Results of the CCA PAVT thus showed that the mean dose contributions from both alpha-emitting radionuclides and from photon- and beta-emitting radionuclides were below the limits in section 191.15 and Part 191 Subpart C.

Based on its review of the material provided by the DOE, the EPA concluded that the DOE demonstrated compliance with the requirements of section 194.55. A complete description of the EPA's 1998 Certification Decision for section 194.55 is found in U.S. Environmental Protection Agency 1998e.

55.4 Changes in the CRA-2004

The DOE's methodology for demonstrating compliance with section 194.55 did not change since the CCA. The CRA-2004, Chapter 8.0 described the DOE's compliance with the individual and groundwater protection requirements. The DOE considered and documented uncertainty as required by 40 CFR § 194.55(a), in the CRA-2004, Section 6.1.2. As noted in the CRA-2004, Chapter 8.0, Section 8.1.5, parameter uncertainty was discussed in the CRA-2004, Appendix PA, Attachment PAR to verify compliance with 40 CFR § 194.55(b). The CRA-2004, Chapter 8.0 describes how the DOE calculated the effective dose and dose equivalent as required by section 194.55(c). The CRA-2004, Chapter 8.0, Section 8.1.4 also noted that the DOE's selection of more than 298 sampled vectors fulfills the requirements of 40 CFR § 194.55(d). The DOE also noted in the CRA-2004, Chapter 8.0, Section 8.1.4 that their bounding analysis adequately fulfilled the requirements of section 194.55(f). The CRA-2004, Chapter 8.0, Section 8.1 showed how the DOE considered the full range of estimated radiation doses and radionuclide concentrations as required by section 194.55(e).

55.5 EPA's Evaluation of Compliance for the 2004 Recertification

The EPA reviewed the DOE's CRA-2004 documents, in particular Chapter 8.0. The EPA found that little had changed since the original certification decision. The EPA did not receive any public comments on the DOE's continued compliance with the compliance assessments requirements of section 194.55. The EPA concluded that DOE continued to demonstrate compliance with the requirements of section 194.55 (CARD 55, U.S. Environmental Protection Agency 2006).

55.6 Changes or New Information Since the 2004 Recertification

The DOE's methodology for demonstrating compliance with section 194.55 has not changed since the CRA-2004 or the CCA. Appendix IGP-2009 is an updated version of the CCA, Chapter 8.0 and the CRA-2004, Chapter 8.0. It documents the DOE's continued compliance with the individual and groundwater protection requirements. Compliance with the various subsections of section 194.55 is demonstrated as follows:

- As indicated in Appendix IGP-2009, Section IGP-2.1, parameter uncertainty is discussed in Fox 2008 which demonstrates compliance with section 194.55(b).

- Appendix IGP-2009, Section IGP-2.2 describes how the DOE calculates the effective dose and dose equivalent as required by 40 CFR § 194.55(c).

- Appendix IGP-2009, Section IGP-2.4 also explains that the DOE's selection of more than 298 sampled vectors fulfills the requirements of section 194.55(d).

- Appendix IGP-2009, Sections IGP-2.1 and 2.2 demonstrate that the DOE considered the full range of estimated radionuclide concentrations and radiation doses as required by section 194.55(e).

- Appendix IGP-2009, Section IGP-2.4 demonstrates that the DOE's bounding analysis approach meets the requirements of section 194.55(f).

Based on this information, the DOE believes that continued compliance with the provisions of section 194.55 is demonstrated.

55.7 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification Application
for the
Waste Isolation Pilot Plant

Appendix AUD-2009
Audits and Surveillances

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix AUD-2009
Audits and Surveillances

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Acronyms and Abbreviations

A	Audit
AK	acceptable knowledge
AMWTF	Advanced Mixed Waste Treatment Facility
ANL-E	Argonne National Laboratory-East
ARP	Accelerated Retrieval Project
ASME	American Society of Mechanical Engineers
CAO	Carlsbad Area Office
CAR	Corrective Action Report
CAST	CAST Specialty Transportation, Inc.
CBFO	Carlsbad Field Office
CCP	Central Characterization Project
CEMRC	Carlsbad Environmental Monitoring and Research Center
CH	contact-handled
CH-TRU WAC	CH-TRU Waste Acceptance Criteria
CMR	Central Monitoring Room
CMS	Central Monitoring System
CO	Carlsbad Operations
CRA	Compliance Recertification Application
CTAC	Carlsbad Field Office Technical Assistance Contractor
CTI	Consonant Technologies, Inc.
DOE	Department of Energy
DQO	data quality objective
EPA	U.S. Environmental Protection Agency
ERA	Environmental Resource Associates
GC/MS	Gas Chromatograph/Mass Spectrometer
GGTP	Gas Generation Testing Program
HGAS	Health Effects Research Laboratory Gas/Aerosol System
HSG	headspace gas
HWFP	Hazardous Waste Facility Permit
I	indeterminate
INEEL	Idaho National Engineering and Environmental Laboratory

INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LANL-CO	Los Alamos National Laboratory – Carlsbad Operations
LLC	Limited Liability Corporation
LLNL	Lawrence Livermore National Laboratory
M	marginal
MGSS	mobile gas generation testing sampling system
N/A	not applicable
NDA	nondestructive assay
NQA	nuclear quality assurance
NTS	Nevada Test Site
NWMP	Nuclear Waste Management Program
ORNL	Oak Ridge National Laboratory
PDP	Performance Demonstration Program
QA	quality assurance
QAP	Quality Assurance Program
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
RADCON	Radiological Control
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
RH	remote-handled
RH-TRU	remote-handled transuranic
RL	Hanford-Richland
RTR	real-time radiography
S	1. satisfactory 2. Surveillance
S/RID	Standards/Requirements Identification Document
SCG	Summary Category Group
SDW	Safe Drinking Water
SGS	segmented gamma scanner
SNL	Sandia National Laboratories
SQA	software quality assurance
SRS	Savannah River Site

SWB	standard waste box
TMP	Transportation Management Plan
TRAMPAC	Transuranic Authorized Methods for Payload Control
TRU	transuranic
TRUPACT-II	Transuranic Package Transporter-II
TSMT	Tri-State Motor Transit Company
TWCP	Transuranic Waste Certification Program
U	unsatisfactory
V&V	verification and validation
VE	visual examination
VOC	volatile organic compound
WAC	Waste Acceptance Criteria
WAP	Waste Analysis Plan
WCPIP	Waste Characterization Program Implementation Plan
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions, LLC
WWIS	WIPP Waste Information System

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AUD-1.0 Introduction

Tables AUD-1 through AUD-16 of this appendix summarize assessments performed between January 11, 2003 and January 15, 2008 of transuranic (TRU) waste sites, Sandia National Laboratories (SNL), Washington TRU Solutions (WTS), Limited Liability Corporation (LLC), suppliers performing quality-affecting work, the Carlsbad Field Office (CBFO), and Los Alamos National Laboratory – Carlsbad Operations (LANL-CO), and supplement the information contained in the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004a). The summaries are grouped in order of assessment number by the auditing agency (A – Audit, S – Surveillance). Some assessments were performed prior to the end of the CRA-2004, Appendix AUD-2004 reporting date; however, the assessments were not considered complete until the final report and associated regulatory approvals (if required) were documented. Each assessment entry outlines the assessment scope and results. Results of the assessment normally determine the adequacy, implementation, and effectiveness of the auditee's quality assurance (QA) program. Adequacy addresses the migration of requirements from upper-tier program documents into implementing procedures. Effectiveness addresses whether the controls established in the implementing procedures produce the desired results or end product. For ease of reference, CBFO is used throughout this appendix to mean CAO (Carlsbad Area Office) or CBFO, as appropriate. All assessments were performed to the current requirements in place at the time of the activity.

The summary tables include the organization that was assessed, the assessment number, the scope of the assessment, and the results of the assessment expressed as "satisfactory" (S), "marginal" (M), "unsatisfactory" (U), "not applicable" (N/A), or "indeterminate" (I) for the three factors considered during an assessment (i.e., "adequacy," "implementation," and "effectiveness"). Indications of M, U, and I are addressed through the corrective action program to bring them up to S. Assessment findings of M, U, and I at TRU waste sites have been corrected or satisfactorily addressed and verified through subsequent audits, surveillances, corrective action reports (CARs), or other means prior to initial certification or continued certification for shipping to the Waste Isolation Pilot Plant (WIPP).

Only those CBFO assessment activities directly related to 40 CFR Parts 191 (2000) and 194 (2004) are included in this appendix. Additional CBFO assessments are performed in other critical areas. In addition, each participant performs internal assessments of their own activities.

Table AUD-1. Idaho National Engineering and Environmental Laboratory Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INEEL	A-03-15	5/19 – 5/22/03	Technical and QA activities related to INEEL analytical laboratory, which functions as an independent sampling and analysis laboratory.	S	S	S
				The defined QA program was satisfactorily implemented in accordance with the CBFO contract and statement of work, as well as the INEEL implementing procedures. Technical areas evaluated were adequate, satisfactorily implemented, and effective.		
INEEL	A-04-17	05/25 – 05/27/04	Technical and QA activities related to the INEEL analytical laboratory, which functions as an independent sampling and analysis laboratory.	S	S	S
				The defined QA program was satisfactorily implemented in accordance with the CBFO contract and statement of work, as well as the INEEL implementing procedures. Technical areas evaluated were adequate, satisfactorily implemented, and effective.		
INEEL	S-04-09	02/10 – 02/11/04	Continued implementation and effectiveness of technical and QA activities related to the INEEL analytical laboratory functioning as an independent sampling and analysis laboratory.	S	S	S
				INEEL technical and QA procedures were adequate relative to the flow down of requirements from the CBFO Quality Assurance Program Document (QAPD) (U.S. Department of Energy 2007); the WIPP Hazardous Waste Facility Permit (HWFP) (State of New Mexico 1999); and the Contact-Handled (CH) transuranic (TRU) (CH-TRU) Waste Acceptance Criteria (WAC) for the WIPP (U.S. Department of Energy 2008a). The QA program was satisfactorily implemented in accordance with the CBFO contract and statement of work, as well as the INEEL implementing procedures. The INEEL technical areas evaluated were satisfactorily implemented and effective.		

Table AUD-2. Idaho National Laboratory Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INL	A-05-12	05/03 – 05/06/05	INL TRU waste characterization activities performed by or for INL by the Central Characterization Project (CCP).	S	S	S
				The defined QA and Technical programs and processes for these activities were satisfactorily implemented in accordance with the CCP TRU Waste Characterization Quality Assurance Project Plan (QAPjP) and its implementing procedures.		
INL	A-05-13	05/02 – 05/04/05	Technical and QA activities related to the INL Transuranic Waste Certification Program (TWCP) analytical laboratory functioning as an independent sampling and analysis laboratory.	S	S	S
				The defined QA program was satisfactorily implemented in accordance with the CBFO contract and statement of work, as well as the INL-TWCP implementing procedures. Technical areas evaluated were adequate, satisfactorily implemented, and effective.		
INL	A-06-14	04/18 – 04/21/06	INL/CCP TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for Summary Category Group (SCG) S3000 homogeneous solids, S4000 soil/gravel, and S5000 debris waste.	S	S	S
				The INL/CCP technical areas evaluated were satisfactorily implemented and are effective.		
INL	A-06-15	04/25 – 04/27/06	INL/CCP TRU waste characterization activities performed by CCP relative to the requirements detailed in the CBFO QAPD (U.S. Department of Energy 2007), the CH-TRU Waste Acceptance Criteria (CH-TRU WAC) for the WIPP (U.S. Department of Energy 2008a), and the WIPP HWFP (State of New Mexico 1999), as related to QA and nondestructive assay (NDA) activities.	S	S	S
				The INL/CCP technical NDA and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
INL	A-06-16	06/05 – 06/08/06	Technical and QA activities related to the INL TWCP, which functions as an independent sampling and analysis laboratory.	S	S	S
				The INL technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007); the WIPP HWFP (State of New Mexico 1999); and the CH-TRU WAC for the WIPP (U.S. Department of Energy 2008a). The defined QA program was still satisfactorily implemented in accordance with the CBFO contract and statement of work, as well as the INL implementing procedures. INL technical areas evaluated were adequate, satisfactorily implemented, and effective.		

Table AUD-2. Idaho National Laboratory Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
INL	A-06-17	01/12 – 01/13/06	INL TWCP for Small Container Sampling activities as they are related to the WIPP HWFP (State of New Mexico 1999) and the CBFO QAPD (U.S. Department of Energy 2007).	S	S	S
				TWCP Small Container Sampling technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
INL	A-06-21	06/13 – 06/16/06	INL TRU waste characterization activities performed for INL by the CCP.	S	S	S
				The INL/CCP QA program, as applicable to audited activities, was satisfactory in addressing established requirements.		
INL	A-07-06	05/08 – 05/10/07	Technical and QA activities related to the INL TWCP. Review of the transition of INL TWCP to the CCP QA Program.	S	S	S
				INL TWCP technical and QA procedures remain adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WIPP HWFP (State of New Mexico 1999) Waste Analysis Plan (WAP).		
INL	A-07-07	04/24 – 04/27/06	INL TRU waste characterization activities.	S	S	S
				The INL/CCP technical and QA programs, as applicable to audited activities, was satisfactory in addressing established requirements.		
INL	A-07-16	11/16 – 11/17/06	INL TRU waste characterization activities performed for INL by the CCP.	S	S	S
				INL/CCP Remote-handled (RH)-TRU technical procedures and QA program activities evaluated were satisfactorily implemented and effective.		
INL	A-07-19	05/08 – 05/10/07	INL/CCP TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for characterization and recertification of CH-TRU SCG S3000 homogeneous solids, S5000 debris, and S4000 soils/gravel wastes, and RH-TRU SCG S5000 debris waste stream ID-ANL-E-S5000.	S	S	S
				INL/CCP technical procedures and QA program activities were satisfactorily implemented and effective.		
INL	A-08-10	10/30 – 11/1/07	TRU waste characterization activities performed for INL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), the WIPP TRU WAC (U.S. Department of Energy 2008a), the RH-TRU Waste Characterization Program Implementation Plan and the Transuranic Authorized Methods for Payload Control	S	S	S
				INL/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		

Table AUD-2. Idaho National Laboratory Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
			(TRAMPAC) (U.S. Department of Energy 2005a).			
INL	A-08-11	01/29 – 01/30/08	INL/CCP TRU waste characterization activities as they relate to the requirements detailed in the WIPP HWFP (State of New Mexico 1999) and the CBFO QAPD (U.S. Department of Energy 2007) for characterization of SCG S4000 soils/gravel waste.	S	S	S
				The INL/CCP program for characterization and certification activities related to SCG S4000 (soil/gravel) was adequate, satisfactorily implemented, and effective.		
INL	S-05-13	07/06/05	Technical and QA activities at the INL conducted by the CCP.	S	S	S
				Activities evaluated were satisfactorily implemented.		
INL	S-06-07	10/11 – 10/13/05	Transfer of the real-time radiography (RTR) Unit 5 system for nondestructive examination, which was transferred from the Nevada Test Site (NTS) CCP to the INL/CCP site for TRU waste characterization activities. System operability and the implementation of associated procedures were also evaluated.	S	S	S
				Activities and procedures evaluated were adequate, satisfactorily implemented, and effective.		
INL	S-06-32	08/09/06	Documentation establishing that a QA program equivalent in effect to the nuclear quality assurance (NQA) standards was applied to mass spectroscopy measurements used to develop the isotopic scaling factors used for characterizing RH-TRU waste.	S	S	S
				The mass spectroscopy measurements were conducted in accordance with a QA program equivalent in effect to the NQA standards applicable to the WIPP.		
INL	S-07-11	10/11 – 10/12/06	Installation, setup, and use of the Gas Chromato-graph/Mass Spectrometer (GC/MS) VOA-5 system for analysis of solidified waste samples for volatile organic compounds (VOCs); system operability and the implementation of associated procedures.	S	S	S
				The GC/MS VOA-5 system was installed properly and initial activities were completed successfully. The VOA-5 system was performing acceptably for TRU waste characterization activities. The applicable implementing procedures for this system and activity were adequate, satisfactorily implemented, and effective.		
INL	S-07-15	01/23 – 01/25/07	Policies, plans, and procedures related to the operation of the INL/CCP RH-TRU RTR and CH-TRU NDA SuperHENC (High Efficiency Neutron Counter) characterization equipment.	S	S	S
				INL/CCP NDA activities, RH-TRU radiography process, CCP software procedures, and software quality assurance (SQA) process were adequate, satisfactorily implemented, and effective for operation of the INL/CCP SuperHENC NDA equipment.		
INL	S-07-33	09/18 – 09/19/07	Policies, plans, and procedures related to the Accelerated Retrieval Project (ARP) sampling	S	S	S
				INL/CCP activities had adequate procedures that were effectively		

Table AUD-2. Idaho National Laboratory Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
			activities for S3000 and S5000 wastes conducted at INL by the CCP.	implemented.		
INL	S-08-05	11/06 – 11/07/07	INL/CCP QA program activities related to headspace gas (HSG) analysis; sampling and analysis of homogeneous solids and soil/gravel waste; and generation-level data verification and validation (V&V).	S	S	S
				INL/CCP procedures were satisfactorily implemented and evaluated processes were effective.		
INL	S-08-07	01/15 – 01/17/08	Policies, plans, and procedures related to the ARP visual examination (VE) process for newly generated wastes performed at INL by the CCP.	S	S	S
				INL/CCP VE activities were adequate, satisfactorily implemented, and effective.		

Table AUD-3. Los Alamos National Laboratory Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL	A-03-07	07/08 – 07/10/03	HSG sampling, analysis, and associated activities utilizing the Entech/Agilent system.	S	S	S
				The LANL process for obtaining manual HSG samples was adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the HWFP (State of New Mexico 1999). LANL technical processes were satisfactorily implemented and effective.		
LANL	A-03-27	09/22 – 09/26/03	LANL TWCP, including QA and WIPP HWFP (State of New Mexico 1999) activities.	S	S	S
				LANL technical and QA processes and procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the HWFP (State of New Mexico 1999).		
LANL	A-04-05	04/26 – 04/30/04	CCP TRU waste characterization and certification activities related to S3000 (homogeneous solid waste) and S5000 (debris waste) and the adequacy, implementation, and effectiveness of the technical and QA activities.	S	S	S
				CCP technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WAP of the HWFP (State of New Mexico 1999), and the WIPP WAC (U.S. Department of Energy 2008a).		
LANL	A-05-09	04/11 – 04/15/05	CCP TRU waste characterization and certification activities related to SCG S3000 (retrievably stored homogeneous solid waste) and S5000 (retrievably stored, newly generated, and repackaged retrievably stored debris waste), and the adequacy, implementation, and effectiveness of the technical and QA activities.	S	S	S
				Assessed activities were satisfactorily implemented in accordance with the CCP QAPjP and the implementing procedures. The established technical processes and the QA program were effective.		

Table AUD-3. Los Alamos National Laboratory Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL	A-06-11	05/15 – 05/18/06	LANL TRU waste characterization activities performed for LANL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the CH-TRU WAC (U.S. Department of Energy 2008a).	S	S	S
				LANL/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements. The defined QA and technical programs for SCG S3000 (homogeneous solids) and S5000 (debris waste) were satisfactorily implemented in accordance with the CCP QAPjP and its implementing procedures, and the processes were effective.		
LANL	A-06-12	05/22 – 05/25/06	LANL TRU waste characterization and transportation activities performed for LANL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the CH-TRU WAC (U.S. Department of Energy 2008a).	S	S	S
				LANL/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements. The defined QA and technical programs for SCG S3000 (homogeneous solids) and S5000 (debris waste) were satisfactorily implemented in accordance with the CCP QAPjP and its implementing procedures, and the processes were effective.		
LANL	A-07-12	05/22 – 05/24/07	LANL TRU waste characterization activities performed for LANL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the WAC (U.S. Department of Energy 2008a).	S	S	S
				LANL/CCP technical and QA programs, as applicable to the audited activities, were satisfactory in meeting requirements.		
LANL	A-07-13	05/15 – 05/17/07	LANL TRU waste characterization and transportation activities performed for LANL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the QAPD (U.S. Department of Energy 2007), the WAC (U.S. Department of Energy 2008a), and the RH-TRU Waste Characterization Program Implementation Plan (WCPIP).	S	S	S
				LANL/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements. The defined QA and technical programs for SCGs S3000 (homogeneous solids) and S5000 (debris waste) (including RH-TRU waste) were satisfactorily implemented in accordance with the CCP QAPjP and its implementing procedures, and the processes were effective.		
LANL	A-07-23	04/9 – 04/11/07	The peer review process conducted for the qualification of VE characterization data to the data quality objectives (DQOs) and QA objectives as defined in the WIPP WCPIP.	S	S	S
				The peer review process was satisfactorily implemented and effective.		
LANL	S-03-17	08/05 – 08/07/03	Implementation of the technical requirements contained in the RH-TRU waste WCPIP as applied to RH-TRU waste packaged in RH-72B canisters. Implementation and effectiveness of using “equivalent	N/A	N/A	N/A
				Because the requirements for RH-TRU waste characterization were not issued at the time of the surveillance, and the work presented at the demonstration was not performed in accordance with the QA		

Table AUD-3. Los Alamos National Laboratory Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
			quality assurance program" as a method of qualifying characterization data for the waste contained in these canisters.	requirements specified in the CBFO QAPD (U.S. Department of Energy 2007), the information reviewed during S-03-17 could not be used for waste certification purposes. Therefore, no report was issued for this surveillance.		
LANL	S-04-05	10/27 – 10/31/03	Adequacy and effectiveness of the Sealed Source Peer Review process conducted by the Offsite Source Recovery Project, LANL.	S	S	S
				The overall process was adequate and effective.		
LANL	S-04-13	09/21 – 09/23/04	LANL 2010 Project characterization and certification activities performed after CBFO Audit A-03-27. Project records disposition and turnover activities, including preparation and turnover of applicable software programs for continued access and use, disposition and turnover of acceptable knowledge (AK) records for waste to be characterized and certified by the LANL/CCP.	S	S	S
				The areas evaluated were satisfactorily implemented.		

Table AUD-4. Los Alamos National Laboratory – Carlsbad Operations Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LANL-CO	A-04-11	01/12 – 01/14/04	Implementation of requirements in the LANL/Carlsbad Environmental Monitoring and Research Center (CEMRC) Memorandum of Understanding, the CEMRC Quality Assurance Plan (QAP), and the QAP Addendum A.	U	U	U
				The QA program for the Actinide Chemistry and Repository Science Program in support of the WIPP, as implemented by LANL-CO in accordance with CEMRC procedures, was unsatisfactory. The following CARs were issued as a result of the assessment: 04-011, CEMRC procedures do not adequately meet the CBFO QAPD (U.S. Department of Energy 2007); 04-012, LANL management has not developed an effective Quality Assurance Program (QAP); 04-013, Records packages and records disposition do not meet requirements; 04-014, Inadequate implementation of management assessments; and 04-015, Use of chain-of-custody forms (U.S. Department of Energy 2008b). Corrective actions were verified on May 19, 2004, and the CARs were closed on June 6, 2004.		
LANL-CO	A-05-06	02/22 – 02/24/05	Implementation of requirements in the LANL-CO/CEMRC Interface Document, LANL-CO QAP, and LANL-CO implementing procedures.	S	S	S
				The LANL-CO QA program, as implemented by LANL-CO in accordance with LANL-CO procedures, was adequate and effective with the exception of procurement, which was indeterminate.		
LANL-CO	A-06-08	02/27 – 03/01/06	Implementation of requirements in the LANL-CO/CEMRC Interface Document, LANL-CO QAP, and LANL-CO implementing procedures.	S	S	S
				The audit team concluded that the LANL-CO QA program was adequate and effective.		
LANL-CO	A-07-08	02/20 – 02/22/07	Implementation of requirements in the LANL-CO/CEMRC Interface Document, LANL-CO QAP, and LANL-CO implementing procedures.	S	S	S
				The LANL-CO QA program was adequate, satisfactorily implemented, and effective.		
LANL-CO	S-05-15	07/26 – 07/27/05	Procurement activities, including training of personnel implementing the procurement procedure, procurement of items for both Quality Level 1 (QL1) and Quality Level 2 (QL2), receipt of QL1 procurement, supplier qualification, determination of quality levels for procurement, and identification of items for procurement.	S	S	S
				Overall, the LANL/CO Procurement program and implementing procedure were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007).		
LANL-CO	S-07-09	07/10 – 07/11/07	Policies, plans, and procedures related to the Actinide Chemistry Program at the LANL-CO/CEMRC.	S	S	S
				LANL-CO/CEMRC activities had appropriate procedures and were effectively implemented.		

Table AUD-5. Nevada Test Site Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
NTS	A-04-04	10/06 – 10/09/03	Reevaluate the NTS/CCP.	S	S	S
				Technical processes and the QA program and procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the CCP QAPjP and implementing procedures, and the WIPP HWFP (State of New Mexico 1999) WAP.		
NTS	A-05-02	10/05 – 10/08/04	NTS TRU waste characterization activities performed by NTS or for NTS by the CCP, including S5000 debris waste, relative to the requirements of the WIPP HWFP (State of New Mexico 1999).	S	S	S
				The NTS/CCP technical processes and QA programs met requirements contained in the HWFP (State of New Mexico 1999), CCP QAPjP, and related NTS/CCP implementing procedures.		
NTS	S-04-11	08/03 – 08/04/04	Technical and QA activities related to the redeployment of characterization equipment at the NTS by the CCP in support of Bechtel Nevada characterization activities.	S	S	S
				The NTS/CCP areas evaluated were satisfactorily implemented.		
NTS	S-06-02	12/05 – 12/07/05	Characterization and certification activities performed since CBFO Audit A-05-02, conducted on October 5 – 8, 2004, NTS/CCP project records disposition, and turnover activities between NTS and CCP.	S	S	S
				The project records and service activities of CCP were procedurally adequate, and the procedures were satisfactorily implemented and effective.		

Table AUD-6. Hanford-Richland Site Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RL	A-03-14	06/16 – 06/20/03	Reevaluate the adequacy, implementation, and effectiveness of the RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WAP of the HWFP (State of New Mexico 1999), the CH-TRU WAC (U.S. Department of Energy 2008a), the Transuranic Package Transporter-II (TRUPACT-II) Safety Analysis Report (U.S. Department of Energy 2005b), the TRAMPAC (U.S. Department of Energy 2005a), and the TRUPACT-II Certificate of Compliance (U.S. Nuclear Regulatory Commission).		
RL	A-03-25	09/08 – 09/11/03	RL/CCP waste characterization activities relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999).	S	S	S
				RL/CCP technical and QA programs, as applicable to the audited activities, met the requirements contained in the HWFP (State of New Mexico 1999).		
RL	A-04-06	11/04 – 11/05/03	RL processes for sample design, reconciliation of DQOs and the administrative processes ensuring project-level V&V, and the subsequent confirmation of AK. Technical and selected QA activities.	S	S	S
				Technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WAP of the WIPP HWFP (State of New Mexico 1999), and the WIPP WAC (U.S. Department of Energy 2008a).		
RL	A-04-07	11/11 – 11/13/03	HSG sampling, analysis, and associated activities utilizing the CCP single-sample manifold HSG sampling and analysis system.	S	S	S
				The single-sample manifold HSG sampling and analysis system and process employed by CCP for obtaining and analyzing HSG samples was adequate relative to the flow down of requirements from the WIPP HWFP (State of New Mexico 1999). CCP technical processes were satisfactorily implemented and effective.		

Table AUD-6. Hanford-Richland Site Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RL	A-04-19	06/15 – 06/18/04	RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WAP of the HWFP (State of New Mexico 1999), the CH-TRU WAC (U.S. Department of Energy 2008a), the TRUPACT-II Safety Analysis Report (U.S. Department of Energy 2005b), the TRAMPAC (U.S. Department of Energy 2005a), and the TRUPACT-II Certificate of Compliance (U.S. Nuclear Regulatory Commission).		
RL	A-05-14	06/20 – 06/24/05	RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the CH-TRU WAC (U.S. Department of Energy 2008a), the TRUPACT-II Safety Analysis Report (U.S. Department of Energy 2005b), the TRAMPAC (U.S. Department of Energy 2005a), and the TRUPACT-II Certificate of Compliance (U.S. Nuclear Regulatory Commission).		
RL	A-05-18	06/13 – 06/16/05	RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WAP of the HWFP (State of New Mexico 1999).		
RL	A-06-18	06/19 – 06/22/06	RL TRU waste characterization and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WAP of the HWFP (State of New Mexico 1999).		
RL	A-06-19	06/26 – 06/29/06	RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the CH-TRU WAC (U.S. Department of Energy 2008a), the TRUPACT-II Safety Analysis Report (U.S. Department of Energy 2005b), the TRAMPAC (U.S. Department of Energy 2005a), and the TRUPACT-II Certificate of Compliance (U.S. Nuclear Regulatory Commission).		

Table AUD-6. Hanford-Richland Site Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RL	A-07-10	06/19 – 06/21/07	RL TRU waste characterization and certification activities.	S	S	S
				RL technical and QA procedures continued to be adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WAP of the HWFP (State of New Mexico 1999).		
RL	A-07-11	06/04 – 06/07/07	RL TRU waste characterization, transportation, and certification activities.	S	S	S
				RL technical and QA programs and procedures continued to be adequate and effectively implemented relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WAC (U.S. Department of Energy 2008a), the TRUPACT-II Safety Analysis Report (U.S. Department of Energy 2005b), the TRAMPAC (U.S. Department of Energy 2005a), and the TRUPACT-II Certificate of Compliance (U.S. Nuclear Regulatory Commission).		
RL	S-03-14	04/29/03	Technical activities related to the RL TRU waste characterization activities for HSG sampling and gastight (a.k.a. airtight) seal of pipe overpack containers at the Waste Receiving and Processing facility, as applied to SCGs S3000, homogeneous solids, and S5000, debris waste.	S	S	S
				RL technical procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), and the WAC (U.S. Department of Energy 2008a). The RL QA Program met the requirements of the QAPD and WAC.		

Table AUD-7. Rocky Flats Environmental Technology Site Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
RFETS	A-03-04	10/01 – 10/02/02	RFETS TRU waste characterization activities relative to the requirements contained in the WIPP HWFP (State of New Mexico 1999), CH-TRU WAC (U.S. Department of Energy 2008a), and QAPD (U.S. Department of Energy 2007).	S	S	S
				RFETS technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
RFETS	A-03-22	07/22 – 07/24/03	RFETS TRU waste characterization activities relative to the requirements contained in the WIPP HWFP (State of New Mexico 1999), CH-TRU WAC (U.S. Department of Energy 2008a), and QAPD (U.S. Department of Energy 2007).	S	S	S
				RFETS technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
RFETS	A-04-08	10/28 – 10/29/03	RFETS TRU waste characterization activities for SCG S4000 soils/gravels, relative to the requirements of the WIPP HWFP (State of New Mexico 1999) and the CBFO QAPD (U.S. Department of Energy 2007).	S	S	S
				RFETS technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
RFETS	A-04-10	03/30 – 04/02/04	RFETS TRU waste characterization activities for debris and solid waste relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999).	S	S	S
				RFETS technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements contained in the HWFP (State of New Mexico 1999).		
RFETS	S-03-12	01/11/03	Life-cycle documentation, configuration management, and change control for software related to RFETS Health Effects Research Laboratory Gas/Aerosol System (HGAS) analysis systems provided by LANL.	S	S	S
				Software for the HGAS systems was classified in accordance with procedures and the life-cycle documentation and software control were acceptable.		
RFETS	S-05-03	12/20 – 12/21/04	Technical and QA activities at RFETS.	S	S	S
				The activities evaluated were satisfactorily implemented.		
RFETS	S-05-10	04/26 – 04/27/05	Technical and QA activities at RFETS at the end of project.	S	S	S
				The activities evaluated were satisfactorily implemented.		

Table AUD-8. Washington TRU Solutions Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
WTS	A-04-28	06/02 – 06/03/04 and 06/07/04	WTS data processing activities over the last seven years as related to selected portions of the Environmental Monitoring program.	S	S	S
				WTS procedures were adequate relative to the flow down of data processing requirements from the Compliance Certification Application and CRA-2004.		
WTS	A-03-17	03/17 – 03/20/07	WTS Repository Development Project procedures and implementation of applicable QA requirements defined in American Society of Mechanical Engineers (ASME) NQA-1, 1989, and the CBFO QAPD (U.S. Department of Energy 2007) and WTS QAPD.	S	S	S
				WTS Repository Development Project QA Program was adequate and the implementing procedures were satisfactorily implemented and effective.		
WTS	A-03-19	05/27 – 05/29/03	WTS Surface Operations and Maintenance activities, procedures, and implementation of the applicable WTS QA requirements as defined in ASME NQA-1, 1989 edition, and the CBFO QAPD (U.S. Department of Energy 2007) and WTS QAPD.	S	S	S
				WTS Surface Operations and Maintenance QA program was adequate and the implementing procedures were satisfactorily implemented and effective.		
WTS	A-03-20	07/14 – 07/16/03	WTS Waste Operations activities and implementation of the applicable WTS QA requirements defined in ASME NQA-1, 1989 edition, and the CBFO QAPD (U.S. Department of Energy 2007) and WTS QAPD. WTS Waste Handling Operation implementing procedures.	S	S	S
				WTS Waste Handling Operation QA program and implementing procedures were adequate, satisfactorily implemented, and effective.		
WTS	A-03-23	09/08 – 09/09/03	Verify that the WTS Safety and Health QA Program met applicable requirements as defined in ASME NQA-1-1989 edition; NQA-2a-1990 addenda, part 2.7, to ASME NQA-2-1989 edition and ASME NQA-3-1989 edition (excluding Sections 2.1 (b) and (c) and Section 17.1); and the CBFO QAPD (U.S. Department of Energy 2007). The adequacy, implementation, and effectiveness of the WTS Safety and Health implementing procedures.	S	S	S
				WTS Safety and Health QA program and implementing procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the ASME NQA documents.		

Table AUD-8. Washington TRU Solutions Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
WTS	A-04-13	02/23 – 02/26/04	WTS continued implementation of the QA requirements defined in the CBFO QAPD (U.S. Department of Energy 2007), NQA-1 elements, and applicable WTS implementing procedures.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), and WTS implementing procedures and processes are effective.		
WTS	A-04-21	08/02 – 08/05/04	Technical and QA processes related to the WTS QA program and waste handling activities.	S	S	S
				The WTS QA Program was adequate relative to the flow down of selected requirements from the CBFO QAPD (U.S. Department of Energy 2007), ASME NQA-1, 1989 edition, the WTS QAPD, ASME NQA-1, 1989 edition, the WTS QAPD, and WTS implementing procedures. Implementing procedures were satisfactorily implemented and effective.		
WTS	A-05-07	04/18 – 04/21/05	WTS QA program as applied to waste processing activities.	S	S	S
				The WTS QA Program was adequate relative to the flow down of selected requirements from the WTS QAPD, ASME NQA-1, 1989 edition, and the WTS QAPD and implementing procedures. Implementing procedures were satisfactorily implemented and are effective.		
WTS	A-05-19	07/05 – 07/06/05	WTS continued implementation of the QA requirements defined in the CBFO QAPD (U.S. Department of Energy 2007) and applicable WTS implementing procedures.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the QA program was effective.		
WTS	A-05-20	09/26 – 09/29/05	WTS continued implementation of NQA-1 Criteria 3, 5, 8 through 14, NQA-2 Part 2.7, and applicable WTS implementing procedures.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the QA program was effective.		
WTS	A-06-13	05/09 – 05/15/06	WTS continued implementation of NQA-1 Criteria 1, 2, 4, 6, 7, 15, 16, 17, and 18, and applicable WTS implementing procedures.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the QA program was effective.		
WTS	A-06-22	08/07 – 08/10/06	WTS continued implementation of Waste Handling Operations procedures.	S	S	S
				WTS waste handling operations procedures contained adequate flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and U.S. Department of Energy		

Table AUD-8. Washington TRU Solutions Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
				(DOE) documents, and the Waste Handling Operations program was effective.		
WTS	A-06-26	09/18 – 09/20/06	WTS continued implementation of DOE/CBFO-94-1012, QAPD (U.S. Department of Energy 2007).	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007).		
WTS	A-07-09	03/20 – 03/22/07	WTS continued implementation of a QA Program related to Criteria 1 through 9 of the QAP Requirements for Nuclear Facilities.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the upper-tier documents.		
WTS	A-07-18	04/09 – 04/17/07	QA and technical activities related to waste handling operations at the WIPP.	S	S	S
				WTS waste handling operations procedures were adequate relative to the flow down of requirements from the upper-tier documents.		
WTS	A-07-25	09/18 – 09/20/07	WTS continued implementation of a QA program in relation to ASME NQA-1, 1989 Edition.	S	S	S
				WTS QA procedures were adequate relative to the flow down of requirements from the upper-tier documents.		
WTS	S-05-19	08/17 – 08/18/05	The adequacy, implementation and effectiveness of the WTS Seismic Monitoring Operations.	S	S	S
				WTS Seismic Monitoring Operations for the surface and underground process and associated activities were satisfactorily implemented and effective.		
WTS	S-05-21	09/26 – 09/28/05	The adequacy, implementation and effectiveness of WTS Ground Control and Mine Safety.	S	S	S
				WTS Ground Control and Mine Safety processes and associated activities were satisfactorily implemented and effective.		
WTS	S-06-01	10/11 – 10/13/05	Fire protection activities in both the surface and underground operations at the WIPP.	S	S	S
				WTS Fire Protection processes and associated activities were satisfactorily implemented and effective.		
WTS	S-06-03	11/15 – 11/17/05	Dosimetry activities in both the surface and underground operations at the WIPP.	S	S	S
				The WTS Dosimetry Program was adequate, satisfactorily implemented, and effective.		
WTS	S-06-04	12/12 – 12/15/05	Subsidence monitoring activities at the WIPP.	S	S	S
				The WTS Subsidence Monitoring Program and associated activities were satisfactorily implemented and effective.		

Table AUD-8. Washington TRU Solutions Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
WTS	S-06-08	01/10 – 01/12/06	The Standards/Requirements Identification Document (S/RID) change and update process and the requirements document impact analysis process.	S	S	S
				The WTS S/RID change and update process and the requirements document impact assessment process and implementing procedures was adequate, implementation was satisfactory, and the process was effective.		
WTS	S-06-10	02/14/06	The Receipt Inspection Process, as implemented by WTS at the WIPP.	S	S	S
				The Receipt Inspection Process was adequately described in the WTS QAPD and implementing procedures. The WTS receipt inspection procedures were satisfactorily implemented and effective.		
WTS	S-06-12	09/26 – 09/27/06	Graded approach documentation and use in work processes, associated independent assessments of the graded approach, and training of personnel making graded approach decisions.	S	S	S
				The WTS and CCP Graded Approach activities were adequate, satisfactorily implemented, and effective.		
WTS	S-06-13	03/14/06	The WTS TRUPACT-III procurement activities being conducted at the WIPP.	S	S	S
				Implementation of the WTS activities involved in the TRUPACT-III procurement and QA oversight were effective and adequate to comply with regulatory and CBFO requirements.		
WTS	S-06-15	06/13 – 06/14/06	The WTS QAP with respect to the discharge permit activities and CBFO documents. WTS discharge permit implementing procedures.	S	S	S
				WTS activities evaluated were adequate, satisfactorily implemented, and effective.		
WTS	S-06-17	04/04 – 04/05/06	Policies, plans and procedures related to the operation, inspection/verification and maintenance of the WTS Mine Ventilation System.	S	S	S
				Activities associated with the operation and maintenance of the mine ventilation system were appropriately proceduralized and effectively implemented. Personnel had received the training appropriate to their assigned task. Records were maintained as required.		
WTS	S-06-22	07/31 – 08/3/06	WTS Radiological Control (RADCON) Program for the entire site operations at the WIPP.	S	S	S
				The WTS RADCON Program is adequate, satisfactorily implemented, and effective.		
WTS	S-06-27	09/11 – 09/12/06	WTS Central Monitoring Room (CMR) operations at the WIPP.	S	S	S
				WTS CMR operations were adequate, satisfactorily implemented, and effective.		

Table AUD-8. Washington TRU Solutions Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
WTS	S-06-28	08/29 – 08/30/06	The WTS Safe Drinking Water (SDW) process at the WIPP.	S	S	S
				The WTS SDW process was adequate, satisfactorily implemented, and effective.		
WTS	S-06-30	09/18 – 09/21/06	SQA controls applied to the WIPP Waste Information System (WWIS).	S	S	S
				WTS SQA controls applied to the WWIS are adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007). Implementation of software controls is satisfactorily performed in compliance with WTS implementing procedures. The SQA control program is effective with respect to WWIS software.		
WTS	S-06-31	09/19 – 09/20/06	The Groundwater Monitoring Program, as implemented by WTS at the WIPP.	S	S	S
				The WTS Groundwater Monitoring Program was adequate, satisfactorily implemented, and effective.		
WTS	S-06-34	08/07 – 08/10/06	Procedure steps for the standing orders process as found in procedure WP 04-CO, Conduct of Operations procedure.	S	S	S
				WTS standing order process procedures were adequate and procedure implementation, documentation, and training were effective.		
WTS	S-06-35	09/13/06	This surveillance was a follow-up to CBFO Surveillance S-06-04, Subsidence Monitoring, conducted December 12-15, 2005. This surveillance evaluated the Subsidence Survey Data Acquisition process not evaluated during Surveillance S-06-04.	S	S	S
				The WTS Subsidence Survey Data Acquisition process was adequate, satisfactorily implemented, and effective.		
WTS	S-07-02	11/06 – 11/07/07	Policies, plans, and procedures related to the procurement process (requisition through purchase order and placement).	S	S	S
				Procurement activities are performed as required. Procedures were adequate, satisfactorily implemented, and effective.		
WTS	S-07-04	10/25/06	WTS processes that allow for the off-site shipment of WTS hazardous waste to permitted disposal sites.	S	S	S
				WTS processes are adequate, satisfactorily implemented, and effective.		
WTS	S-07-06	01/16 – 01/18/07	WTS VOC monitoring program for site operations at the WIPP.	S	S	S
				The VOC monitoring program is adequate, satisfactorily implemented, and effective.		

Table AUD-8. Washington TRU Solutions Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
WTS	S-07-07	02/05 – 02/06/07	WTS policies, plans, and procedures related to the electrical safety program at the WIPP.	S	S	S
				The electrical safety program was adequately described in the WTS QAPD and implementing procedures. The WTS electrical safety program and procedures were satisfactorily implemented and effective.		
WTS	S-07-08	03/06 – 03/08/07	WTS activities associated with the WTS maintenance program at the WIPP.	S	S	S
				The WTS maintenance program is adequate, satisfactorily implemented, and effective.		
WTS	S-07-14	06/12/07	The WTS Monitoring Program – Delaware Basin operations at the WIPP.	S	S	S
				WTS Monitoring Program – Delaware Basin operations were adequate, satisfactorily implemented, and effective.		
WTS	S-07-24	06/19 – 06/20/07	Fire protection activities in both the surface and underground operations at the WIPP.	S	S	S
				WTS Fire Protection processes and associated activities were satisfactorily implemented and effective.		
WTS	S-07-31	09/05/07	Software activities in association with the Central Monitoring System (CMS) at the WIPP.	S	S	S
				The WTS CMS software activities were adequate, satisfactorily implemented, and effective.		
WTS	S-07-32	07/19/07	Procedures describing software back-up activities applied to safety-related software such as the CMS and other software applications used for design and modeling of possible release of material from the WIPP.	S	S	S
				WTS software QA activities related to safety software applications were acceptable, and procedure implementation and software QA documentation were effective.		

Table AUD-9. Sandia National Laboratories Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
SNL	A-04-02	11/17 – 11/20/03	SNL NWMP QA Program for the WIPP.	S	S	S
				The SNL NWMP QA program for the WIPP remained adequate, satisfactorily implemented, and effective.		
SNL	A-05-05	11/15 – 11/18/04	SNL NWMP QA Program for the WIPP.	S	S	S
				The SNL NWMP QA program for the WIPP remained adequate, satisfactorily implemented, and effective.		
SNL	A-06-05	11/28 – 12/2/05	SNL NWMP QA Program for the WIPP.	S	S	S
				The SNL NWMP QA program for the WIPP remains adequate, satisfactorily implemented, and effective.		
SNL	A-07-04	11/27 – 11/30/06	SNL NWMP QA Program for the WIPP.	S	S	S
				The SNL NWMP QA program for the WIPP was adequate, satisfactorily implemented, and effective.		
SNL	A-08-05	1113 – 11/15/07	SNL WIPP QA Program for the WIPP.	S	S	S
				The SNL WIPP QA program for the WIPP was adequate, satisfactorily implemented, and effective.		

Table AUD-10. Savannah River Site Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
SRS	A-03-16	03/25 – 03/27/03	The CCP IQ3 NDA at the SRS relative to TRU waste characterization activities for waste shipped to the WIPP.	S	S	S
				CCP technical processes and procedures associated with the IQ3 NDA System and selected QA program elements were satisfactory in meeting requirements.		
SRS	A-04-01	10/21 – 10/24/03	SRS TRU waste characterization activities performed by SRS or for SRS by the CCP for debris waste relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999).	S	S	S
				The defined QA and technical processes for the audited activities were implemented in accordance with the CCP TRU waste QAPjP and related SRS/CCP implementing procedures. Audited processes were adequate, satisfactorily implemented, and effective.		
SRS	A-05-01	10/26 – 10/29/04	SRS TRU waste characterization activities performed by SRS or for SRS by the CCP for debris waste, relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999).	S	S	S
				SRS/CCP technical and QA programs, as applicable to the audited activities, met requirements contained in the HWFP (State of New Mexico 1999).		
SRS	A-06-01	10/24 – 10/28/05	SRS TRU waste characterization activities performed by SRS or for SRS by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the CH-TRU WAC for the WIPP (U.S. Department of Energy 2008a).	S	S	S
				SRS technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
SRS	A-07-01	10/24 – 10/26/06	SRS TRU waste characterization activities performed by the SRS CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the CH-TRU WAC for the WIPP (U.S. Department of Energy 2008a).	S	S	S
				The SRS/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
SRS	A-07-02	10/31 – 11/02/07	SRS TRU waste characterization activities performed for SRS by the CCP relative to the requirements detailed in the CBFO QAPD (U.S. Department of Energy 2007) and the CH-TRU WAC (U.S. Department of Energy 2008a).	S	S	S
				The SRS/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		

Table AUD-10. Savannah River Site Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
SRS	A-07-24	07/31 – 08/02/07	SRS TRU waste characterization activities of the Battelle Columbus RH-TRU SCG S5000 (debris waste) performed for SRS by the CCP, relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the WAC (U.S. Department of Energy 2008a).	S	S	S
				SRS/CCP technical and QA programs, as applicable to the audited activities, were satisfactory in meeting requirements.		
SRS	A-08-01	10/30 – 11/01/07	SRS TRU waste characterization activities performed by the SRS CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the WAC for the WIPP (U.S. Department of Energy 2008a).	S	S	S
				SRS/CCP technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
SRS	S-03-10	01/14/03	Characterization and certification activities for CCP shipment of overpack containers from the SRS to the WIPP.	S	S	S
				Procedures and associated data for characterization and certification of the standard waste box (SWB) overpacks were reviewed and were found acceptable. The selection process of overpack candidate drums complied with the WIPP WAC (U.S. Department of Energy 2008a). Input of overpack documentation into the CCP database was correct for the sampled fields. WIPP WAC limits were acceptable for the overpack shipment payload.		
SRS	S-06-21	04/18/06	RTR and VE activities being conducted at the SRS.	S	S	S
				Implementation of the SRS/CCP activities involved in the RTR and VE activities were effective and adequate to comply with regulatory and CBFO requirements.		
SRS	S-07-28	08/07 – 08/08/07	SRS Mobile segmented gamma scanner (SGS) operations performed by CCP relative to the requirements detailed in DOE/WIPP-02-3122, Rev. 6, WIPP WAC (U.S. Department of Energy 2008a).	S	S	S
				SGS activities were determined to be adequate, satisfactorily implemented, and effective.		

Table AUD-11. Carlsbad Field Office Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
CBFO	A-04-16	05/10 – 05/13/04 and 05/26/04	The adequacy, implementation, and effectiveness of selected CBFO QAPD (U.S. Department of Energy 2007) requirements in accordance with selected criteria of ASME NQA-1, 1989 edition.	S	S	S
				CBFO QAPD (U.S. Department of Energy 2007) and applicable implementing procedures were adequate relative to the flow down of requirements from NQA-1 selected criteria, with the exception of CBFO Management Procedure 2.1, Personnel Qualification and Training, which was determined to be unsatisfactory. Corrective actions continued to be effective for selected CARs (U.S. Department of Energy 2008b) generated during CBFO Surveillance S-03-08.		
CBFO	A-04-24	09/07 – 09/09/04	Selected CBFO QAPD (U.S. Department of Energy 2007) sections addressing selected criteria of the ASME NQA-1, 1989 edition and NQA-2-1990a, part 2.7, and the associated QAPD implementing procedures.	I	I	I
				Although the CBFO organizational structure appeared to meet the intent of ASME/NQA-1-1989, the implementation and effectiveness of the organization were indeterminate because of the lack of implementing procedures reflecting the new organization.		
CBFO	A-06-06	12/13– 12/20/05	Selected sections of DOE-CBFO-94-1012, CBFO QAPD, Rev. 7, and implementing procedures, addressing selected criteria of the ASME NQA-1-1989 edition.	S	S	S
				The CBFO QAPD (U.S. Department of Energy 2007) was adequate relative to the flow down of requirements from the applicable NQA-1 criteria, and the CBFO QA implementing procedures were adequate relative to the flow down of requirements from the CBFO QAPD.		
CBFO	A-07-05	02/20 – 02/22/07	Selected sections of DOE-CBFO-94-1012, CBFO QAPD, Rev. 8, and associated implementing procedures, addressing selected criteria of the ASME NQA-1-1989 edition.	S	S	S
				The CBFO QAPD (U.S. Department of Energy 2007) was adequate relative to the flow down of requirements from the applicable NQA-1 criteria, and the CBFO QA implementing procedures were adequate relative to the flow down of requirements from the CBFO QAPD.		
CBFO	A-07-20	06/04 – 06/05/07	Selected sections of DOE-CBFO-94-1012, CBFO QAPD, Rev. 8, and associated implementing procedures, addressing selected criteria of the ASME NQA-1-1989 edition.	S	S	S
				The CBFO QAPD (U.S. Department of Energy 2007) was adequate relative to the flow down of requirements from the applicable NQA-1 criteria, and the CBFO QA implementing procedures were adequate relative to the flow down of requirements from the CBFO QAPD.		

Table AUD-11. Carlsbad Field Office Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
CBFO	S-03-16	06/09 – 06/10/03	The effectiveness of the CBFO corrective action reporting and tracking system.	S	S	S
				The CAR tracking information, CBFO Management Assessment finding information, and U.S. Environmental Protection Agency (EPA) finding information was being gathered, reported, and distributed adequately to facilitate prompt completion of corrective actions and closure of related CARs and findings.		

Table AUD-12. Lawrence Livermore National Laboratory Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
LLNL	A-04-25	05/04 – 05/07/04	LLNL/CCP TRU waste characterization and certification activities related to SCG S5000 (debris waste), including technical and QA activities (U.S. Department of Energy 2004b).	S	S	S
				CCP technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WIPP HWFP (State of New Mexico 1999).		
LLNL	S-05-11	07/19/05	Characterization and certification activities performed after the CBFO Audit A-04-25, which was conducted on May 4 – 7, 2004, and LLNL/CCP project records disposition and turnover activities between LLNL and CCP.	S	S	S
				CCP project records service activities were adequately proceduralized, procedures were satisfactorily implemented and effective. Characterization and certification activities ensured continuing processing to implementing procedures.		

Table AUD-13. Oak Ridge National Laboratory Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
ORNL	A-08-04	12/04 – 12/06/07	ORNL TRU waste characterization activities performed for ORNL by the CCP relative to the requirements detailed in the WIPP HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the WAC (U.S. Department of Energy 2008a).	S	S	S
				ORNL/CCP technical and QA programs, as applicable to the audited activities, were adequate and satisfactory in meeting requirements.		
ORNL	A-08-06	11/13 – 11/15/07	ORNL technical processes related to the CCP program as applied to AK and NDA.	S	S	S
				The procedures, processes, and controls in place were adequate, efficient, and effectively implemented to comply with the technical and QA processes to control the work and waste certification.		

Table AUD-14. Advanced Mixed Waste Treatment Facility Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
AMWTF	A-03-05	08/18 – 08/22/03	Technical processes of INEEL AMWTF TRU waste characterization activities as they relate to the addition of the Consonant Technologies, Inc. (CTI) headspace sampling system for S3000 (solids) waste.	S	S	S
				The AMWTF technical and QA programs, as applicable to audited activities, were satisfactory relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WIPP HWFP (State of New Mexico 1999).		
AMWTF	A-04-12	04/12 – 04/15/04	The technical processes of INEEL AMWTF TRU waste characterization activities as they relate to the addition of the CTI HSG sampling and analysis system for SCG S3000 (solids) waste.	S	S	S
				AMWTF technical and QA programs, as applicable to audited activities, was satisfactory in meeting the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007) and the WIPP HWFP (State of New Mexico 1999). Defined QA and technical programs for these activities were implemented in accordance with applicable requirement documents and the implementing procedures.		
AMWTF	A-04-22	08/16 – 08/20/04	Technical and QA processes related to the INEEL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S3000 homogenous solids waste.	S	S	S
				AMWTF technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), WIPP HWFP (State of New Mexico 1999) WAP, and CH-TRU WAC (U.S. Department of Energy 2008a). The defined QA Program was being satisfactorily implemented in accordance with the AMWTF QAPjP (Arbon 2003), and the Certification Plan.		
AMWTF	A-05-08	03/05 – 03/04/05	Technical and QA processes related to INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S5000 debris waste, including supercompacted waste.	S	S	S
				AMWTF technical activities and QA Program and procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WIPP HWFP (State of New Mexico 1999) WAP, and the AMWTF QAPjP (Arbon 2003).		

Table AUD-14. Advanced Mixed Waste Treatment Facility Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
AMWTF	A-05-17	08/23 – 08/25/05	Technical and QA processes related to the INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S3000 homogeneous solids waste.	S	S	S
				AMWTF technical procedures and the QA Program and procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the HWFP (State of New Mexico 1999) WAP, the CH-TRU WAC (U.S. Department of Energy 2008a), the AMWTF QAPjP (Arbon 2003), the Certification Plan, and implementing procedures.		
AMWTF	A-05-21	08/30 – 09/01/05	INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S3000 (homogeneous solids waste).	S	S	S
				AMWTF technical procedures were adequate relative to the flow down of requirements from the WAP of the WIPP HWFP (State of New Mexico 1999), and the CH-TRU WAC (U.S. Department of Energy 2008a).		
AMWTF	A-06-09	03/21 – 03/24/06	INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S5000 (debris waste).	S	S	S
				AMWTF technical procedures were adequate relative to the flow down of requirements from the WAP of the WIPP HWFP (State of New Mexico 1999), and the CH-TRU WAC (U.S. Department of Energy 2008a).		
AMWTF	A-06-10	03/28 – 03/31/06	AMWTF TRU waste characterization activities performed by AMWTF, relative to the requirements detailed in the CBFO QAPD (U.S. Department of Energy 2007), the WIPP CH-TRU WAC (U.S. Department of Energy 2008a), the CH-TRAMPAC (U.S. Department of Energy 2005a), and the WIPP HWFP(State of New Mexico 1999), as related to SCG 5000 QA and transportation activities.	S	S	S
				AMWTF technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements. The audit team verified that the AMWTF QA program for characterization and certification activities related to SCG S5000 (debris waste) was adequate, satisfactorily implemented, and effective.		
AMWTF	A-06-24	08/15 – 08/17/06	INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCGs S3000 (homogeneous solids) and S5000 (debris waste).	S	S	S
				AMWTF technical procedures were adequate relative to the flow down of requirements from the WAP of the WIPP HWFP (State of New Mexico 1999), and the CH-TRU WAC (U.S. Department of Energy 2008a).		
AMWTF	A-06-25	08/21 –	AMWTF TRU waste characterization activities	S	S	S

Table AUD-14. Advanced Mixed Waste Treatment Facility Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
		08/24/06	performed by AMWTF relative to the requirements detailed in the CBFO QAPD (U.S. Department of Energy 2007), the WIPP CH-TRU WAC (U.S. Department of Energy 2008a), the CH-TRAMPAC (U.S. Department of Energy 2005a), and the WIPP HWFP(State of New Mexico 1999), as related to QA, NDA, and transportation activities.	AMWTF technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
AMWTF	A-07-14	08/28 – 08/30/07	INL AMWTF TRU waste characterization and certification activities as they relate to the WIPP HWFP (State of New Mexico 1999) for SCG S3000 (homogeneous solids) and S5000 (debris) wastes, and drum coring of homogeneous solids (S3000) and soils/gravel (S4000) wastes.	S	S	S
				AMWTF technical procedures were adequate relative to the flow down of requirements from the WAP of the WIPP HWFP (State of New Mexico 1999), and the WAC (U.S. Department of Energy 2008a).		
AMWTF	A-07-15	08/20 – 08/23/07	AMWTF TRU waste characterization activities relative to the requirements of the CBFO QAPD (U.S. Department of Energy 2007), the CH-TRU WAC for the WIPP (U.S. Department of Energy 2008a), and the WIPP HWFP (State of New Mexico 1999), as related to QA and NDA.	S	S	S
				AMWTF technical and QA programs, as applicable to audited activities, were satisfactory in meeting requirements.		
AMWTF	S-04-10	04/12 – 04/15/04	Identification and correction of recent nonconforming conditions in the waste certification process at the AMWTF. Specific areas evaluated included waste certification, payload certification, WWIS certification, project-level review, nonconformance control, and training.	I	I	I
				AMWTF was in the process of implementing short-term corrective actions that would assure compliance with program requirements. AMWTF was in the process of establishing long-term corrective actions that would preclude recurrence of the issues. No new conditions adverse to quality that required the issuance of a CAR were identified.		
AMWTF	S-05-12	05/10 – 05/11/05	Specific elements of the contract transition that recently occurred. The evaluation examined objective evidence relating to the AMWTF contract transition process.	I	I	I
				AMWTF was still in the process of contract transition. The transition had not impacted personnel, equipment, and procedures that had been previously evaluated.		
AMWTF	S-07-16	01/10 – 01/11/07	Policies, plans, and procedures related to solids sampling activities.	S	S	S
				Activities associated with coring operations at the AMWTF continued to comply with the requirements of the WIPP HWFP (State of New Mexico 1999).		

Table AUD-14. Advanced Mixed Waste Treatment Facility Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
AMWTF	S-07-21	04/04 – 04/05/07	Equipment, sample collection, sample chain-of-custody, sample storage, and shipment of waste samples using the AMWTF manual coring system. System operability and the implementation of associated procedures.	S	S	S
				The manual coring system for collection of samples for waste analysis was installed properly and initial activities were completed successfully. The system was performing acceptably for TRU waste characterization activities. The applicable implementing procedures for this system and activity were adequate, satisfactorily implemented, and effective.		

Table AUD-15. Argonne National Laboratory – East Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
ANL-E	A-02-03 and A-03-13	09/09 – 09/13/02 and 02/10 – 02/13/03	ANL-E/CCP TRU waste characterization and certification activities related to SCGs S5000 (debris waste) and S3000 (homogeneous solid waste). Audit A-02-03 assessed HWFP (State of New Mexico 1999) WAP-related QA activities and technical processes for characterization and certification of SCG S5000 retrievably stored CH-TRU debris waste. Audit A-03-13 assessed the HWFP (State of New Mexico 1999) WAP technical processes related to characterization and certification of SCG S3000 retrievably stored CH-TRU homogeneous solid waste.	S	S	S
				ANL-E/CCP technical and QA programs, as applicable to the audited activities, met the requirements contained in the HWFP (State of New Mexico 1999).		
ANL-E	A-03-18	06/24 – 06/25/01	ANL-E QA and technical support activities for the preparation of samples needed to support the WIPP HSG Performance Demonstration Program (PDP).	S	S	S
				The activities evaluated relating to QA were adequate, satisfactorily implemented, and effective.		
ANL-E	A-03-26	08/26 – 08/27/03	CCP characterization and certification activities related to ANL-E solid wastes.	S	S	S
				The technical and QA procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WIPP HWFP (State of New Mexico 1999) WAP, the WIPP WAC (U.S. Department of Energy 2008a), and the CCP QAPjP (Arbon 2003) and implementing procedures.		
ANL-E	A-04-03	10/06 – 10/09/03	ANL-E/CCP TRU technical processes and QA program and procedures for waste characterization and certification activities related to SCG S3000 homogeneous solid waste and S5000 retrievably stored debris waste streams.	S	S	S
				CCP technical processes and the QA program and procedures were adequate relative to the flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WIPP HWFP (State of New Mexico 1999) WAP, and the CCP QAPjP (Arbon 2003).		
ANL-E	A-04-18	06/08 – 06/09/04	ANL QA and technical support activities for the preparation of samples needed to support the WIPP HSG PDP.	S	S	S
				Activities relating to QA were adequate, satisfactorily implemented, and effective. HSG PDP implementing procedures and activities for sample preparation, verification and distribution remained adequate, satisfactorily implemented, and effective.		

Table AUD-15. Argonne National Laboratory – East Assessments (Continued)

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
ANL-E	A-05-11	09/13 – 09/14/05	ANL-E QA and technical support activities for the preparation of samples needed to support the WIPP HSG PDP.	S	S	S
				Activities evaluated relating to QA were adequate, satisfactorily implemented, and effective. HSG PDP implementing procedures and activities for sample preparation, verification and distribution remained adequate, satisfactorily implemented, and effective.		
ANL-E	A-06-27	Phase 1: 08/29 – 08/31/06 Phase 2: 09/11 – 09/14/06	ANL TRU waste characterization activities performed for ANL by the CCP.	S	S	S
				The ANL/CCP QA program, as applicable to audited activities, was satisfactory in addressing established requirements. The technical elements assessed were adequate in addressing the established requirements for the activities observed.		
ANL-E	A-07-03	08/14 – 08/16/07	ANL TRU waste characterization activities performed for ANL by the CCP.	S	S	S
				ANL/CCP technical procedures were adequate relative to the flow down of requirements from the HWFP (State of New Mexico 1999), the CBFO QAPD (U.S. Department of Energy 2007), and the WAC (U.S. Department of Energy 2008a). ANL/CCP technical areas evaluated were satisfactorily implemented and are effective.		
ANL-E	S-05-04	12/07 – 12/08/04	Characterization and certification activities for the period between CBFO Audit A-04-03 and the last shipment of TRU waste to the WIPP.	S	S	S
				ANL-E/CCP areas evaluated were adequately proceduralized, procedures were satisfactorily implemented, and implementation was effective.		

Table AUD-16. Supplier Assessments

Organization Assessed	Assessment Number	Assessment Dates	Scope of Assessments	Adequacy	Implementation	Effectiveness
CEMRC	A-07-21	02/13 – 02/16/07	Technical and QA activities related to the CEMRC/CCP, which functions as an independent HSG analysis laboratory.	S	S	S
				CEMRC/CCP technical and QA procedures contained adequate flow down of requirements from the CBFO QAPD (U.S. Department of Energy 2007), the WIPP HWFP (State of New Mexico 1999), and the WIPP CH-TRU WAC (U.S. Department of Energy 2008a). The defined QA program was implemented in accordance with the CEMRC/CCP contract and statement of work documents, as well as the CEMRC/CCP implementing procedures and interface documents. The HSG analysis program was effective.		
Environmental Resource Associates (ERA)	A-05-03	11/10/04	Adequacy of previous work performed for Cycles 10A and 11A of the Resource Conservation and Recovery Act (RCRA) PDP, and to verify capability to perform work required for Cycle 12A.	S	S	S
				The adequacy of past work was acceptable. ERA facilities were adequate and the ERA quality program was adequate and effectively implemented for performing RCRA PDP Cycle 12A.		
L&M Technologies, Project Records Services	S-05-14	07/11 – 07/12/05	Project Records Services performed by L&M Technologies, with emphasis on the records retrieval process.	S	S	S
				The project records service activities of L&M Technologies were adequately proceduralized, procedures were satisfactorily implemented and implementation was effective.		
Portage Environmental, Inc.	A-05-04	03/14/05, 03/16/05, 03/18/05, and 03/22 – 03/23/05	WIPP RCRA PDP management and oversight activities.	S	M	S
				QA and technical activities of the PDP were adequate, marginally implemented, and effective. Programmatic direction and oversight activities by the DOE/CBFO and Carlsbad Field Office Technical Assistance Contractor (CTAC)/Portage, as specified in the PDP plans and CTAC implementing procedures, were adequate, marginally implemented, and effective.		

AUD-2.0 References

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification Application
for the
Waste Isolation Pilot Plant

Appendix DATA-2009
Monitoring Data and Reports

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix DATA-2009
Monitoring Data and Reports

Table of Contents

Attachments

Acronyms and Abbreviations

CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
CMP	Compliance Monitoring Program
COMP	compliance monitoring parameter
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	foot
GMP	Geotechnical Monitoring Program
GWMP	Groundwater Monitoring Program
m	meter
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
RH-TRU	remote-handled transuranic
SMP	Subsidence Monitoring Program
TRU	transuranic
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

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DATA-1.0 Introduction

Appendix DATA-2009 provides references to the data used to develop the 2009 Compliance Recertification Application (CRA-2009). Interpretation and analysis of those data are provided in the appropriate sections of CRA-2009.

40 CFR § 194.15(a)(1), (2), (3), and (5) (U.S. Environmental Protection Agency 1996), Content of Recertification Applications, require that the U.S. Department of Energy (DOE) provide information obtained since the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) related to site geology, hydrology, and meteorology. Additional monitoring results and the results of laboratory investigations completed after the CRA-2004 (U.S. Department of Energy 2004) must also be provided, as well as information regarding the waste emplaced in the disposal system.

In the initial U.S. Environmental Protection Agency (EPA) certification of compliance for the Waste Isolation Pilot Plant (WIPP) (U.S. Environmental Protection Agency 1998), the EPA agreed that 10 compliance monitoring parameters (COMPs) would be monitored during the operational period of the project.

The DOE uses various programs to capture and analyze all relevant information. These programs and the information they collect are discussed in the appropriate sections of this appendix.

DATA-1.1 Reported Data

This document also provides monitoring data related to the COMPs. The locations, in this appendix, of the data for the COMPs are listed below:

COMP	Location in Appendix DATA-2009
Change in the Culebra groundwater flow	Section DATA-5.0, Section DATA-10.0, and Section DATA-11.0
Creep closure and stresses	Section DATA-4.0 and Section DATA-10.0
Culebra groundwater composition	Section DATA-5.0, Section DATA-10.0, and Section DATA-11.0
Displacement of deformation features	Section DATA-4.0 and Section DATA-10.0
Drilling rate	Section DATA-2.0 and Section DATA-10.0
Extent of brittle deformation	Section DATA-4.0, Section DATA-9.0, and Section DATA-10.0
Initiation of brittle deformation	Section DATA-4.0 and Section DATA-10.0
Probability of encountering a Castile brine reservoir	Section DATA-2.0 and Section DATA-10.0
Subsidence measurement	Section DATA-3.0 and Section DATA-10.0
Waste activity	Section DATA-7.0 and Section DATA-10.0

Monitoring is performed to detect substantial deviations from the assumptions used in the CCA. The above COMPs are being monitored during the preclosure period. Parameters not being monitored but used by performance assessment (PA) can be found in Fox 2008.

DATA-2.0 Delaware Basin Drilling Surveillance Program

The Delaware Basin Drilling Surveillance Program (DBDSP) monitors drilling activities in the vicinity of the WIPP. This section provides a brief discussion of the program and identifies the relevant data reports.

DATA-2.1 Program Overview

The EPA requires the DOE to demonstrate the expected containment performance of the disposal system using a PA. The PAs documented in the CCA and CRA-2004 demonstrated that the WIPP complies with the EPA's containment standards for undisturbed and human intrusion scenarios.

The criteria in 40 CFR § 194.33 (U.S. Environmental Protection Agency 1996) require the use of historic drilling information to derive the drilling rate for PA intrusion scenarios. The DBDSP continues to monitor drilling-related activities, providing data used to determine whether the assumptions and scenarios used in PA remain valid, and uses the monitoring data to determine the drilling rate. These monitoring activities will continue until the DOE and the EPA agree that no additional benefit can be gained by further monitoring.

DATA-2.2 Reported Data

The two COMP parameters monitored by the DBDSP are the drilling rate (58.5 boreholes per square kilometer) and the probability of encountering a Castile brine reservoir (0.05%), which are discussed in the annual reports for this program and also in the COMPS assessments described in Section DATA-10.0. Other information collected by this program include drilling related data, mining information, and seismic information.

Relevant data generated through the Delaware Basin Monitoring Program are provided in the following reports:

- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 4, September 2003.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 5, September 2004.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-99-2308 Rev. 6, September 2005.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-06-2308, September 2006.
- Delaware Basin Monitoring Annual Report; DOE/WIPP-07-2308, September 2007.
- Callicoat, J., Calculation of Shallow Drilling for 2007, Memo to File, Washington Regulatory and Environmental Services, Carlsbad, NM, July 2, 2008. WRES:08:251.
- Hughes, D., Status of Potash Activities – 2007, Memo to File, Washington Regulatory and Environmental Services, Carlsbad, NM, July 2, 2008. WRES:08:250.

- Hughes, D., Castile Brine Encounters. 2007, Memo to File, Washington Regulatory and Environmental Services, Carlsbad, NM, WRES:08:302.

- Hughes, D., Seismic Activity within the Delaware Basin, Memo to File, Washington Regulatory and Environmental Services, Carlsbad, NM, WRES:08:303.

DATA-3.0 Subsidence Monitoring Program

Subsidence monitoring measures vertical movement of the land surface relative to a reference location. This section provides a brief discussion of the Subsidence Monitoring Program (SMP) and identifies the relevant data reports.

DATA-3.1 Program Overview

The SMP uses a leveling survey to measure the relative vertical height differences between benchmarks. A level survey consists of taking one benchmark as having a constant elevation and determining the elevation of all other benchmarks relative to it. Comparison between level surveys allows vertical movement patterns to be established over time. These comparative surveys would allow substantial deviation of actual subsidence from expected subsidence to be detected.

DATA-3.2 Reported Data

Each year approximately 15 miles of leveling surveying was completed utilizing nine vertical control loops consisting of 48 subsidence monuments and 14 National Geodetic Survey vertical control points. Subsidence rates are small and are approximately at the resolution level of the survey accuracy. The benchmarks with the highest rates are seen above the mined panels. All subsidence rates fall within the predicted values. Data generated through the SMP are provided in the following reports. Each report includes previous years' data as well.

- WIPP Subsidence Monument Leveling Survey 2003, DOE/WIPP 04-2293, October 2003.
- WIPP Subsidence Monument Leveling Survey 2004, DOE/WIPP 05-2293, December 2004.
- WIPP Subsidence Monument Leveling Survey 2005, DOE/WIPP 06-2293, December 2005.
- WIPP Subsidence Monument Leveling Survey 2006, DOE/WIPP 07-2293, December 2006.
- WIPP Subsidence Monument Leveling Survey 2007, DOE/WIPP 08-2293, December 2007.

DATA-4.0 Geotechnical Monitoring Program

The geotechnical monitoring program (GMP) measures in situ geotechnical data in the WIPP repository. This section provides a brief discussion of the GMP and identifies the relevant data reports.

DATA-4.1 Program Overview

The GMP obtains in situ data to support the continuous assessment of underground facilities. A detailed description of the geotechnical programs and procedures is presented in WP07-1, Geotechnical Engineering Program Plan. Specifically, the program provides for

- Early detection of conditions that could affect operational safety
- Guidance for design modifications and remedial actions
- Data for interpreting the behavior of underground openings compared to established design criteria

The GMP collects data from instruments and observation. These data are used to confirm the understanding of geomechanical characteristics, and aid in assessing the stability and performance of the underground facility. Constituent programs, described below, include the Geosciences Program, the Geomechanics Program, and the Rock Mechanics Program.

The Geosciences Program includes the collection of underground data used to assess the repository by documenting the existing geologic conditions and characteristics and monitoring excavation response. Activities associated with this program include geologic and fracture mapping of the excavation surface, core logging, and borehole observations.

The Geomechanics Program monitors the geomechanical response of the underground openings after mining using instrumentation installed in the shafts and drifts of the facility. Geotechnical instrumentation installed underground in the shafts and drifts includes tape extensometer points, convergence meters, borehole extensometers, piezometers, strain gauges, load cells, and crack meters. The instrumentation is sensitive enough to detect small changes in rock displacements and stresses.

To determine significant deviations from expected conditions, the Rock Mechanics Program assesses the performance of the underground excavation for safety and stability during the operational phase. The results from these assessments allow the identification of potentially instable areas and the application of remedial actions, if necessary. Field data are used to compare the actual mechanical performance of the excavations to expected results. Analytical methods, such as numerical modeling, determine the potential effects of mining new excavations, excavation sequence, and long-term behavior of the repository. Extensive experimental work and observations have established an understanding of time-dependent geomechanical properties of the salt that are used to predict its in situ mechanical performance. These assessments rely heavily on the in situ instrumentation data and field observations from the geosciences and geomechanics programs.

DATA-4.2 Reported Data

Data generated through the GMP are reported annually in the Geotechnical Analysis Report. References for reports prepared since the development of the CRA-2004 are provided below. Each report includes previous years' data as well. Four parameters the DOE is required to monitor and assess were identified relating to the information collected by the GMP are creep closure, extent of deformation, initiation of brittle deformation, and displacement of deformation features. Creep closure and displacement of deformation features can be quantified. The other two are qualitative. These four parameters are discussed and analyzed in the COMPs reports listed in Section DATA-10.2.

- Washington TRU Solutions, LLC, 2004, Geotechnical Analysis Report for July 2002–June 2003, DOE/WIPP 04-3177, Carlsbad, NM.

- Washington TRU Solutions, LLC, 2005, Geotechnical Analysis Report for July 2003–June 2004, DOE/WIPP 05-3177, Carlsbad, NM.

- Washington TRU Solutions, LLC, 2006, Geotechnical Analysis Report for July 2004–June 2005, DOE/WIPP 06-3177, Carlsbad, NM.

- Washington TRU Solutions, LLC, 2007, Geotechnical Analysis Report for July 2005–June 2006, DOE/WIPP 07-3177, Carlsbad, NM.

- Washington TRU Solutions, LLC, 2008, Geotechnical Analysis Report for July 2006–June 2007, DOE/WIPP 08-3177, Carlsbad, NM.

DATA-5.0 Groundwater Monitoring Program

The Groundwater Monitoring Program (GWMP) collects and analyzes data for various wells at or near the WIPP site. This section briefly describes the GWMP and identifies relevant reports.

DATA-5.1 Program Overview

One function of the GWMP is the collection of Culebra groundwater data, such as water levels and water quality, from numerous wells located at and near the facility. The Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra) was selected as the focus of the GWMP. It has been extensively studied during past hydrologic characterization programs and was found to be the most likely hydrologic pathway to the accessible environment for any potential human-intrusion-caused release scenario. Data obtained through this program are used to generate the Culebra groundwater composition and the Culebra groundwater flow COMPs. Details on how the program is implemented are provided in Appendix MON-2009.

DATA-5.2 Reported Data

The water quality data collected by the GWMP is discussed and analyzed in the reports listed below and also in the COMPs reports listed in Section DATA-10.2. This analysis provides validation of the various CCA models. Appendix HYDRO-2009 and the COMPs reports provide analysis of the water levels and the fluid density of the water columns in the various wells used in gathering data for the WIPP hydrological model.

- U.S. Department of Energy, 2003, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2002, DOE/WIPP 03-2225, Carlsbad, NM.

- U.S. Department of Energy, 2004, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2003, DOE/WIPP 04-2225, Carlsbad, NM.

- U.S. Department of Energy, 2005, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2004, DOE/WIPP 05-2225, Carlsbad, NM.

- U.S. Department of Energy, 2006, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2005, DOE/WIPP 06-2225, Carlsbad, NM.

- U.S. Department of Energy, 2007, Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 2006, DOE/WIPP 07-2225, Carlsbad, NM.

DATA-6.0 Meteorological Monitoring Program

The Meteorological Monitoring Program measures atmospheric data for the WIPP site. This section provides a brief description of the program and a list of relevant reports.

DATA-6.1 Program Description

The primary WIPP meteorological station is located 600.5 meters (m) (1,970 feet (ft)) northeast of the Waste Handling Building. The main function of the station is to provide data for atmospheric modeling. The station measures and records wind speed, wind direction, and temperature at elevations of 2, 10, and 50 m (6.5, 33, and 165 ft). The station records ground-level measurements of barometric pressure, relative humidity, precipitation, and solar radiation.

DATA-6.2 Reported Data

The annual site environmental reports listed in Section DATA-5.2 provide data relevant to the Meteorological Monitoring Program. The CCA, Appendix CLI provides information on past (long-term) climatic conditions and predicted future conditions at the WIPP site. A discussion of the wind, rainfall, and temperature variation can be found in 40 CFR § 194.15.

DATA-7.0 Waste Information

Two types of information related to waste characteristics are collected: (1) information regarding waste that has been emplaced in the WIPP underground repository and (2) information regarding future inventory that will be emplaced in the WIPP underground repository during the entire lifetime of the project. This section provides a brief description of the programs and a list of relevant reports.

DATA-7.1 Program Overview

Information concerning waste that has been emplaced in the repository is tracked and recorded using the WIPP Waste Information System (WWIS). Information concerning future wastes is developed through periodic updates of the Transuranic Waste Baseline Inventory Report (the CCA, Appendix BIR). The inventory for the CRA-2009 PA is the same inventory that was used for the CRA-2004 Performance Assessment Baseline Calculation (PABC). This approach is consistent with the fact that the CRA-2009 PA is based on the CRA-2004 PABC. Since the CRA-2004 PABC was completed, the *Annual Transuranic Waste Inventory Report–2007* (U.S. Department of Energy 2008) was published and provides updated inventory information. The DOE anticipates that these inventory updates will have only a small impact on normalized releases relative to the CRA-2009 PA, and therefore have no significant impact on compliance.

DATA-7.2 Reported Data

Summary information on emplaced waste and radionuclides generated through the WWIS are provided in the following reports. See page 25 of the Annual Change Report 2006/2007, DOE/WIPP-07-3317 for a detailed listing of the emplaced waste in the repository.

- U.S. Department of Energy, Letter to EPA dated November 13, 2003, 2003 Annual Change Report.

- U.S. Department of Energy, Annual Change Report 2003/2004, DOE/WIPP 04-3317, November 10, 2004.

- U.S. Department of Energy, Annual Change Report 2004/2005, DOE/WIPP 05-3317, November 10, 2005.

- U.S. Department of Energy, Annual Change Report 2005/2006, DOE/WIPP 06-3317, October 2006.

- U.S. Department of Energy, Annual Change Report 2006/2007, DOE/WIPP 07-3317, November 16, 2007.

Information regarding future inventories planned for emplacement in the WIPP are provided in U.S. Department of Energy, Annual Transuranic Waste Inventory Report–2007, DOE/TRU-2008-3379, Revision 1 (U.S. Department of Energy 2008).

DATA-8.0 WIPP Boreholes

Information regarding WIPP monitoring wells is identified in this section and relevant data are provided.

DATA-8.1 Program Overview

Information provided in this section was reported in DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant Borehole Data Report (the CCA, Appendix BH). The CCA, Appendix BH serves as a central document providing data on boreholes. The report contains a comprehensive database of wells drilled in support of the WIPP and boreholes that were located within the 16-section land withdrawal area.

DATA-8.2 Reported Data

Attachment A to this appendix provides updates on all of the monitoring wells used in the CCA, Appendix BH and the new monitoring wells drilled since the initial certification. The attachment also adds wells that were in use, but inadvertently omitted from the CCA, Appendix BH. There were 21 wells drilled and 19 old wells plugged during the CRA monitoring period from October 1, 2002, through September 30, 2007.

DATA-9.0 Repository Investigations Program

The WIPP Repository Investigations Program conducts research activities to confirm assumptions, reduce uncertainty, and resolve issues regarding the conceptual models and parameters used in PA. The program is briefly described in this section and references to relevant reports are provided.

DATA-9.1 Program Overview

The DOE has implemented and/or continued several experimental activities designed to address specific issues and needs of the WIPP repository. In addition, other investigations have been initiated to examine impacts of planned changes. The general areas covered under these investigations include

- Geochemistry
- Actinide chemistry
- Engineered barriers
- Rock mechanics

DATA-9.2 Reported Data

Data acquired by the DOE from the repository investigations are available in the following reports published since the CRA-2004:

- Borkowski, M., D.T. Reed, J.F. Lucchini, M.K. Richmann. "Solubility of Neodymium in Simulated WIPP (Waste Isolation Pilot Plant) Brines." Poster, 24th Rare Earth Research Conference, June 26-30, 2005, Keystone, CO –LAUR-05-3916.

- Borkowski, M., J.F. Lucchini, M.K. Richmann, and D.T. Reed, "Neodymium Analog Study of An(III) Solubility in WIPP Brine," poster presented at Plutonium Futures 2006 Conference, July 2006, Monterey, CA. LA-UR 06-2900.

- Borkowski, M., J.F. Lucchini, M.K. Richmann, and D.T. Reed. "Actinide Chemistry and Repository Science Program in support of the Waste Isolation Pilot Plant (WIPP)." Oral Communication presented at the American Nuclear Society's 14th Biennial Topical Meeting of the Radiation Protection and Shielding Division, April 3–6, 2006, Carlsbad, NM, USA–LAUR-05-9615.

- Borkowski, M., J.F. Lucchini, M.K. Richmann, S. Ballard, and D.T. Reed, "Effect of carbonate and borate complexation on Nd^{3+} and UO_2^{2+} solubility in WIPP brine," presented at the National American Chemical Society Meeting, Chicago, IL, March 2007. LAUR-06-8317.

- Borkowski, M., J.F. Lucchini, M.K. Richmann, and D.T Reed. 2008. Actinide (III) Solubility in WIPP Brine: Data Summary and Recommendations. LCO-ACP-08, LANL\ACRSP Report. Los Alamos, NM: Los Alamos National Laboratory.

- Borkowski, M., D.T. Reed, and M.K. Richmann, "Plutonium Speciation in a Salt-Based Repository," presented at American Nuclear Society Annual Meeting "Nuclear Science and Technology: Now Arriving on Main Street," Anaheim, CA, June 8–12, 2008. LA-UR 08-03605.

- Brush, L.H. 2004b. "Review of the Calculations of the Quantity of MgO That Could Be Lost from the WIPP By Dissolution in Brine: Mg Solubility in Castile Brine." Analysis report, September 1, 2004. Carlsbad, NM: Sandia National Laboratories. ERMS 536580.

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- Brush, L.H., and J.W. Garner. 2005. "Additional Justification of the Insignificant Effect of Np on the Long-Term Performance of the WIPP." Memorandum to D.S. Kessel, February 1, 2005. Carlsbad, NM: Sandia National Laboratories. ERMS 538533.

- Brush L.H. 2005. "Results of Calculations of Actinide Solubilities for the WIPP Performance-Assessment Baseline Calculations," Carlsbad, NM: Sandia National Laboratories Carlsbad Programs Group. May 18, 2005. ERMS 539800.

- Brush, L.H. and Y. Xiong. 2003. "Calculation of Actinide Solubilities for the WIPP Compliance Recertification Application." Unpublished analysis report. May 8, 2003. Carlsbad, NM: Sandia National Laboratories. ERMS 529131.

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- Brush, L.H., and Y.-L. Xiong, 2005. "Calculation of Organic-Ligand Concentrations for the WIPP Performance-Assessment Baseline Calculations." Analysis report. May 4, 2005. Carlsbad, NM: Sandia National Laboratories. ERMS 539635.

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- Brush, L.H., and G.T. Roselle. 2006. "Geochemical Information for Calculation of the MgO Effective Excess Factor." Memorandum to E.D. Vugrin, November 17, 2006. Carlsbad, NM: Sandia National Laboratories. ERMS 544840.

- Brush, L.H., and Y.-L. Xiong. 2004. "Sensitivities of the Solubilities of +III, +IV, and +V Actinides to the Concentrations of Organic Ligands in WIPP Brines, Rev. 0." Analysis report, December 15, 2004. Carlsbad, NM: Sandia National Laboratories. ERMS 538203.

- Brush, L.H., Y.-L. Xiong, J.W. Garner, A. Ismail, and G.T. Roselle. 2006. "Consumption of Carbon Dioxide by Precipitation of Carbonate Minerals Resulting from Dissolution of Sulfate Minerals in the Salado Formation in Response to Microbial Sulfate Reduction in the WIPP." Analysis report, November 17, 2006. Carlsbad, NM: Sandia National Laboratories. ERMS 544785.

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- Clayton, D.J. 2006. "Update of the Minimum Brine Volume for a Direct Brine Release and New Maximum Castile and Salado Brine Volumes in a Waste Panel." Memorandum to L.H. Brush, October 11, 2006. Carlsbad, NM: Sandia National Laboratories. ERMS 544453.

- Clayton, D.J., and M.B. Nemer. 2006. "Normalized Moles of Castile Sulfate Entering the Repository and Fraction of MgO Lost Due to Brine Flow Out of the Repository." Memorandum to E.D. Vugrin, October 9, 2006. Carlsbad, NM: Sandia National Laboratories. ERMS 544385.

- Clayton, D., "Justification of Relative Permeability and Capillary Pressure Model Parameters for Use by BRAGFLO Version 6.0," 2007. Carlsbad NM: Sandia National Laboratories. ERMS 545764.

- Clayton, D., "Corrections to Input Files for DBR PABC Calculations," 2007. Carlsbad NM: Sandia National Laboratories. ERMS 546311.

- Crawford, B.A., and C.D. Leigh. 2003. "Estimate of Complexing Agents in TRU Waste for the Compliance Recertification Application." Analysis report, August 28, 2003. Carlsbad, NM: Los Alamos National Laboratory. ERMS 531107.

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- Deng, H., M.B. Nemer, and Y. Xiong. 2007. "Experimental Study of MgO Reaction Pathways and Kinetics, Rev. 1." TP 06-03, Rev. 1, January 10, 2007. Carlsbad, NM: Sandia National Laboratories. ERMS 545182.

- Deng, H., Y. Xiong, and M.B. Nemer. 2007. "Experimental Work Conducted on MgO Characterization and Hydration." Milestone report, August 7, 2007. Carlsbad, NM: Sandia National Laboratories. ERMS 546570.

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- Kanney, J.F., and W. Zelinski. 2004. "Input for CaCO3 precipitation Modeling." Memorandum to Y.-L. Xiong, September, 9, 2004. Carlsbad, NM: Sandia National Laboratories. ERMS 536665.

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- Reed, D.T., invited presentation, "WIPP Actinide Chemistry Research Project," New Mexico State University, chemistry department seminar, April 26, 2007.

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- Reed, D.T., D. Moody, and R. Patterson. "Waste Isolation Pilot Plant (WIPP) Transuranic Repository," Invited talk at Migration 2007, Munich, Germany, September 2007.

- Reed, D.T., H. Boukhalfa, G.A. Icopini, S.D. Reilly, and M. Neu, "Plutonium Reduction By Metal-Reducing Bacteria," presented at Migration 2007, Munich, Germany, September 2007.

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DATA-10.0 Compliance Monitoring Program

Annually, the Compliance Monitoring Program (CMP) extracts data from the repository investigations and five of the monitoring programs described above (DBDSP, SMP, GMP, GWMP, and WWIS) to derive values for the 10 COMPs described in Section DATA-1.0 and to evaluate whether significant changes in the parameters have occurred. The CMP activities are briefly described in this section. Data generated under the CMP are also identified.

DATA-10.1 Program Overview

The objective of the CMP is to provide assurance that any deviations from the expected long-term performance of the repository are identified at the earliest possible time. The CMP is implemented in accordance with DOE/WIPP-99-3119, 40 CFR Parts 191 and 194, Compliance Monitoring Implementation Plan. Annual evaluations of the compliance parameters follow the requirements found in Sandia Analysis Plan AP-069, An Analysis Plan for Annually Deriving Compliance Monitoring Parameters and their Assessment Against Performance Expectations to Meet the Requirements of 40 CFR § 194.42 (U.S. Environmental Protection Agency 1996).

DATA-10.2 Reported Data

The data and the results of the annual COMPs assessments performed in accordance with the requirements of the CMP are provided in the reports cited below. There are no COMPs data or results that indicate a reportable event or condition adverse to predicted performance.

- Sandia National Laboratories, "Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment for 2003, WBS 1.3.1, Revision 1, June 2004," Carlsbad, NM.

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- Sandia National Laboratories, "Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment for 2006, WBS 1.3.1, October 2006," Carlsbad, NM.

- Sandia National Laboratories, "Sandia National Laboratories Annual Compliance Monitoring Parameter Assessment for 2007, WBS 1.3.1, January 2008," Carlsbad, NM.

DATA-11.0 Hydrological Investigation

The Exhaust Shaft Hydraulic Assessment, now the Shallow Subsurface Investigation, was initiated in September 1996 to investigate the source and extent of water seepage into the exhaust shaft at the WIPP, and an investigation of rising water levels in the Culebra was initiated in 1999. These hydrologic investigations are briefly described in this section. Sources of data generated from the investigations are also identified.

DATA-11.1 Program Overview

DATA-11.1.1 Shallow Subsurface Investigation

Investigations of water entering the exhaust shaft led to the observation of a shallow perched groundwater horizon in a saturated layer within the lower Santa Rosa Formation and the upper Dewey Lake Redbeds Formation, about 15 m (49 ft) below ground surface. During the original drilling and geological mapping of the shaft, no water was encountered at that horizon, indicating that the presence of water may be related to site activities subsequent to shaft drilling. Three wells and 12 piezometers were installed over an 80-acre area between September 1996 and July 1997 (INTERA 1997). In 2007, three more piezometers were installed. Water level and water quality parameters have been monitored and reported on a regular basis since installation.

DATA-11.1.2 Culebra Water-Level Rise Investigation

During the 1999 annual COMPs assessment, Culebra water levels in many of the WIPP monitoring wells exceeded the CCA ranges of uncertainty established for equilibrium freshwater heads to calibrate transmissivity fields needed for Culebra flow and transport calculations. Culebra water-level rises had also been observed at the time of the CCA submittal in 1996, but were attributed to natural recovery of water levels following years of hydraulic well testing at the WIPP site and grouting of the WIPP shafts. Subsequent to the 1999 COMPs assessment, Culebra water levels showed a continued rise even though water levels at the WIPP site were thought to have fully recovered from hydraulic testing and shaft grouting. In response to this observation, the DOE initiated an investigation into the cause of the water-level rise and the impact of the rise on the long-term performance of the WIPP, which is discussed in Appendix HYDRO-2009.

DATA-11.2 Reported Data

Data acquired from the two hydrologic investigations are provided in the reports cited below for the Shallow Subsurface Investigation and the Culebra water-level rise investigation.

DATA-11.2.1 Shallow Subsurface Investigation

The Geotechnical Analysis Reports listed in Section DATA-4.2 provide data relevant to the Shallow Subsurface Investigation. In addition, the following two reports contain detailed information on this subject:

- U.S. Department of Energy, Basic Data Report for Piezometers PZ-13, PZ-14, and PZ-15 and Shallow Subsurface Water, Revision 1, DOE-WIPP 08-3375, April 2008.

- Daniel B. Stephens & Associates, Inc. 2003. Water Budget Analysis of the Shallow Subsurface Water at the Waste Isolation Pilot Plant, Carlsbad, NM.

DATA-11.2.2 Culebra Water-Level Rise Investigation

The following reports are related to Culebra water-level investigations:

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- Beauheim, R.L. 2003. Analysis Report for AP-100 Task 1: Development and Application of Acceptance Criteria for Culebra Transmissivity (T) Fields. ERMS 531136. Carlsbad, NM: Sandia National Laboratories, WIPP Records Center.

- Beauheim, R.L. 2003. Analysis Plan for Evaluation of Culebra Water-Level-Rise Scenarios, AP-110. ERMS 532799. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

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- Klise, K.A., and R.L. Beauheim. 2005. Task 3 of AP-114, Evaluation of Alternatives to the Southwestern No-Flow Boundary Condition. ERMS 542147. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

- Leigh, C., R. Beauheim, and J. Kanney. 2003. Analysis Plan for Calculations of Culebra Flow and Transport: Compliance Recertification Application, AP-100. ERMS 530172. Carlsbad, NM: Sandia National Laboratories, WIPP Records Center.

- Lowry, T.S., and R.L. Beauheim. 2004. Analysis Report, Task 2 of AP-110, Evaluation of Water-Level Rise in the Culebra Due to Recharge from Refining Process Water Discharged onto Potash Tailings Piles. ERMS 536239. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

- Lowry, T.S., and R.L. Beauheim. 2005. Analysis Report, Task 3 of AP-110, Evaluation of Water-Level Rise in the Culebra Due to Leakage Through Poorly Plugged and Abandoned Potash Boreholes. ERMS 540187. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

- McKenna, S.A. 2004. Analysis Report, AP-111, Culebra Water Level Monitoring Network Design. ERMS 540477. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

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DATA-12.0 Waste Containers and Emplacement

Information regarding WIPP waste emplacement containers and underground waste emplacement layouts are provided in this section. Approved containers that are inside other containers, such as pipe overpacks, will not be discussed.

DATA-12.1 Program Overview

Information provided in this section was compiled from several sources to serve as a central document describing both waste emplacement containers and waste emplacement layouts. Both contact-handled (CH) transuranic (TRU) (CH-TRU) and remote-handled (RH) transuranic (TRU) (RH-TRU) waste containers are described along with CH-TRU and RH-TRU waste emplacement layouts in a typical panel in the repository. Only containers approved for disposal in the repository will be discussed.

DATA-12.2 Reported Data

Attachment B to this appendix provides detailed information on the various waste containers and their emplacement in the underground repository.

DATA-13.0 References

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Borkowski, M., J.F. Lucchini, M.K. Richmann, and D.T. Reed. 2008. *Actinide (III) Solubility in WIPP Brine: Data Summary and Recommendations*. LCO-ACP-08. LANL\ACRSP Report. Los Alamos, NM: Los Alamos National Laboratory.

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Brush, L.H. 2004. *Review of the Calculations of the Quantity of MgO That Could Be Lost from the WIPP By Dissolution in Brine: Mg Solubility in Castile Brine*. Analysis report. September 1, 2004. ERMS 536580. Carlsbad, NM: Sandia National Laboratories.

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Brush, L.H., and Y. Xiong. 2005. *Calculation of Organic-Ligand Concentrations for the WIPP Performance-Assessment Baseline Calculations* (May 4). ERMS 539635. Carlsbad, NM: Sandia National Laboratories.Brush, L.H., H. Deng, J.W. Garner, C.D. Leigh, M.B. Nemer, E.J. Nowak, D.E. Wall, N.A. Wall, and Y.L. Xiong. 2006. "Overview of Long-Term, Near-Field WIPP Geochemistry." 14th Biennial Topical Meeting of the American Nuclear Society Radiation Protection and Shielding and Protection. April 4. ERMS 543167. SAND2006-2167C. Carlsbad, NM.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix DATA
Attachment A: WIPP Borehole Update

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix DATA
Attachment A: WIPP Borehole Update

Table of Contents

List of Tables

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Acronym List

BLM	Bureau of Land Management
CCA	Compliance Certification Application
CRA	Compliance Recertification Application
DOE	Department of Energy
WIPP	Waste Isolation Pilot Plant

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DATA-A-1.0 WIPP Boreholes

The U.S. Department of Energy (DOE) prepared DOE/WIPP 95-2092, Rev. 1, Waste Isolation Pilot Plant (WIPP) Borehole Data Report (the Compliance Certification Application [CCA], Appendix BH) to serve as a central document, providing data on boreholes used in characterizing the site. The report contains a comprehensive database on wells drilled in support of the Waste Isolation Pilot Plant (WIPP) and boreholes located within the 16-section land withdrawal area.

The CCA, Appendix BH describes seven groups of boreholes: commercially drilled boreholes, DOE wells, geologic exploration boreholes, hydrologic test boreholes, potash boreholes, subsurface exploration boreholes, and Water Quality Sampling Program boreholes. There are 179 boreholes listed in the report. At the time of the CCA, 80 of those boreholes were being used as monitoring wells. The rest of the boreholes were plugged and abandoned after being drilled for their specific purpose, i.e., potash information, hydrocarbon information, or WIPP site characterization information.

The 2004 Compliance Recertification Application (CRA-2004), Appendix DATA, Attachment G, WIPP Borehole Update, was provided to add the new monitoring wells drilled since the initial certification and wells that were in use but omitted from the CCA, Appendix BH. The CRA-2004, Appendix DATA, Attachment G provided information on 112 boreholes.

For the CRA-2009, a thorough search was performed to define the number of boreholes associated with the WIPP site characterization and monitoring. Currently, there are 215 boreholes that were either specifically drilled to support the WIPP site characterization process or obtained for monitoring purposes. This update provides the status for those boreholes.

Table DATA-A-1 provides the status of all 215 boreholes, including the name of the formation being monitored, whether the borehole is currently configured as a water or observation well, and whether it has been plugged and abandoned. A status of "N/A" means the borehole was not being used or had not yet been drilled at the time of the status report. "Observation" means the borehole was drilled for site characterization, but left unplugged for future monitoring purposes.

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
AEC-7	Culebra	Culebra	Culebra	4,734 ft.	1974
AEC-8	Bell Canyon	Bell Canyon	Plugged	4,922 ft.	1974
B-1	Observation	Observation	Observation	58 ft.	1978
B-1A	Observation	Observation	Observation	13 ft.	1978
B-2	Plugged	Plugged	Plugged	34 ft.	1978
B-3	Plugged	Plugged	Plugged	29 ft.	1978
B-4	Observation	Observation	Observation	39 ft.	1978
B-4A	Observation	Observation	Observation	14 ft.	1978
B-5	Plugged	Plugged	Plugged	32 ft.	1978

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
B-6	Plugged	Plugged	Plugged	26 ft.	1978
B-7	Plugged	Plugged	Plugged	35 ft.	1978
B-8	Plugged	Plugged	Plugged	100 ft.	1979
B-9	Plugged	Plugged	Plugged	38 ft.	1978
B-10	Plugged	Plugged	Plugged	32 ft.	1978
B-11	Plugged	Plugged	Plugged	30 ft.	1978
B-12	Plugged	Plugged	Plugged	41 ft.	1978
B-13	Observation	Observation	Observation	28 ft.	1978
B-14	Plugged	Plugged	Plugged	25 ft.	1978
B-15	Plugged	Plugged	Plugged	57 ft.	1978
B-16	Observation	Observation	Observation	31 ft.	1978
B-17	Plugged	Plugged	Plugged	26 ft.	1978
B-18	Observation	Observation	Observation	33 ft.	1978
B-19	Plugged	Plugged	Plugged	39 ft.	1978
B-20	Observation	Observation	Observation	14 ft.	1978
B-20A	Observation	Observation	Observation	34 ft.	1978
B-21	Plugged	Plugged	Plugged	40 ft.	1978
B-22	Plugged	Plugged	Plugged	28 ft.	1978
B-23	Plugged	Plugged	Plugged	41 ft.	1978
B-24	Plugged	Plugged	Plugged	29 ft.	1978
B-25	Plugged	Plugged	Plugged	902 ft.	1978
B-26	Plugged	Plugged	Plugged	28 ft.	1979
B-27	Plugged	Plugged	Plugged	26 ft.	1979
B-28	Plugged	Plugged	Plugged	27 ft.	1979
B-29	Plugged	Plugged	Plugged	29 ft.	1978
B-30	Plugged	Plugged	Plugged	28 ft.	1978
B-31	Plugged	Plugged	Plugged	31 ft.	1978
B-32	Plugged	Plugged	Plugged	100 ft.	1979
B-33	Plugged	Plugged	Plugged	31 ft.	1978
B-34	Plugged	Plugged	Plugged	100 ft.	1979
B-35	Plugged	Plugged	Plugged	32 ft.	1979
B-36	Plugged	Plugged	Plugged	28 ft.	1979
B-37	Plugged	Plugged	Plugged	28 ft.	1979
B-37A	Plugged	Plugged	Plugged	22 ft.	1979
B-38	Observation	Observation	Observation	50 ft.	1979
B-39	Plugged	Plugged	Plugged	28 ft.	1979
B-40	Plugged	Plugged	Plugged	28 ft.	1979

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
B-41	Plugged	Plugged	Plugged	100 ft.	1979
B-42	Plugged	Plugged	Plugged	100 ft.	1979
B-43	Plugged	Plugged	Plugged	100 ft.	1979
B-44	Plugged	Plugged	Plugged	100 ft.	1979
B-45	Plugged	Plugged	Plugged	100 ft.	1979
B-46	Plugged	Plugged	Plugged	100 ft.	1979
B-47	Plugged	Plugged	Plugged	18 ft.	1979
B-48	Plugged	Plugged	Plugged	16 ft.	1979
B-49	Plugged	Plugged	Plugged	19 ft.	1979
B-50	Plugged	Plugged	Plugged	24 ft.	1979
B-51	Plugged	Plugged	Plugged	15 ft.	1979
B-52	Plugged	Plugged	Plugged	30 ft.	1979
B-53	Plugged	Plugged	Plugged	30 ft.	1979
B-54	Observation	Observation	Observation	210 ft.	1979
B-301	Plugged	Plugged	Plugged	40 ft.	1979
B-302	Plugged	Plugged	Plugged	39 ft.	1979
B-303	Plugged	Plugged	Plugged	39 ft.	1979
B-304	Plugged	Plugged	Plugged	42 ft.	1979
B-305	Plugged	Plugged	Plugged	41 ft.	1979
B-306	Plugged	Plugged	Plugged	38 ft.	1979
B-307	Plugged	Plugged	Plugged	40 ft.	1979
B-308	Plugged	Plugged	Plugged	40 ft.	1979
B-309	Plugged	Plugged	Plugged	39 ft.	1979
C-2505	N/A	Santa Rosa/Dewey Lake	Santa Rosa/Dewey Lake	97 ft.	1996
C-2506	N/A	Santa Rosa/Dewey Lake	Santa Rosa/Dewey Lake	69 ft.	1996
C-2507	N/A	Santa Rosa/Dewey Lake	Santa Rosa/Dewey Lake	73 ft.	1996
C-2737	N/A	Culebra/Magenta	Culebra/Magenta	800 ft.	2001
C-2811	N/A	Santa Rosa/Dewey Lake	Santa Rosa/Dewey Lake	80 ft.	2001
CB-1	Culebra	Culebra/Bell Canyon	Bell Canyon	4,299 ft.	1974
D-268	Culebra	Rancher's Water Well	Rancher's Water Well	1,411 ft.	1984
DOE-1	Culebra	Culebra	Plugged	4,057 ft.	1982
DOE-2	Culebra	Magenta	Bell Canyon	4,325 ft.	1984
ERDA-6	Plugged	Plugged	Plugged	2,775 ft.	1975
ERDA-9	Culebra	Culebra	Culebra	2,886 ft.	1976
ERDA-10	Plugged	Plugged	Plugged	4,430 ft.	1977
ERDA-11	Plugged	Plugged	Plugged	40 ft.	1977
ES-001	N/A	Plugged	Plugged	54 ft.	1996

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
ES-002	N/A	Plugged	Plugged	19 ft.	1996
H-1	Culebra/Magenta	Plugged	Plugged	856 ft.	1976
H-2A	Culebra	Culebra	Plugged	672 ft.	1977
H-2B1	Magenta	Magenta	Magenta	661 ft.	1977
H-2B2	Culebra	Culebra	Culebra	660 ft.	1983
H-2C	Magenta	Culebra	Plugged	795 ft.	1977
H-3B1	Magenta	Magenta	Magenta	902 ft.	1976
H-3B2	Culebra	Culebra	Culebra	725 ft.	1983
H-3B3	Magenta	Culebra	Plugged	730 ft.	1983
H-3D	Dewey Lake	Dewey Lake/Forty-niner	Santa Rosa/Dewey Lake	554 ft.	1987
H-4A	N/A	Plugged	Plugged	532 ft.	1978
H-4B	Culebra	Culebra	Culebra	529 ft.	1978
H-4C	Magenta	Magenta	Magenta	661 ft.	1978
H-5A	Culebra	Culebra	Plugged	930 ft.	1978
H-5B	Culebra	Culebra	Culebra	925 ft.	1978
H-5C	Magenta	Magenta	Not in Use	1,076 ft.	1978
H-6A	Culebra	Culebra	Plugged	637 ft.	1978
H-6B	Culebra	Culebra	Culebra	640 ft.	1978
H-6C	Culebra	Culebra	Magenta	741 ft.	1978
H-7A	N/A	Plugged	Plugged	154 ft.	1979
H-7B1	Culebra	Culebra	Culebra	286 ft.	1979
H-7B2	Culebra	Culebra	Plugged	295 ft.	1983
H-7C	N/A	N/A	Rancher's Water Well	420 ft.	1979
H-8A	Magenta	Magenta	Magenta	505 ft.	1979
H-8B	N/A	Rancher's Water Well	Rancher's Water Well	624 ft.	1979
H-8C	Rustler	Rustler	Rancher's Water Well	808 ft.	1979
H-9A	Culebra	Plugged	Plugged	692 ft.	1979
H-9B	Culebra	Culebra	Not in Use	708 ft.	1979
H-9C	Culebra	Magenta	Culebra/Magenta	816 ft.	1979
H-10A	Magenta	Magenta	Magenta	1,318 ft.	1979
H-10B	Magenta	Plugged	Plugged	1,398 ft.	1979
H-10C	N/A	Culebra	Culebra	1,550 ft.	1979
H-11B1	Culebra	Culebra	Plugged	785 ft.	1983
H-11B2	Culebra	Magenta	Magenta	776 ft.	1983
H-11B3	Culebra	Plugged	Plugged	789 ft.	1983
H-11B4	N/A	Culebra	Culebra	765 ft.	1988
H-12	Culebra	Culebra	Culebra	1,001 ft.	1983

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
H-14	Culebra	Magenta	Magenta	589 ft.	1986
H-15	Culebra	Magenta	Culebra/Magenta	900 ft.	1986
H-16	Dewey Lake	N/A	Rustler	851 ft.	1987
H-17	Culebra	Culebra	Culebra	880 ft.	1987
H-18	Culebra	Magenta	Magenta	840 ft.	1987
H-19B	N/A	N/A	N/A	40 ft.	1995
H-19B0	N/A	Culebra	Culebra	779 ft.	1995
H-19B1	N/A	Plugged	Plugged	733 ft.	1995
H-19B2	N/A	Culebra	Culebra	785 ft.	1995
H-19B3	N/A	Culebra	Culebra	785 ft.	1995
H-19B4	N/A	Culebra	Culebra	782 ft.	1995
H-19B5	N/A	Culebra	Culebra	786 ft.	1995
H-19B6	N/A	Culebra	Culebra	788 ft.	1995
H-19B7	N/A	Culebra	Culebra	785 ft.	1995
IMC-461	N/A	N/A	Culebra	1,316 ft.	2004
P-1	Plugged	Plugged	Plugged	1,591 ft.	1976
P-2	Plugged	Plugged	Plugged	1,895 ft.	1976
P-3	Plugged	Plugged	Plugged	1,676 ft.	1976
P-4	Plugged	Plugged	Plugged	1,857 ft.	1976
P-5	Plugged	Plugged	Plugged	1,830 ft.	1976
P-6	Plugged	Plugged	Plugged	1,573 ft.	1976
P-7	Plugged	Plugged	Plugged	1,574 ft.	1976
P-8	Plugged	Plugged	Plugged	1,660 ft.	1976
P-9	Plugged	Plugged	Plugged	1,796 ft.	1976
P-10	Plugged	Plugged	Plugged	2,009 ft.	1976
P-11	Plugged	Plugged	Plugged	1,940 ft.	1976
P-12	Plugged	Plugged	Plugged	1,598 ft.	1976
P-13	Plugged	Plugged	Plugged	1,576 ft.	1976
P-14	Culebra	Plugged	Plugged	1,545 ft.	1976
P-15	Culebra	Plugged	Plugged	1,465 ft.	1976
P-16	Plugged	Plugged	Plugged	1,585 ft.	1976
P-17	Culebra	Culebra	Plugged	1,660 ft.	1976
P-18	Culebra	Plugged	Plugged	1,998 ft.	1976
P-19	Plugged	Plugged	Plugged	2,000 ft.	1976
P-20	Plugged	Plugged	Plugged	1,995 ft.	1976
P-21	Plugged	Plugged	Plugged	1,915 ft.	1976
PZ-1	N/A	Santa Rosa	Santa Rosa/Dewey Lake	68 ft.	1997

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
PZ-2	N/A	Santa Rosa	Santa Rosa/Dewey Lake	65 ft.	1997
PZ-3	N/A	Santa Rosa	Santa Rosa/Dewey Lake	71 ft.	1997
PZ-4	N/A	Santa Rosa	Santa Rosa/Dewey Lake	65 ft.	1997
PZ-5	N/A	Santa Rosa	Santa Rosa/Dewey Lake	72 ft.	1997
PZ-6	N/A	Santa Rosa	Santa Rosa/Dewey Lake	66 ft.	1997
PZ-7	N/A	Santa Rosa	Santa Rosa/Dewey Lake	72 ft.	1997
PZ-8	N/A	Santa Rosa	Santa Rosa/Dewey Lake	68 ft.	1997
PZ-9	N/A	Santa Rosa	Santa Rosa/Dewey Lake	82 ft.	1997
PZ-10	N/A	Santa Rosa	Santa Rosa/Dewey Lake	57 ft.	1997
PZ-11	N/A	Santa Rosa	Santa Rosa/Dewey Lake	82 ft.	1997
PZ-12	N/A	Santa Rosa	Santa Rosa/Dewey Lake	72 ft.	1997
PZ-13	N/A	N/A	Santa Rosa/Dewey Lake	77 ft.	2007
PZ-14	N/A	N/A	Santa Rosa/Dewey Lake	73 ft.	2007
PZ-15	N/A	N/A	Gatuña/Santa Rosa	56 ft.	2007
SNL-1	N/A	N/A	Culebra	644 ft.	2004
SNL-2	N/A	N/A	Culebra	614 ft.	2003
SNL-3	N/A	N/A	Culebra	970 ft.	2003
SNL-5	N/A	N/A	Culebra	687 ft.	2004
SNL-6	N/A	N/A	Culebra	1,360 ft.	2005
SNL-8	N/A	N/A	Culebra	981 ft.	2005
SNL-9	N/A	N/A	Culebra	845 ft.	2003
SNL-10	N/A	N/A	Culebra	651 ft.	2006
SNL-12	N/A	N/A	Culebra	905 ft.	2003
SNL-13	N/A	N/A	Culebra	480 ft.	2005
SNL-14	N/A	N/A	Culebra	719 ft.	2005
SNL-15	N/A	N/A	Culebra	950 ft.	2005
SNL-16	N/A	N/A	Culebra	224 ft.	2006
SNL-17A	N/A	N/A	Culebra	375 ft.	2006
SNL-17	N/A	N/A	Plugged	365 ft.	2006
SNL-18	N/A	N/A	Culebra	566 ft.	2006
SNL-19	N/A	N/A	Culebra	381 ft.	2006
WIPP-11	N/A	N/A	Culebra	3,580 ft.	1978
WIPP-12	Culebra	Culebra	Plugged	3,928 ft.	1978
WIPP-13	Culebra	Culebra	Culebra	3,856 ft.	1978
WIPP-14	Plugged	Plugged	Plugged	1,000 ft.	1981
WIPP-15	Water Well	Rancher's Water Well	Rancher's Water Well	810 ft.	1978
WIPP-16	Plugged	Plugged	Plugged	1,300 ft.	1980

Table DATA-A-1. Status of WIPP Boreholes October 2007 WIPP (Continued)

Well Name	CCA Status	CRA-04 Status	CRA-09 Status	Original Depth	Year Drilled
WIPP-18	Culebra	Magenta	Magenta	1,060 ft.	1978
WIPP-19	Culebra	Culebra	Culebra	1,038 ft.	1978
WIPP-21	Culebra	Culebra	Plugged	1,045 ft.	1978
WIPP-22	Culebra	Culebra	Plugged	1,450 ft.	1978
WIPP-25	Culebra/Magenta	Culebra/Magenta	Culebra/Magenta	650 ft.	1978
WIPP-26	Culebra	Culebra	Plugged	503 ft.	1978
WIPP-27	Culebra/Magenta	Culebra	Plugged	592 ft.	1978
WIPP-28	Rustler	Plugged	Plugged	801 ft.	1978
WIPP-29	Culebra	Culebra	Plugged	377 ft.	1978
WIPP-30	Culebra/Magenta	Culebra/Magenta	Culebra/Magenta	913 ft.	1978
WIPP-31	Plugged	Plugged	Plugged	1,982 ft.	1980
WIPP-32	Plugged	Plugged	Plugged	390 ft.	1979
WIPP-33	Plugged	Plugged	Plugged	840 ft.	1979
WIPP-34	Plugged	Plugged	Plugged	1,820 ft.	1979
WQSP-1	Culebra	Culebra	Culebra	737 ft.	1994
WQSP-2	Culebra	Culebra	Culebra	846 ft.	1994
WQSP-3	Culebra	Culebra	Culebra	879 ft.	1994
WQSP-4	Culebra	Culebra	Culebra	800 ft.	1994
WQSP-5	Culebra	Culebra	Culebra	681 ft.	1994
WQSP-6	Culebra	Culebra	Culebra	617 ft.	1994
WQSP-6A	Dewey Lake	Dewey Lake	Dewey Lake	225 ft.	1994

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DATA-A-2.0 Individual Well Reports

This section provides basic data on the new wells drilled (21) and the wells plugged (19) during the CRA-2009 monitoring period (October 2002 through September 2007).

The Bureau of Land Management (BLM) controls the drilling, operation, and abandonment of hydrocarbon wells on federal land in New Mexico. The New Mexico Oil Conservation Division controls the drilling, operation, and abandonment of hydrocarbon wells on state and patented lands in New Mexico. The New Mexico Office of the State Engineer regulates the drilling, operation, and abandonment of groundwater wells (this includes mineral exploration, monitoring, and observation wells) in the State of New Mexico. This agency has regulatory oversight of wells in the WIPP land withdrawal area. All WIPP monitoring wells have been permitted through this agency and drilled according to the regulations in place at the time of drilling. Right-of-way permits have been acquired from the BLM when monitoring wells are located on federal lands.

DATA-A-2.1 New Wells (since CRA-2004)

IMC-461
Location: T22S-R30E-22 Year Drilled: 2004 Total Depth: 1316 ft (401 m)
Status: Culebra Monitoring Well Elevation: 3281 ft (1000 m)

PZ-13
Location: T22S-R31E-21 Year Drilled: 2007 Total Depth: 77 ft (23 m)
Status: Santa Rosa/Dewey Lake Monitoring Well Elevation: 3422 ft (1043 m)

PZ-14
Location: T22S-R31E-21 Year Drilled: 2007 Total Depth: 73 ft (22 m)
Status: Santa Rosa/Dewey Lake Monitoring Well Elevation: 3420 ft (1042 m)

PZ-15
Location: T22S-R31E-21 Year Drilled: 2007 Total Depth: 56 ft (17 m)
Status: Santa Rosa Monitoring Well Elevation: 3431 ft (1046 m)

SNL-1
Location: T21S-R31E-16 Year Drilled: 2004 Total Depth: 644 ft (196 m)
Status: Culebra Monitoring Well Elevation: 3510 ft (1070 m)

SNL-2
Location: T22S-R30E-12 Year Drilled: 2003 Total Depth: 614 ft (187 m)
Status: Culebra Monitoring Well Elevation: 3321 ft (1012 m)

SNL-3
Location: T21S-R31E-34 Year Drilled: 2003 Total Depth: 970 ft (296 m)
Status: Culebra Monitoring Well Elevation: 3488 ft (1063 m)

SNL-5
Location: T22S-R31E-06 Year Drilled: 2004 Total Depth: 687 ft (209 m)
Status: Culebra Monitoring Well Elevation: 3377 ft (1029 m)

SNL-6
Location: T21S-R32E-07 Year Drilled: 2005 Total Depth: 1360 ft (414 m)
Status: Culebra Monitoring Well Elevation: 3643 ft (1110 m)

SNL-8
Location: T22S-R31E-14 Year Drilled: 2005 Total Depth: 981 ft (299 m)
Status: Culebra Monitoring Well Elevation: 3552 ft (1083 m)

SNL-9
Location: T22S-R30E-23 Year Drilled: 2003 Total Depth: 845 ft (257 m)
Status: Culebra Monitoring Well Elevation: 3358 ft (1024 m)

SNL-10
Location: T22S-R31E-30 Year Drilled: 2006 Total Depth: 651 ft (198)
Status: Culebra Monitoring Well Elevation: 3374 ft (1028 m)

SNL-12
Location: T23S-R31E-20 Year Drilled: 2003 Total Depth: 905 ft (275 m)
Status: Culebra Monitoring Well Elevation: 3337 ft (1017 m)

SNL-13
Location: T23S-R30E-01 Year Drilled: 2005 Total Depth: 480 ft (146 m)
Status: Culebra Monitoring Well Elevation: 3291 ft (1003 m)

SNL-14
Location: T23S-R31E-04 Year Drilled: 2005 Total Depth: 719 ft (219 m)
Status: Culebra Monitoring Well Elevation: 3365 ft (1026 m)

SNL-15
Location: T22S-R31E-26 Year Drilled: 2005 Total Depth: 950 ft (290 m)
Status: Culebra Monitoring Well Elevation: 3477 ft (1060 m)

SNL-16
Location: T22S-R30E-33 Year Drilled: 2006 Total Depth: 224 ft (68 m)
Status: Culebra Monitoring Well Elevation: 3132 ft (955 m)

SNL-17
Location: T22S-R30E-12 Year Drilled: 2006 Total Depth: 375 ft (114 m)
Status: Plugged Elevation: 3235 ft (986 m)

SNL-17A
Location: T22S-R30E-12 Year Drilled: 2006 Total Depth: 365 ft (111 m)
Status: Culebra Monitoring Well Elevation: 3235 ft (986 m)

SNL-18
Location: T21S-R31E-20 Year Drilled: 2006 Total Depth: 566 ft (172 m)
Status: Culebra Monitoring Well Elevation: 3372 ft (1028 m)

SNL-19
Location: T21S-R30E-35 Year Drilled: 2006 Total Depth: 381 ft (116 m)
Status: Culebra Monitoring Well Elevation: 3219 ft (981 m)

DATA-A-2.2 Plugged Wells

AEC-8
Location: T22S-R31E-11 Year Drilled: 1974 Total Depth: 4922 ft (1500 m)
Status: Plugged in 2005 Elevation: 3532 ft (1077 m)
Notes: Plugged solid with Class C neat cement.

DOE-1
Location: T22S-R31E-28 Year Drilled: 1982 Total Depth: 4057 ft (1237 m)
Status: Plugged in 2006 Elevation: 3466 ft (1056 m)
Notes: Hole was plugged with a salt-saturated cement to the top of the salt formation, and Class C neat cement from there to the surface.

H-2A
Location: T22S-R31E-29 Year Drilled: 1977 Total Depth: 672 ft (204 m)
Status: Plugged in 2005 Elevation: 3378 ft (1030 m)
Notes: During a sampling event, a pump and packer assembly was dropped into the well and jammed at the bottom of the casing. Retrieval attempts proved unsuccessful. The regulating agency approved leaving the gear in the hole. The well was cemented to the surface using Class C neat cement.

H-2C
Location: T22S-R31E-29 Year Drilled: 1977 Total Depth: 795 ft (242 m)
Status: Plugged in 2005 Elevation: 3378 ft (1030 m)
Notes: The well was cemented to the surface using Class C neat cement.

H-3B3
Location: T22S-R31E-29 Year Drilled: 1983 Total Depth: 730 ft (222 m)
Status: Plugged in 2005 Elevation: 3389 ft (1033 m)
Notes: The well was cemented to the surface using Class C neat cement.

H-5A
Location: T22S-R31E-15 Year Drilled: 1978 Total Depth: 930 ft (283 m)
Status: Plugged in 2005 Elevation: 3506 ft (1069 m)
Notes: Attempts were made to remove packer assembly. Retrieval attempts proved unsuccessful. The regulating agency approved leaving the packer in the well but driving it as far down the well bore as possible. The well was cemented to the surface using Class C neat cement.

H-6A
Location: T22S-R31E-18 Year Drilled: 1978 Total Depth: 637 ft (194 m)
Status: Plugged in 2005 Elevation: 3348 ft (1020 m)
Notes: Attempts were made to remove packer assembly. Retrieval attempts proved unsuccessful. The regulating agency approved leaving the packer in the well but driving it as far down the well bore as possible. The well was cemented to the surface using Class C neat cement.

H-7C
Location: T23S-R30E-14 Year Drilled: 1979 Total Depth: 420 ft (128 m)
Status: Water Well Elevation: 3162 ft (964 m)
Notes: The well was converted to a water well for local rancher use and removed from the WIPP monitoring well system.

H-7B2
Location: T23S-R30E-14 Year Drilled: 1983 Total Depth: 295 ft (90 m)
Status: Plugged in 2005 Elevation: 3164 ft (964 m)
Notes: Prior to plugging, circulation was lost due to split casing while the well was being cleaned out. To allow sufficient cementing, Baro-Seal® was used to assist in plugging open spaces. The well was cemented to the surface using Class C neat cement.

H-8C
Location: T24S-R30E-23 Year Drilled: 1979 Total Depth: 808 ft (246 m)
Status: Water Well Elevation: 3433 ft (1046 m)
Notes: The well was converted to a water well for local rancher utilization and removed from the WIPP monitoring well system.

H-11B1
Location: T22S-R31E-33 Year Drilled: 1983 Total Depth: 785 ft (239 m)
Status: Plugged in 2005 Elevation: 3411 ft (1040 m)
Notes: The well was cemented to the surface using Class C neat cement.

P-17
Location: T23S-R31E-04 Year Drilled: 1976 Total Depth: 1660 ft (505 m)
Status: Plugged in 2006 Elevation: 3336 ft (1017 m)
Notes: The well was cemented to the surface using Class C neat cement.

SNL-17
Location: T22S-R30E-12 Year Drilled: 2006 Total Depth: 365 ft (111 m)
Status: Plugged in 2006 Elevation: 3235 ft (986 m)
Notes: Well was plugged after being drilled due to the failure of the bottom plug.

WIPP-12
Location: T22S-R31E-17 Year Drilled: 1978 Total Depth: 3928 ft (1197 m)
Status: Plugged in 2005 Elevation: 3472 ft (1058 m)
Notes: During the deepening of this well in 1982, a pressurized brine pocket in the Castile was encountered. In 1983, the brine reservoir was sealed from the upper part of the well bore by installing a borehole plug. During plugging, extra precautions were taken to protect workers and

the environment from the possible release of brine or H_2S. None was encountered. The well was cemented to the surface using Class C neat cement.

WIPP-21
Location: T22S-R31E-20 Year Drilled: 1978 Total Depth: 1045 ft (318 m)
Status: Plugged in 2005 Elevation: 3419 ft (1042 m)
Notes: The well was cemented to the surface using Class C neat cement.

WIPP-22
Location: T22S-R31E-20 Year Drilled: 1978 Total Depth: 1450 ft (441 m)
Status: Plugged in 2005 Elevation: 3428 ft (1045 m)
Notes: The well was cemented to the surface using Class C neat cement.

WIPP-26
Location: T22S-R30E-29 Year Drilled: 1978 Total Depth: 503 ft (153 m)
Status: Plugged in 2006 Elevation: 3150 ft (960 m)
Notes: The well was cemented to the surface using Class C neat cement.

WIPP-27
Location: T21S-R30E-21 Year Drilled: 1978 Total Depth: 592 ft (180 m)
Status: Plugged in 2006 Elevation: 3179 ft (969 m)
Notes: The well was cemented to the surface using Class C neat cement.

WIPP-29
Location: T22S-R29E-34 Year Drilled: 1978 Total Depth: 377 ft (114 m)
Status: Plugged in 2005 Elevation: 2978 ft (908 m)
Notes: The well was cemented to the surface using Class C neat cement.

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Appendix DATA
Attachment B: WIPP Waste Containers and Emplacement

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix DATA
Attachment B: WIPP Waste Containers and Emplacement

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Acronym List

CH-TRU	contact-handled transuranic
EPA	U.S. Environmental Protection Agency
gal	gallon
RH-TRU	remote-handled transuranic
SWB	Standard Waste Box
TDOP	10-Drum Overpack
TRU	transuranic

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DATA-B-1.0 Authorized Waste Emplacement Containers

DATA-B-1.1 Container Descriptions

The Compliance Certification Application to the U.S. Environmental Protection Agency (EPA) identified the following containers as outer containment vessels for waste emplacement in the repository:

- 55-gallon (gal) Drum
- 85-gal Drum (Short)
- 85-gal Drum (Tall)
- 100-gal Drum
- Standard Waste Box (SWB)
- Ten-Drum Overpack (TDOP)
- Remote-handled (RH) transuranic (TRU) (RH-TRU) 72B Cask Removable Lid Canister (RH-TRU Waste Canister)

DATA-B-1.2 Dunnage Containers

Dunnage containers are empty containers used to complete a shipping configuration, such as the seven-pack, if too few containers that meet transportation requirements are available. Dunnage containers are clearly marked "Empty." The TDOP and the RH-TRU Waste Canister are not used as dunnage containers for shipping purposes. For emplacement purposes in the repository, the 55-, 85-, and 100-gal drums can be used as dunnage containers only if they arrive in a shrink-wrapped package assembly, such as the seven-pack, four-pack, or three-pack. To date, only 55-gal drums and several SWBs have been emplaced in the repository as dunnage containers.

DATA-B-1.3 Payload Descriptions

This section gives a brief description of each payload container and its configuration for emplacement. This description also includes a figure and a table for each container.

The 55-gal drum is shipped in a seven-pack configuration and is normally emplaced in the repository in the same configuration, but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste. An illustration of the 55-gal drum components and emplacement configuration is provided in Figure DATA-B-1. The drum specifications are provided in Table DATA-B-1.

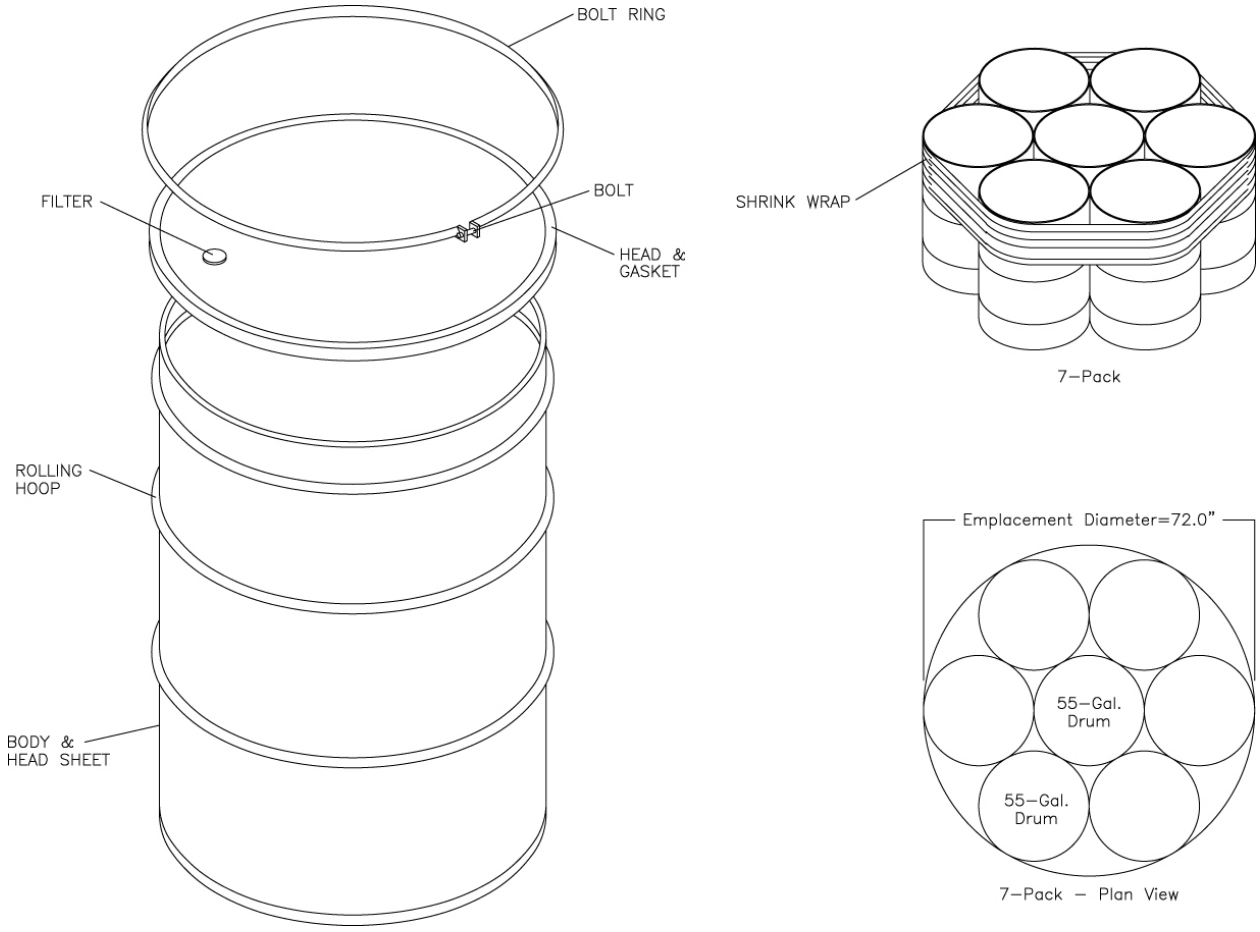

Figure DATA-B-1. 55-gal Drum Components and Emplacement Configuration

Table DATA-B-1. 55-gal Drum Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	33 ¼	35	845	889
Diameter	22 ½	24	572	610
—	—	—	—	—
—	—	—	—	—

The 85-gal drum (short) is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration, but can be emplaced as an individual unit should the need arise. A single drum can be used for collecting and storing site-derived waste or for overpacking a 55-gal drum. An illustration of the 85-gal drum (short) components and emplacement configuration is provided in Figure DATA-B-2. The drum specifications are provided in Table DATA-B-2.

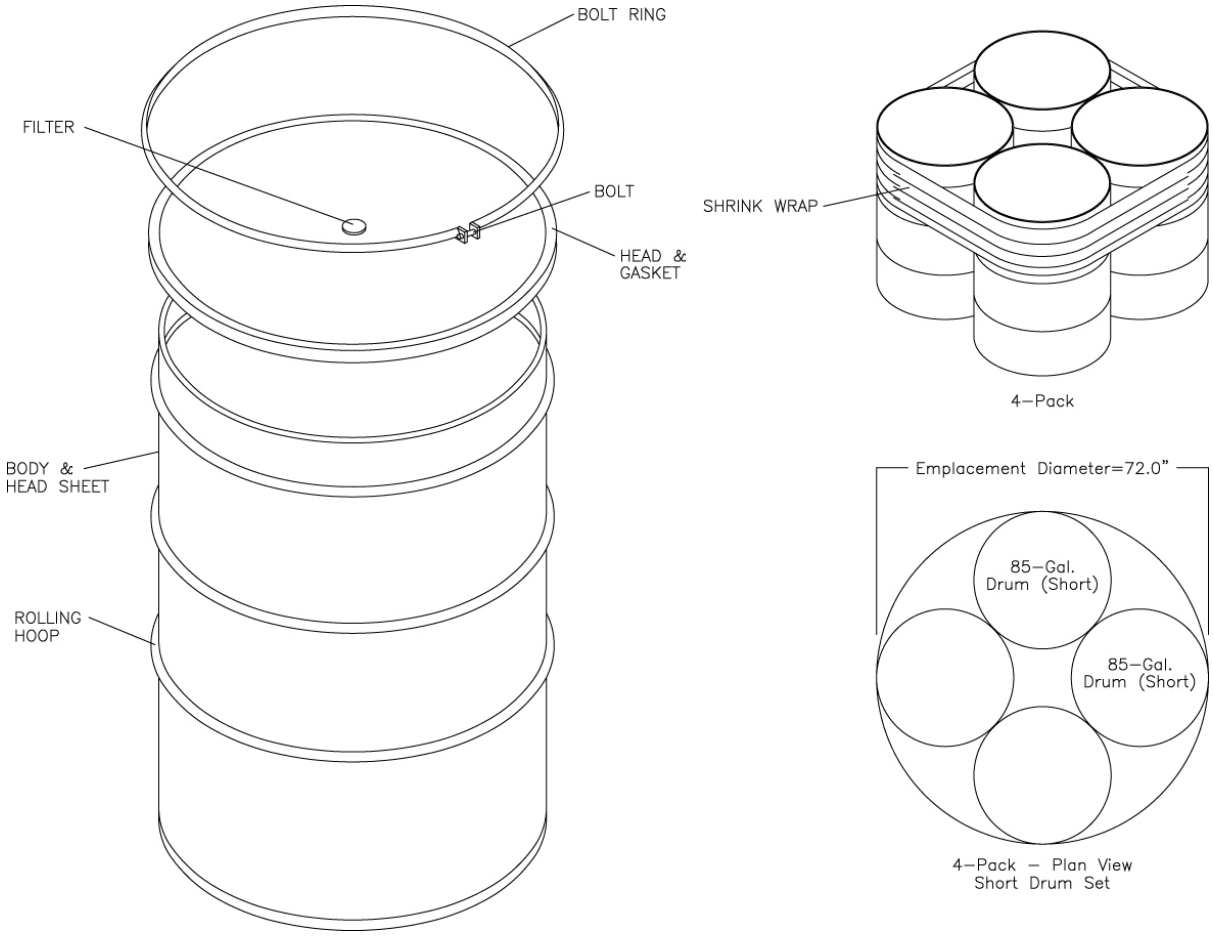

Figure DATA-B-2. 85-gal Drum (Short) Components and Emplacement Configuration

Table DATA-B-2. 85-gal Drum (Short) Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	O.D. (mm)
Height	33 ¼	35	845	889
Diameter	27 ⅛	29 ¾	689	756
—	—	—	—	—
—	—	—	—	—

The 85-gal drum (tall) is shipped in a four-pack configuration and will be emplaced in the repository in the same configuration. It is also used for overpacking 55-gal drums that are individually emplaced in the repository. A single drum can be used for collecting and storing site-derived waste. An illustration of the 85-gal drum (tall) components and emplacement configuration is provided in Figure DATA-B-3. The drum specifications are provided in Table DATA-B-3.

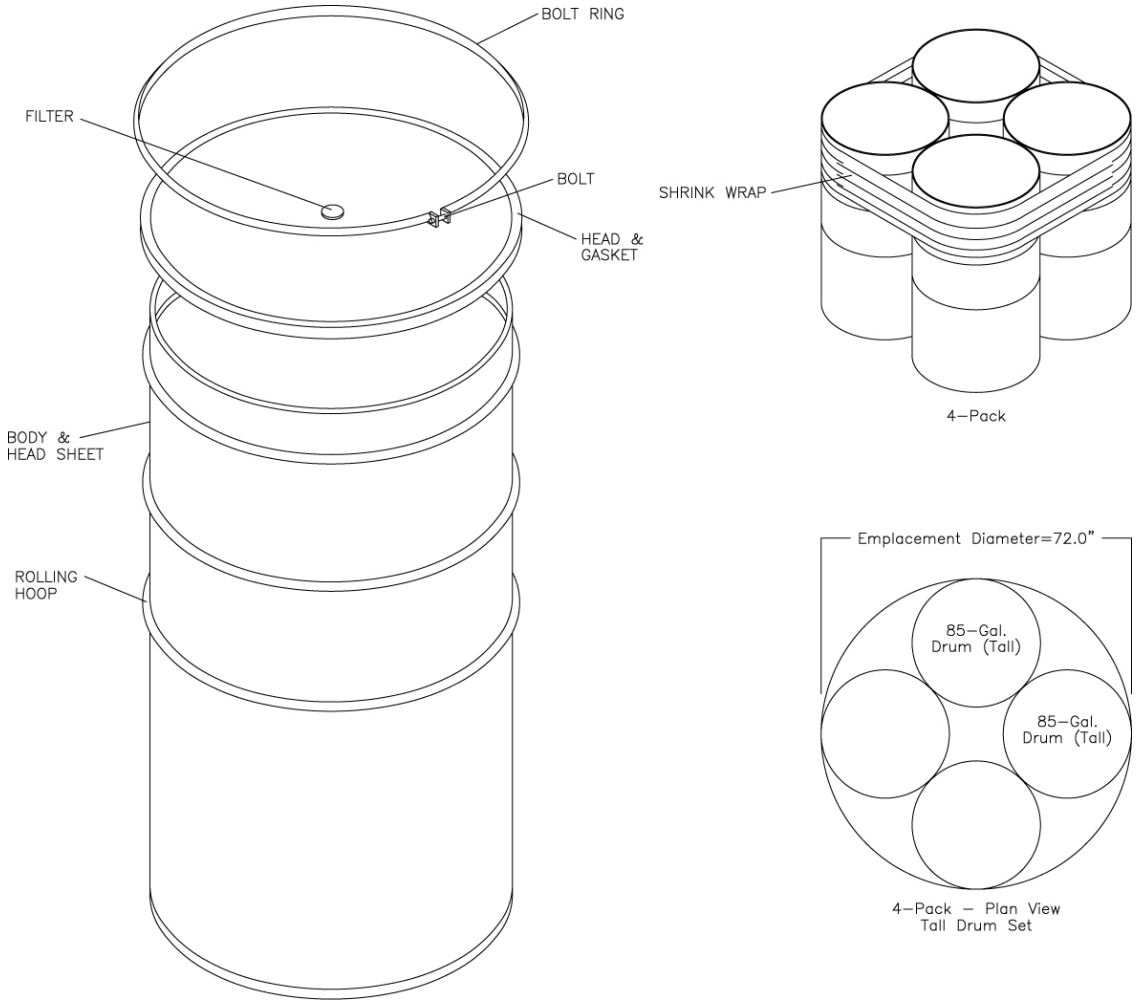

Figure DATA-B-3. 85-gal Drum (Tall) Components and Emplacement Configuration

Table DATA-B-3. 85-gal Drum (Tall) Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	38 ¼	40 ¼	972	1,022
Diameter	26	28 ⅝	660	728
—	—	—	—	—
—	—	—	—	—

The 100-gal drum is shipped in a three-pack configuration and will be emplaced in the repository in the same configuration. The 100-gal drum can be emplaced as an individual unit should the need arise. An illustration of the 100-gal drum components and emplacement configuration is provided in Figure DATA-B-4. The drum specifications are provided in Table DATA-B-4.

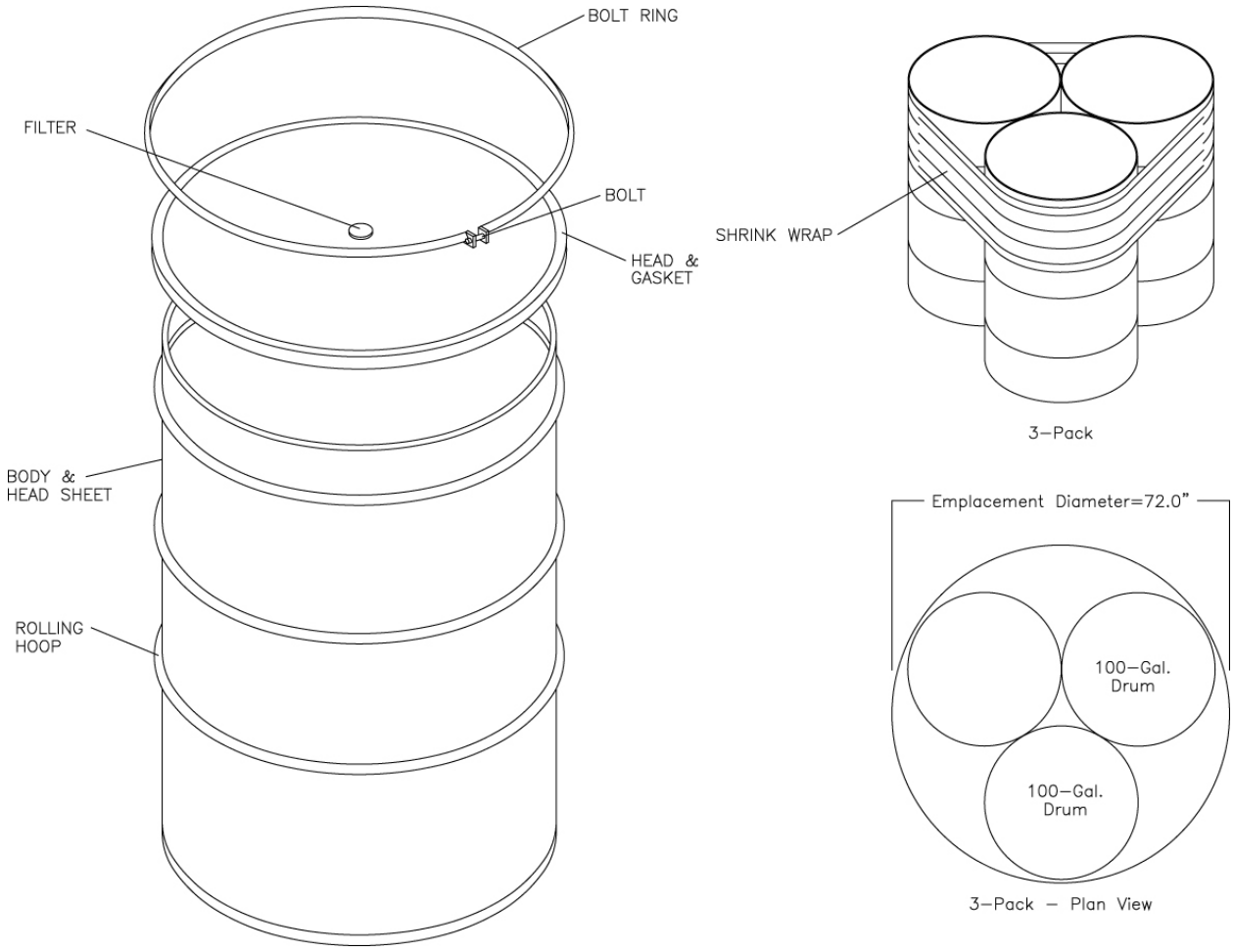

Figure DATA-B-4. 100-gal Drum Components and Emplacement Configuration

Table DATA-B-4. 100-gal Drum Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	33	35	838	889
Diameter	30	32	762	813
—	—	—	—	—
—	—	—	—	—

The SWB is shipped and emplaced as an individual unit. Typically, two SWBs are shipped in a TRUPACT-II shipping container. An illustration of the SWB is provided in Figure DATA-B-5. The box specifications are provided in Table DATA-B-5.

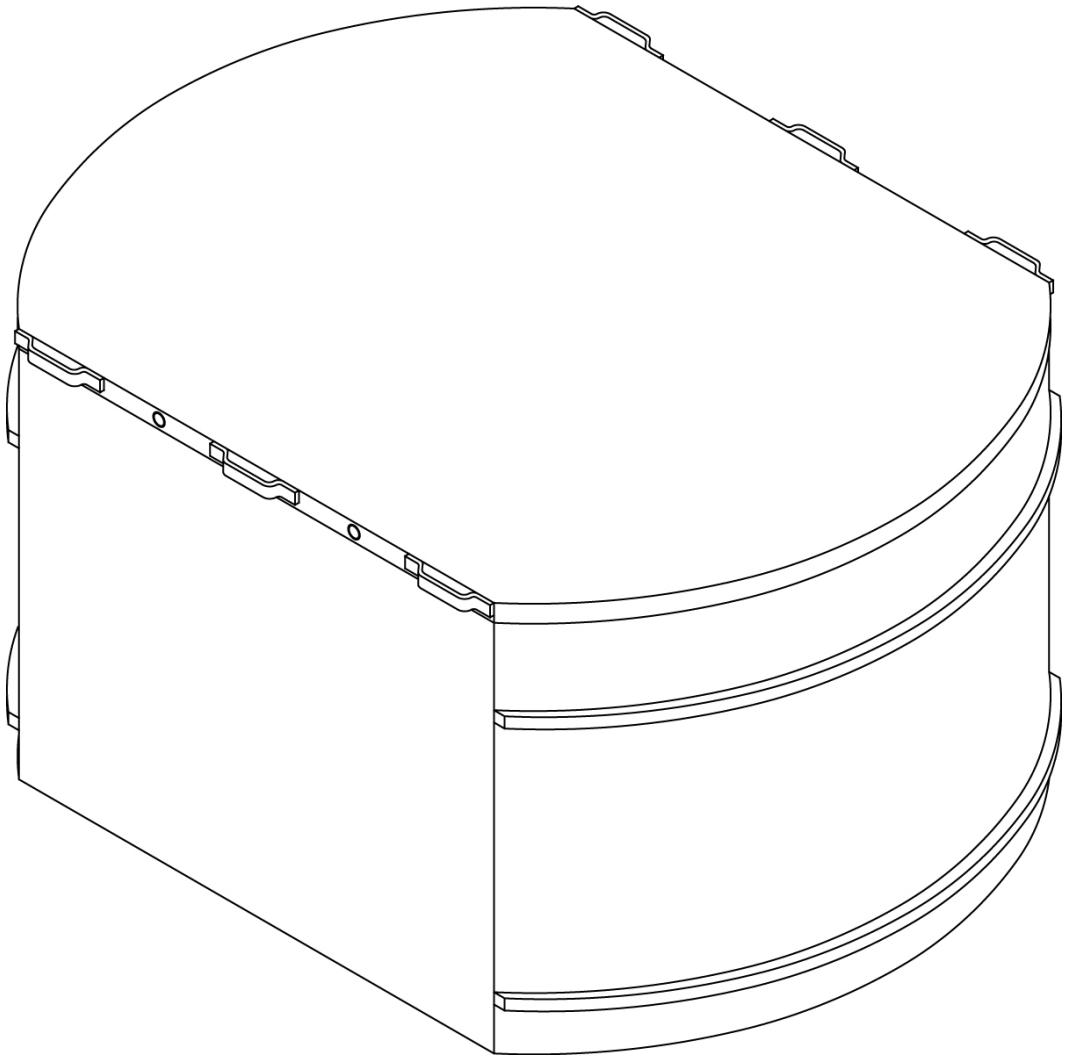

Figure DATA-B-5. Illustration of an SWB

Table DATA-B-5. SWB Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	36 9/16	36 7/8	929	937
Length	68 3/4	71	1,746	1,803
Width	52	54 1/2	1,321	1,384
—	—	—	—	—

The TDOP is shipped as an individual unit and emplaced as an individual unit. An illustration of the TDOP's components is provided in Figure DATA-B-6. The TDOP specifications are provided in Table DATA-B-6.

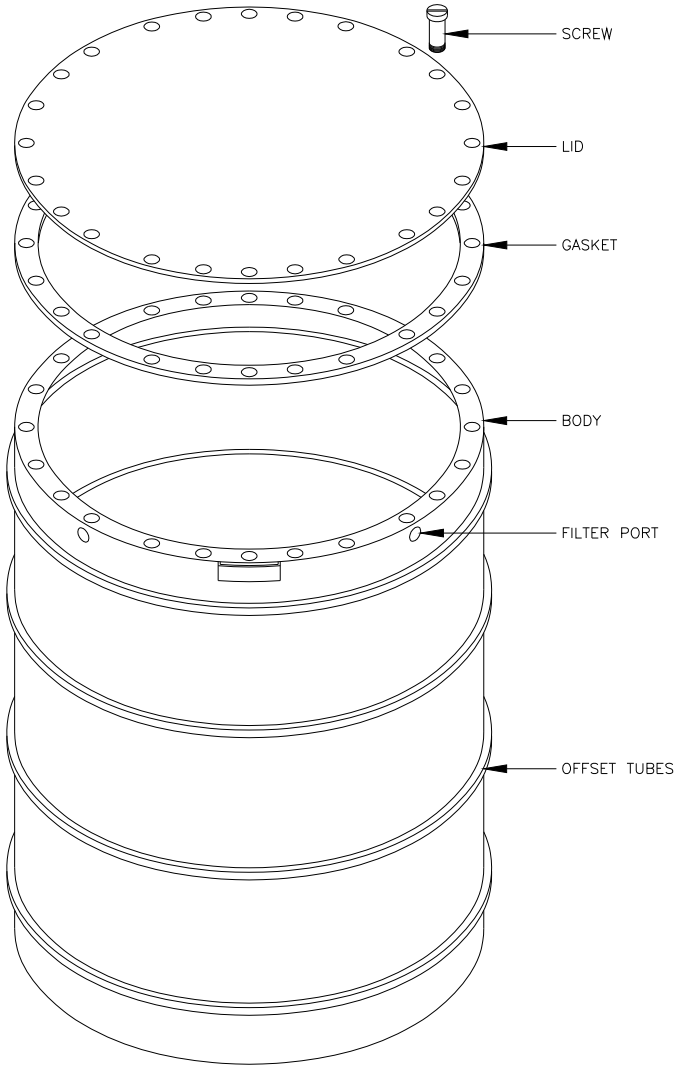

Figure DATA-B-6. TDOP Components

Table DATA-B-6. TDOP Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	72 ⅝	73 ⅛	1845	1,858
Diameter	68 ¾	71 ¼	1,746	1,810
—	—	—	—	—
—	—	—	—	—

The RH-TRU Waste Canister is shipped as a single unit and emplaced as a single unit. Illustrations of the canister's components are provided in Figure DATA-B-7. The canister specifications are provided in Table DATA-B-7.

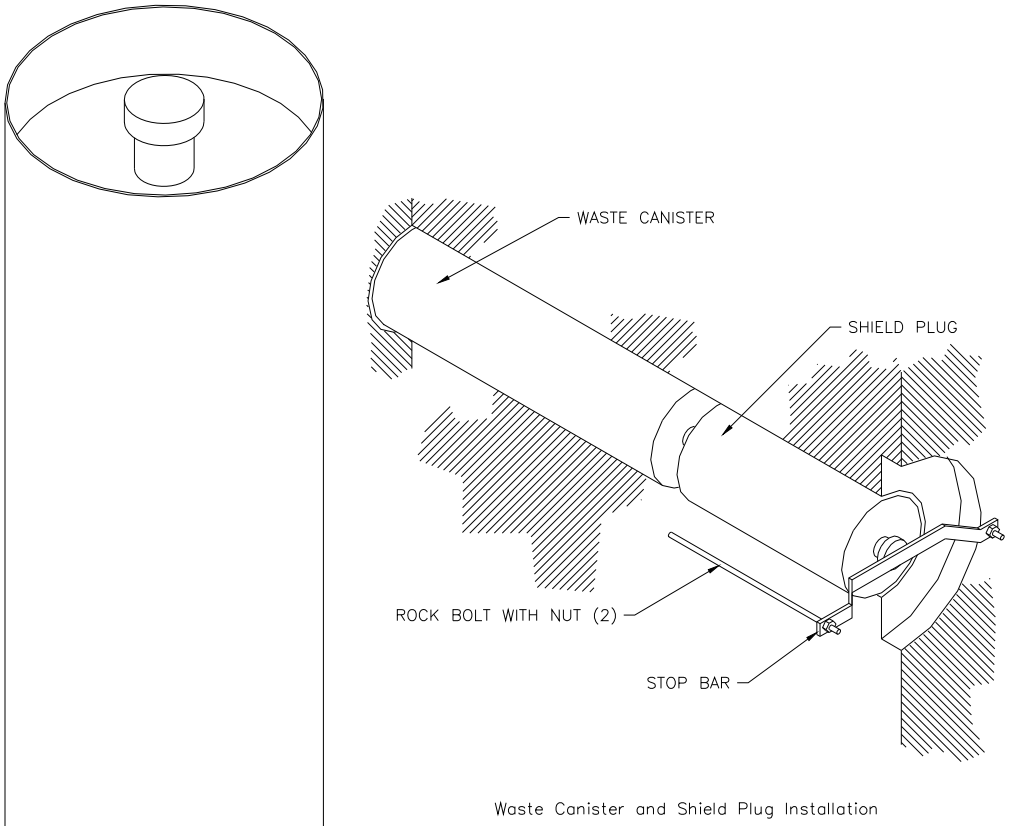

Figure DATA-B-7. RH-TRU Waste Canister Components

Table DATA-B-7. RH-TRU Waste Canister Specifications

Dimension	Approximate Measurement			
	Inside Dimension (inches)	Outside Dimension (inches)	Inside Dimension (mm)	Outside Dimension (mm)
Height	108	120 ½	2,743	3,061
Diameter	25 ½	26	648	660
—	—	—	—	—
—	—	—	—	—

DATA-B-1.4 Emplacement Configurations

Shown in Figure DATA-B-8 is the typical position for waste emplacement containers randomly emplaced in the room of a panel. TDOPs are only emplaced on the bottom position with another assembly stacked on top. All of the other assemblies can be stacked three high before the MgO supersack is emplaced on the top of the stack. Contact-handled (CH) transuranic TRU (CH-TRU) waste emplacement within the repository panels is shown in Figure DATA-B-9. The planned RH-TRU waste emplacement is shown in Figure DATA-B-10.

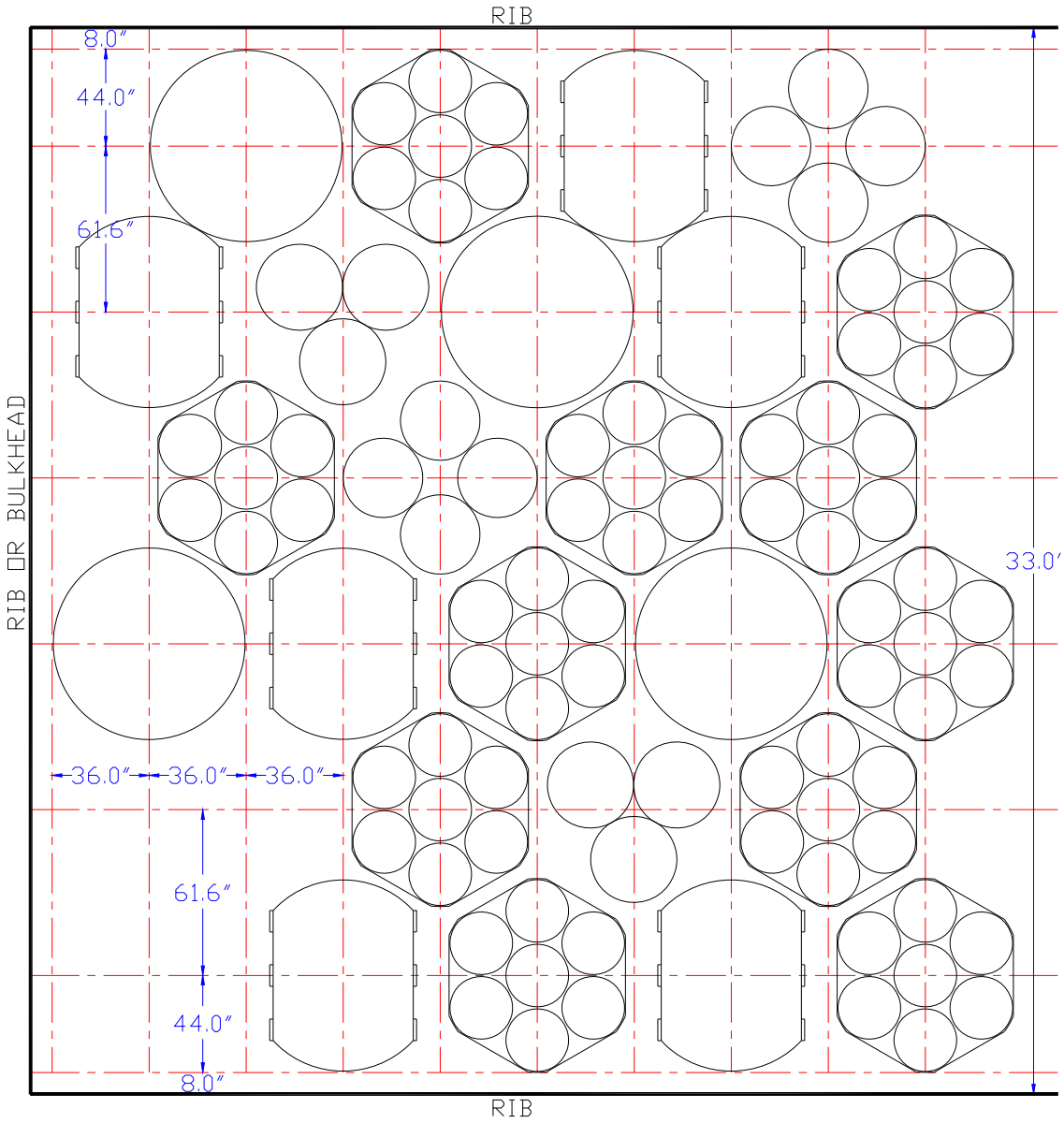

Figure DATA-B-8. CH-TRU Waste Emplacement Layout

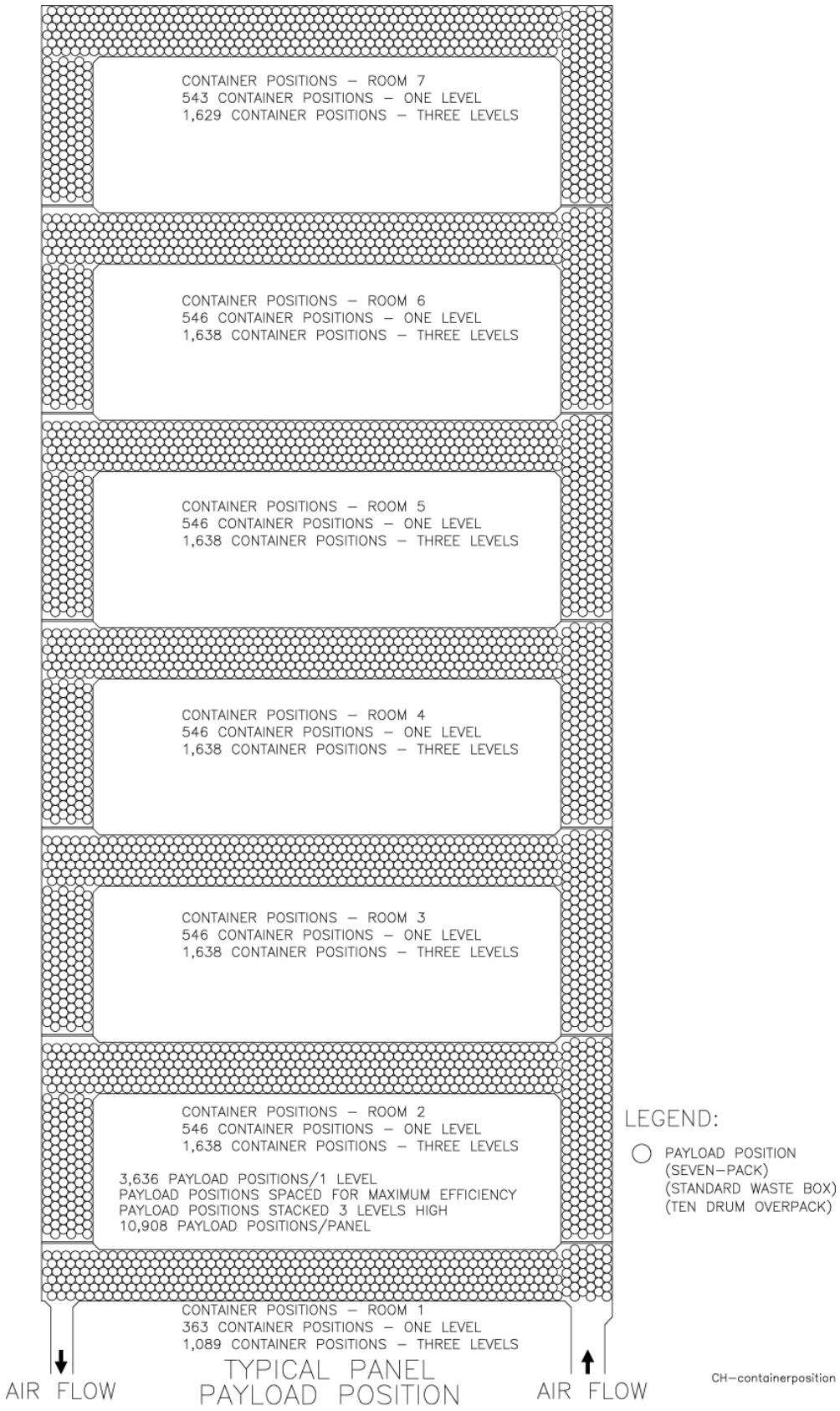

Figure DATA-B-9. CH-TRU Waste Emplacement

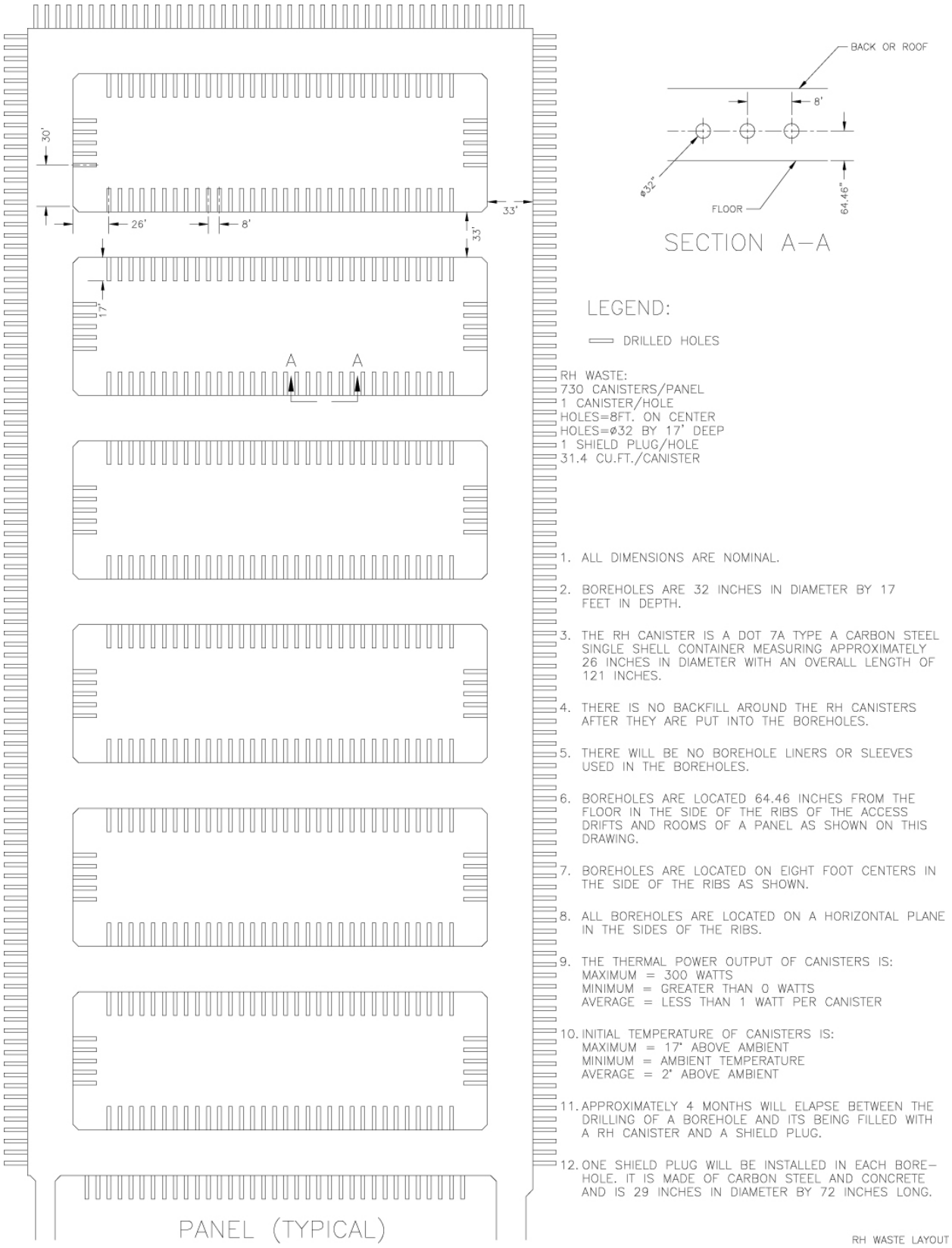

Figure DATA-B-10. RH-TRU Waste Emplacement

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Appendix HYDRO-2009
Hydrological Investigations

United States Department of Energy
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Appendix HYDRO-2009
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Acronyms and Abbreviations

µmhos/cm	micromhos per centimeter
acre-ft	acre-foot
amsl	above mean sea level
AP	analysis plan
ASER	Annual Site Environmental Report
bgs	below ground surface
BLM	U.S. Bureau of Land Management
CB	Cabin Baby
cm	centimeter
CRA	Compliance Recertification Application
D	diffusivity
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	feet
ft^2/day	square feet per day
gpm	gallons per minute
HCl	hydrochloric
high-T	high transmissivity
hr	hour
in.	inch
km	kilometer
L/s	liters per second
low-T	low transmissivity
m	meter
m^2/s	square meters per second
m^3	cubic meters
m^3/s	cubic meters per second
mg/L	milligrams per liter
mi	mile
mm	millimeter
molal	moles per kilogram

NR	no response
P&A	plugging and abandonment
PIP	production-injection packer
S	storativity
SNL	Sandia National Laboratories
S_s	specific storage
T field	transmissivity field
TD	total depth
TDS	total dissolved solids
TP	test plan
T/S	transmissivity and storativity
USGS	U.S. Geological Survey
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WTS	Washington TRU Solutions
yr	year

HYDRO-1.0 Hydrological Studies

This appendix provides a summary of the new information on Waste Isolation Pilot Plant (WIPP) hydrology collected since the September 2002 data-cutoff date for the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004a) through 2007, in accordance with the requirements of 40 CFR § 194.15 (U.S. Environmental Protection Agency 1996). Over that period, the U.S. Department of Energy (DOE) collected a significant amount of new information on WIPP hydrogeology, both in response to various requests from the U.S. Environmental Protection Agency (EPA) and as a result of ongoing monitoring programs. The EPA's November 15, 2002, letter (Marcinowski 2002) requested that the DOE drill new monitoring wells completed to the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra) both north and south of the WIPP site to improve the understanding of flow properties and the causes of water-level changes. The EPA's May 20, 2004 letter (Cotsworth 2004a) requested that a new well be drilled in the vicinity of the southeastern part of the WIPP site to establish whether high or low Culebra transmissivity existed in that area. The EPA's September 2, 2004 letter (Cotsworth 2004b) requested that the DOE update the groundwater basin modeling and groundwater chemistry interpretations for the units above the Salado Formation.

The new hydrogeologic studies were initially laid out in a multiyear program plan for fiscal years 03-09 (Sandia National Laboratories [SNL] 2003). The overall program evolved as activities progressed, with specific activities being added and subtracted as conditions and new information warranted and as new requests were received from the EPA. A variety of test plans (TPs) and analysis plans (APs) were also written for specific activities (Table HYDRO-1). The activities performed under these plans are described in the following sections. The reader is referred to the reports cited in each section for additional, more detailed information on the work performed.

Section HYDRO-2.0 describes a modeling study used to optimize the number and locations of wells in the Culebra monitoring network. Section HYDRO-3.0 describes new wells that have been drilled and Section HYDRO-4.0 describes wells that have been plugged and abandoned since the CRA-2004. Section HYDRO-5.0 describes the water-level monitoring performed since the CRA-2004 and the changes in water levels that have been observed. Hydraulic testing and test analyses performed since the CRA-2004 are described in Section HYDRO-6.0. Section HYDRO-7.0 describes the geologic studies that have been performed since 2003, and Section HYDRO-8.0 describes the groundwater sampling and water-quality analyses performed over the same period. Section HYDRO-9.0 describes modeling exercises aimed at understanding what might be causing the observed rise in Culebra water levels. Section HYDRO-10.0 provides an integration of all the new hydrological information collected since the CRA-2004.

For general reference, Figure HYDRO-1 provides a map showing the locations of all wells discussed below. Figure HYDRO-2 and Figure HYDRO-3 are stratigraphic columns showing the geologic units discussed below.

Table HYDRO-1. Test and Analysis Plans Guiding Hydrological Studies, 2003–2007

Plan	Title	Author	Effective Date
TP 00-03	Compliance Monitoring Program: Recompletion and Testing of Wells for Evaluation of Monitoring Data from the Magenta Member of the Rustler Formation (Fm.) at the WIPP Site, Revision 1	Chace	2/18/03
TP 03-01	Test Plan for Testing of Wells at the WIPP Site, Revision 2	Chace and Beauheim	1/18/06
TP 06-01	Monitoring Water Levels in WIPP Wells, Revision 1	Hillesheim	4/9/07
AP-070	Analysis Plan for Non-Salado Hydraulic-Test Interpretations, Revision 1	Beauheim	10/20/04
AP-110	Analysis Plan for Evaluation of Culebra Water-Level-Rise Scenarios	Beauheim	11/11/03
AP-111	Analysis Plan for Optimization and Minimization of the Culebra Monitoring Network for the WIPP	Beauheim and McKenna	11/24/03
AP-114	Analysis Plan for Evaluation and Recalibration of Culebra T-Fields	Beauheim	10/11/04
AP-125	Analysis Plan for the Evaluation of Culebra Brine Compositions	Domski and Beauheim	8/18/05

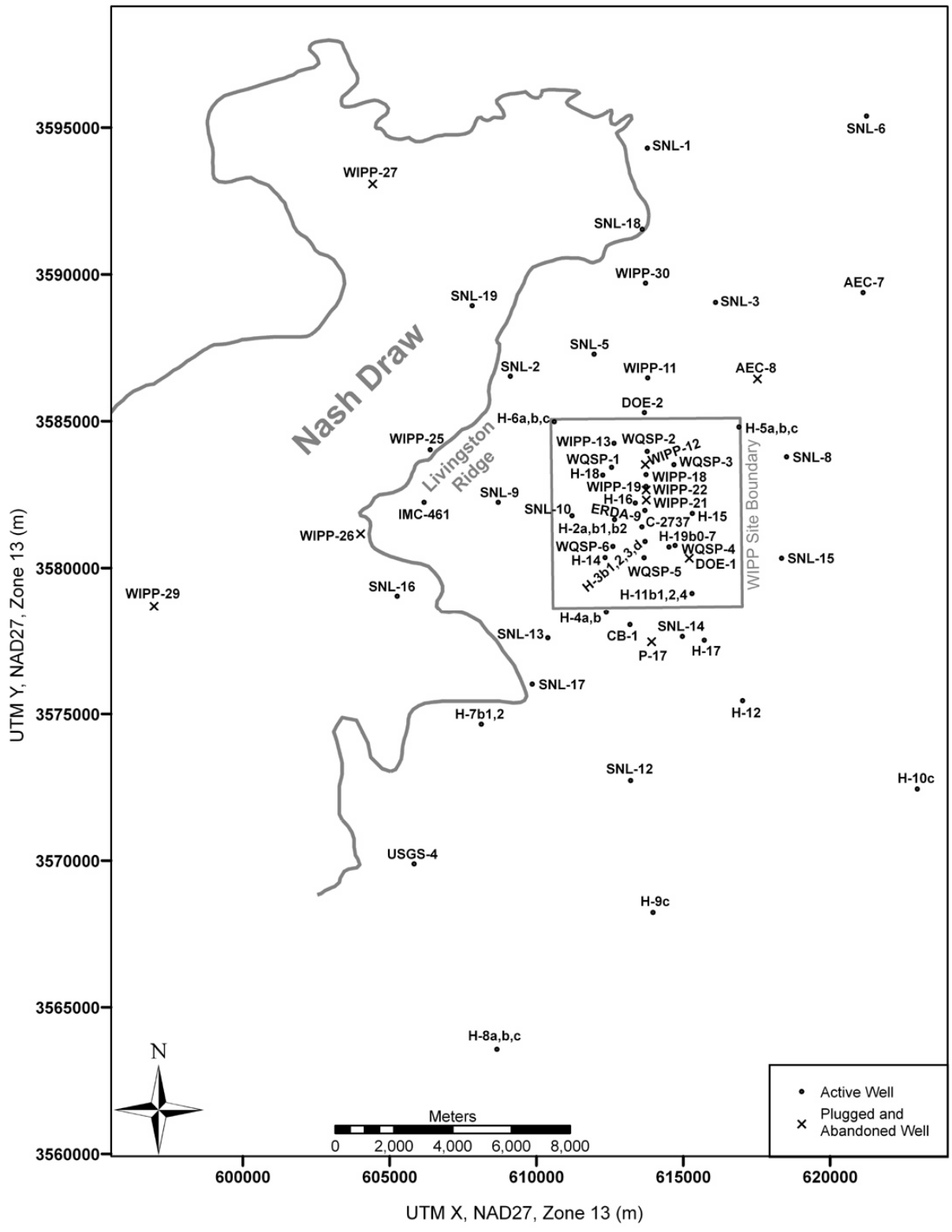

Figure HYDRO-1. Locations of WIPP Wells

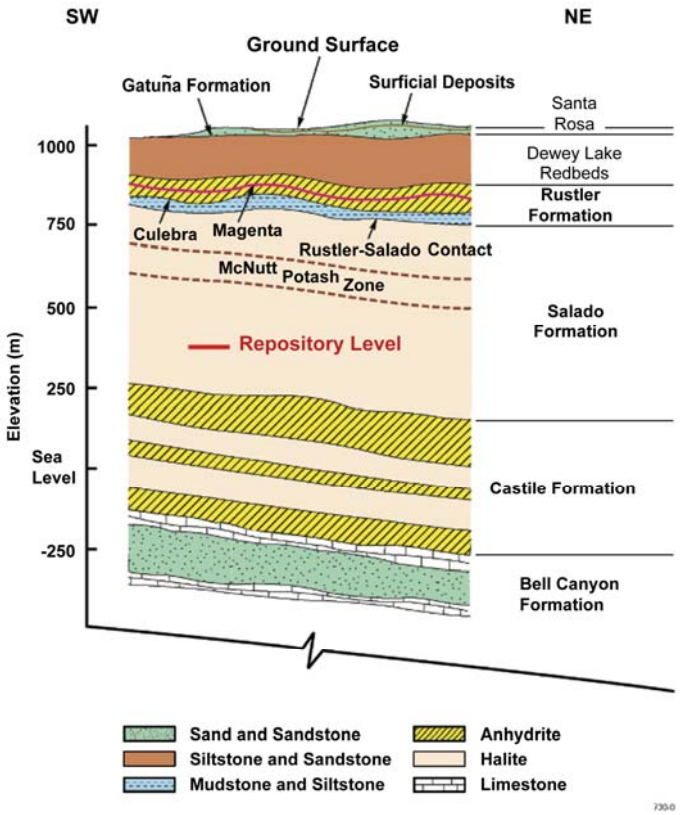

Figure HYDRO-2. General Stratigraphic Column of Geologic Units at the WIPP Site

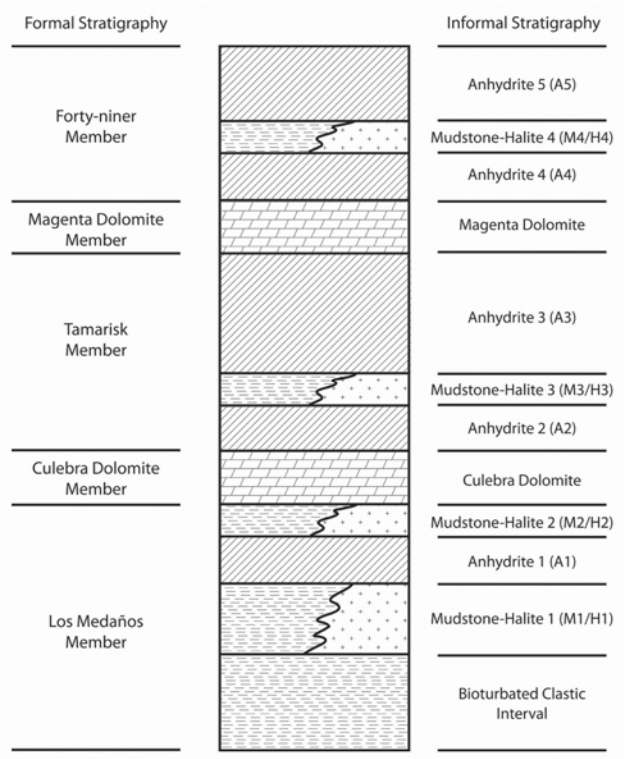

Figure HYDRO-3. Detailed Rustler Formation Stratigraphy

HYDRO-2.0 Optimization of Culebra Monitoring Well Network

McKenna (2004) performed a well-network minimization and optimization study under *AP-111, Analysis Plan for Optimization and Minimization of the Culebra Monitoring Network for the WIPP,* developed by Beauheim and McKenna (2003). This study used the 100 transmissivity fields (T fields) developed for the CRA-2004 by McKenna and Hart (2003) to identify the locations where head and transmissivity data from new wells would cause the greatest reduction in uncertainty associated with calculating groundwater travel times in the Culebra from a point above the center of the WIPP disposal panels to the site boundary. McKenna (2004) used three different methods to determine the value of a well or potential well location, and then integrated the results to create "combined-score values" maps showing the relative value of additional head and transmissivity data at points throughout the modeling domain. The three methods used were geostatistical variance reduction, three-point estimation of local gradients, and spatial sampling-based sensitivity analysis.

Geostatistical variance reduction involves the use of ordinary kriging to interpolate head values between measurement points (Rouhani 1985). In addition to estimating head at a location, ordinary kriging also provides a variance about that estimate. Because the estimation variance is based on the spatial distribution of measurements, and not directly on the measurements themselves, the change in variance caused by adding an additional measurement point can be mapped over the area of interest (assuming that the underlying variogram model remains valid).

Hydraulic gradients can be estimated from head measurements at three points. Given some amount of noise (uncertainty) in the head measurements, the accuracy of the estimated gradient is dependent on the size, shape, and orientation of the triangle formed by the three measurement points. McKenna (2004) developed criteria for triangles that would provide accurate gradient estimates, and then calculated for each cell in the model grid how many new suitable triangles would be created, when combined with existing wells, by adding a well in that cell.

Spatial sampling-based sensitivity analysis was possible because 100 calibrated T fields were available for the CRA-2004, along with a calculated groundwater travel time from a point above the center of the WIPP disposal panels to the site boundary for each. By sampling on all 100 T fields, McKenna (2004) was able to calculate the sensitivity of the travel time to the head and transmissivity in every cell of the model grid. These sensitivities, however, are specific to the set of T fields used in the calculations. They do not show what the effects on travel time would be of high-T or low-T areas that are not present in any of the 100 T fields used.

By normalizing the results from each of these analysis methods, McKenna (2004) was able to add the "scores" from each to create a combined score for each model cell, which he then mapped and contoured to show relative sensitivities. He first performed the analysis using the 30 wells for which head data were available in August 2003 (shown by the unlabeled + symbols in Figure HYDRO-4 and Figure HYDRO-5). He then included the locations of the first six "SNL" wells and IMC-461 drilled in 2003 and January 2004 (see Section HYDRO-3.0) in the geostatistical estimation variance and three-point gradient estimation procedures to produce revised combined-score values maps that were used to guide the locations of wells installed in

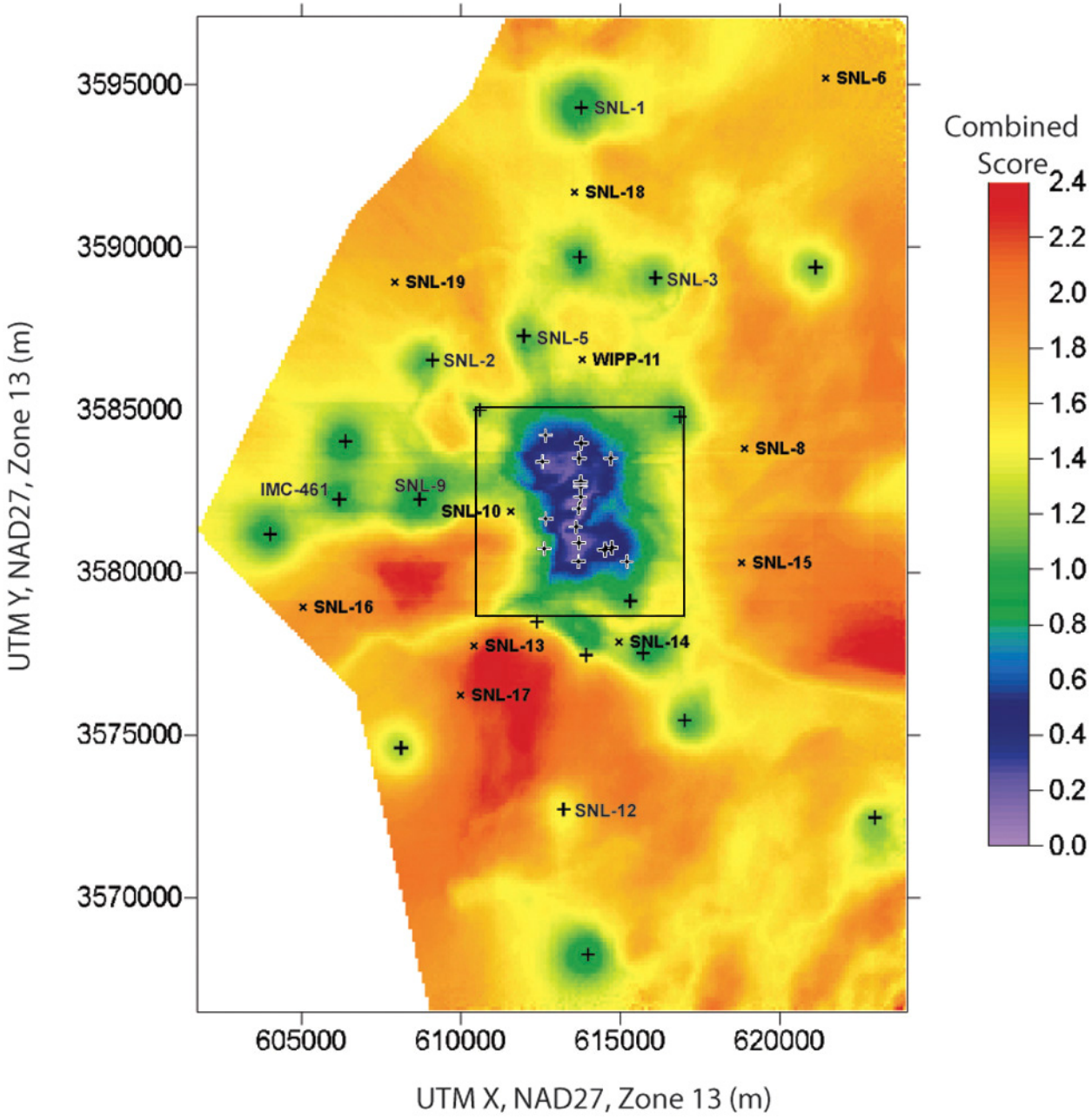

Figure HYDRO-4. Combined-Score Values Map From McKenna (2004) Including Estimation Variance, Number of Three-Point Estimators, and Sensitivity of Travel Time to Head. The Wells Used in the Study are Shown as + Symbols. Wells Sited Since this Map was Created are Shown as × Symbols. White Areas are Inactive Parts of Modeling Domain.

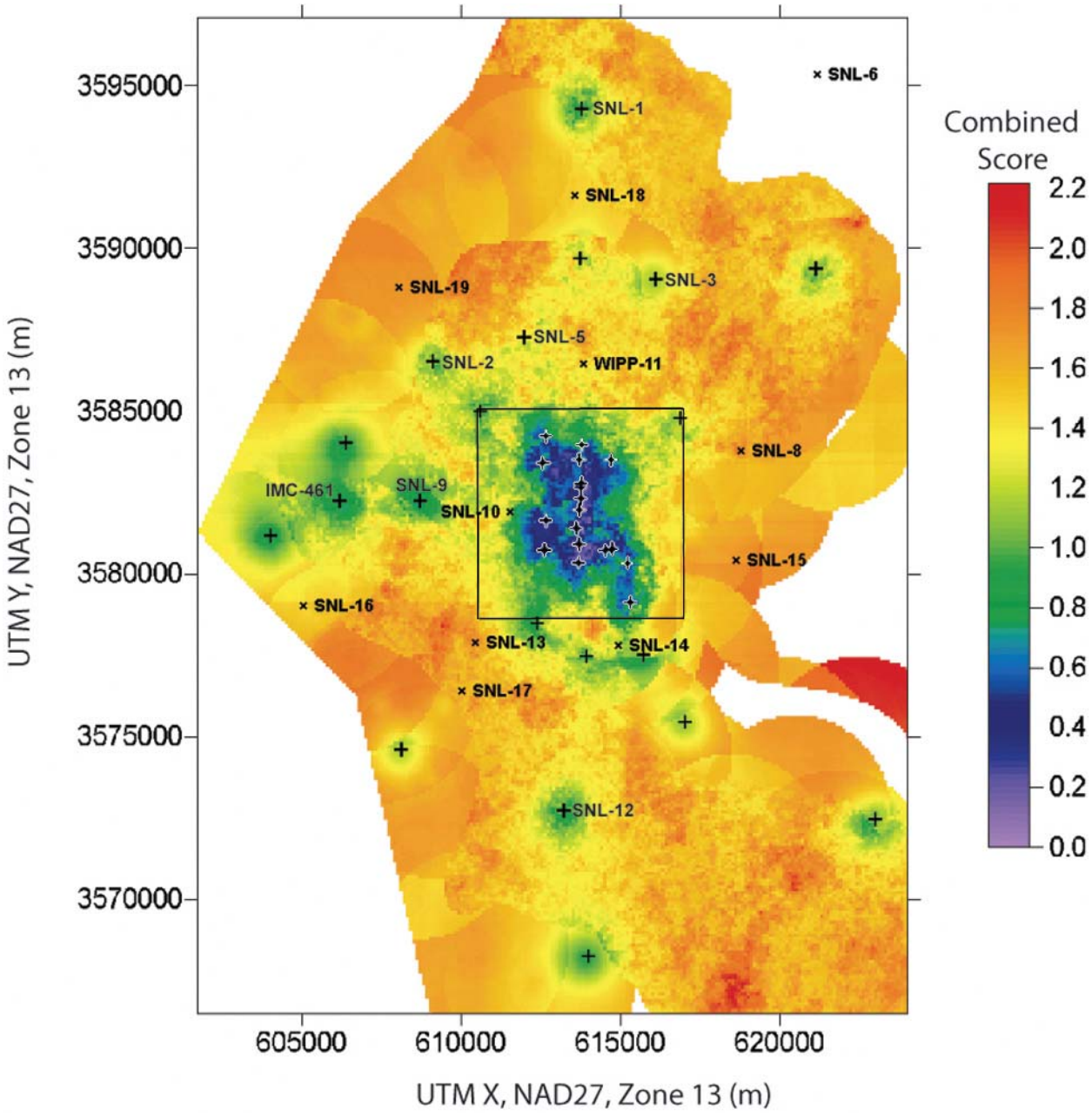

Figure HYDRO-5. Combined-Score Values Map From McKenna (2004) Including Estimation Variance, Number of Three-Point Estimators, and Sensitivity of Travel Time to Transmissivity. The Wells Used in the Study are Shown as + Symbols. Wells Sited Since this Map was Created are Shown as × symbols. White Areas are Inactive Parts of Modeling Domain or Areas Where Transmissivity Did Not Vary.

2005 and 2006 (Figure HYDRO-4 and Figure HYDRO-5). Figure HYDRO-4 combines the geostatistical variance, three-point estimation, and sensitivity of travel time to head while Figure HYDRO-5 combines the geostatistical variance, three-point estimation, and sensitivity of travel time to transmissivity.

Figure HYDRO-4 and Figure HYDRO-5 are qualitatively similar, with the differences reflecting the difference between travel-time sensitivity to head and sensitivity to transmissivity. Both figures show that additional wells in the center of the WIPP site, where many wells are already clustered, would be of little value (low sensitivity). Figure HYDRO-4 shows that the areas with the most travel-time sensitivity to head lie southwest of the WIPP. Based on these results, as well as geological and logistical considerations, new wells SNL-13, SNL-17A, and SNL-16 were drilled and now provide head information in that region, while others of the new wells provide head information in regions of moderate sensitivity. Figure HYDRO-5 shows that travel-time sensitivity to transmissivity does not differ greatly in regions distant from existing wells. SNL-8, SNL-13, SNL-15, SNL-16, SNL-17, SNL-18, SNL-19, and WIPP-11 have provided useful transmissivity information.

In something of a reversal of the process by which optimal positions for new wells were found, McKenna (2004) evaluated which wells could be eliminated without losing hydraulic head information needed to model flow through the Culebra, and which wells should be maintained in the Culebra monitoring network. He calculated the increase in head estimation variance and the decrease in the number of three-point estimators that would result from removal of each well in the existing network, and ranked the wells in order of value to the network. Wells WIPP-12 and WIPP-22 were identified as being of least value to the monitoring network, and hence candidates for plugging and abandonment (P&A), because their removal resulted in the smallest increase in head estimation variance and the smallest decrease in the number of three-point estimators. With those two wells removed from the network, the next candidates for P&A were WIPP-21 and ERDA-9. These four wells, along with a fifth well, WIPP-19, were situated along a north-south line extending about 1.6 kilometers (km) (1 mile [mi]) north from the center of the WIPP site (Figure HYDRO-1), and effectively provided an overabundance of head information within a small region. The wells identified as of most value to the monitoring network, as it then existed, were AEC-7, H-5b, WIPP-30, H-9c, and H-10c.

In summary, the monitoring network optimization study identified areas where new wells would be of value and where existing wells could be removed from the network with little loss of information. The study provided input for subsequent drilling and P&A decisions that also took factors such as costs of road construction, geologic objectives, well casing deterioration, and modeling data needs into account. The following two sections of this appendix describe the wells that were drilled (Section HYDRO-3.0) and plugged and abandoned (Section HYDRO-4.0) on the basis of the monitoring network optimization study in conjunction with these other considerations.

HYDRO-3.0 Drilling of New Wells

Eighteen new Culebra wells (Table HYDRO-2) were added to the monitoring network described in Section HYDRO-2.0 and shown in the CRA-2004, Chapter 2.0, Figure 2-3 and Figure 2-4 between April 2003 and October 2006. No additional Culebra wells were drilled between October 2006 and the data cutoff date for the CRA-2009 (12/31/2007). Drilling of these new wells began under a program plan (Sandia National Laboratories 2003) that included a preliminary design for a 41-well, long-term Culebra monitoring network. Twelve new wells given "SNL-#" designations were proposed in specific locations to confirm the correlations described in Powers et al. (2003) between Culebra transmissivity and various geologic conditions, provide information needed for numerical modeling, and provide information relevant to possible scenarios explaining the rise in Culebra water levels (see Section HYDRO-9.0). In addition, 21 proposed well locations given Washington TRU Solutions ("WTS-#") designations were laid out in a geometric pattern to provide the long-term monitoring network required for the WIPP. Five of the "WTS" locations coincided with "SNL" locations, 12 coincided with existing (or previous) well locations, and 4 represented new locations. Seven existing "far-field" wells and the six Water Quality Sampling Program (WQSP) Culebra wells required by the WIPP Hazardous Waste Facility Permit were also planned to be retained. The remaining existing Culebra wells would be plugged and abandoned over time. The 35 proposed well locations exclusive of the WQSP wells are shown in Figure HYDRO-6 (originally published as Figure 8 in Sandia National Laboratories 2003), along with the Rustler halite margin information available at that time (see Figure HYDRO-3 and Section HYDRO-7.1).

The drilling program began in 2003, as SNL-2, 9, 12, and 3 were successively drilled between April and September of that year (Powers and Richardson 2003a, 2003b, 2004a, and 2004b). An unplanned well, IMC-461 (see Figure HYDRO-1), was completed in January 2004 when Mosaic Potash Carlsbad, Inc. (then known as IMC Potash Carlsbad, Inc) offered an exploratory borehole to the DOE west of the WIPP site (Beauheim 2005). SNL-1 and SNL-5 were then drilled between March and May 2004 (Powers and Richardson 2004c and 2004d) after preliminary results of the McKenna (2004) study were used to shift the final location of SNL-5 west of its originally planned location shown in Figure HYDRO-6 to an area where transmissivity information would be of more value (see Figure HYDRO-1). In September 2004, WIPP-11, an exploration hole originally drilled in 1978 (Sandia National Laboratories and U.S. Geological Survey 1982) that had lain sealed and dormant for decades, was completed in the Culebra by perforating the well casing across the Culebra interval.

Based on the work of McKenna (2004), six areas were identified for installation of new wells: SNL-13, 15, 16, 17, 18, and 19. The precise locations of these wells were selected to minimize the need for new road construction. SNL-13 is approximately 1150 meters (m) (3773 feet [ft]) south and 226 m (741 ft) west of the proposed WTS-4 (which was to be on the old P-15 well pad) and takes the place of that proposed long-term monitoring well. SNL-15 is the same as the proposed WTS-3, situated on the old P-18 well pad. SNL-17 is effectively the proposed WTS-6, shifted 763 m (2503 ft) to the east and 1274 m (4180 ft) to the south. SNL-16, 18, and 19 were sited at entirely new locations in or on the edge of Nash Draw. SNL-14 was sited based on detailed geologic information, independently of the work of McKenna (2004), in response to a direct request from EPA for a well in that vicinity (Cotsworth 2004a). SNL-13, 14, 15, 8, and 6

Table HYDRO-2. Purposes of New Culebra Wells

Well	Purposes
SNL-1	Look for potentiometric and geochemical evidence of leakage from Intrepid East tailings pile; test Culebra near margin of Salado dissolution
SNL-2	Test Culebra near margin of Salado dissolution
SNL-3	Confirm presence of inferred Salado dissolution reentrant and test Culebra
SNL-5	Provide data in area of high sensitivity identified by McKenna (2004)
SNL-6	Confirm high heads and very low-T expected in area east of M2-H2 and M3-H3 halite margins; provide head estimate for northern numerical model boundary condition
SNL-8	Confirm low-T east of the WIPP site and look for evidence of dissolution along M3-H3 boundary
SNL-9	Confirm presence of inferred Salado dissolution reentrant and test Culebra; provide pumping well for large-scale test west of the WIPP site
SNL-10	Provide transmissivity data in western WIPP site near M1-H1 margin
SNL-12	Confirm high-T expected south of WIPP site and look for evidence of Salado dissolution; provide potential pumping well for large-scale test south of the WIPP site
SNL-13	Provide transmissivity data SW of the WIPP site near the edge of Nash Draw
SNL-14	Specific request from EPA to confirm/disprove high-T zone extending from SE WIPP site to the south; provide pumping well for large-scale test south of the WIPP site
SNL-15	Confirm high heads and very low-T expected in area east of M2-H2 and M3-H3 halite margins
SNL-16	Evaluate effects of Salado dissolution on Culebra transmissivity and confinement
SNL-17A	Evaluate effects of Salado dissolution on Culebra transmissivity and confinement
SNL-18	Evaluate effects of Salado dissolution on Culebra transmissivity and confinement; look for geochemical evidence of leakage from Intrepid East tailings pile
SNL-19	Evaluate effects of Salado dissolution on Culebra transmissivity and confinement
IMC-461	Well of opportunity near Nash Draw and edge of Salado dissolution
WIPP-11	Well of opportunity that could serve as a replacement for DOE-2 and provide a pumping well for a large-scale test north of the WIPP site

were drilled between April and September 2005 (Powers and Richardson 2008a, 2008b, and 2008c; Powers 2009a and [In progress]a) and SNL-16, 19, 10, 18, and 17A (the original SNL-17 had to be abandoned and redrilled) were drilled between April and July 2006 (Powers 2009b, [In progress]b, 2009c, [In progress]c, and [In progress]d).

Most of the new wells encountered geologic conditions typical for boreholes drilled at the WIPP. Six wells, however, encountered atypical (although not necessarily unpredicted) conditions. SNL-6 and SNL-15, the only two wells drilled on the eastern (halite) side of the Rustler M2-H2 and M3-H3 halite margins (see Figure HYDRO-3) (Powers 2007, Section HYDRO-7.1), encountered halite in the Culebra (Powers et al. 2006a), as predicted by Holt (1997). At SNL-1, a 0.6-m (2-ft) drilling bit drop occurred while drilling through the Culebra, and drilling fluid circulation was temporarily lost (Powers and Richardson 2004c). In addition, brine was encountered at a depth of approximately 11 m (36 ft) in the upper Dewey Lake in this drillhole located immediately south of the Intrepid (formerly Mississippi) East tailings pile (see

Figure HYDRO-6). High brine flows were encountered in a sandy, poorly indurated section of the M1 unit of the Los Medaños Member of the Rustler Formation in SNL-13, a first-of-its-kind encounter (Powers and Richardson 2008a). None of these conditions affected proper completion of the wells.

At SNL-17, sulfate beds of the Forty-niner Member of the Rustler were not distinguishable in either cuttings or geophysical logs, and the Magenta dolomite was altered. The cuttings indicate Dewey Lake above this zone, and the uppermost Rustler was apparently altered and partially dissolved along the Nash Draw escarpment that marks upper Salado dissolution. A 0.6-m (2-ft) drilling bit drop occurred while drilling through the lower Tamarisk in SNL-17 (Powers [In progress]d). High water production from the Culebra and problems with the core barrel sticking below the Culebra led to the decision to stop drilling and complete SNL-17 without drilling to the top of Salado as planned. Several cubic meters (m^3) of gravel were required to fill voids in the Tamarisk (and possibly Culebra) when gravel-packing the well screen. SNL-17 could not be completed with certain isolation of the Culebra, so it was plugged and abandoned. A replacement well (SNL-17A) was drilled on the pad and successfully completed for monitoring.

SNL-18 (Powers [In progress]c) was drilled along the escarpment in the northeast arm of Nash Draw. Water was encountered while drilling the Dewey Lake. The Forty-niner Member of the Rustler is represented by poorly preserved gypsite in a zone of very poor core recovery; a tool drop of 0.3 m (1 ft) also occurred near the contact with the Dewey Lake. Short recovered intervals of the Magenta revealed high dips to the bedding. Little, if any, of the upper Tamarisk sulfate (A3) was recovered, as circulation of drilling fluid was limited or lost. The lower Tamarisk and upper Culebra were partially recovered in cores. A large amount of drilling mud was lost when drilling the well. Sections above the Culebra were cemented and redrilled to provide additional hole stability. An earlier attempt by Intrepid (then known as New Mexico Potash) to drill a potash exploration hole at the location of SNL-18 encountered drilling difficulties and was abandoned before reaching the Rustler.

SNL-4, 7, and 11 and WTS-7 and 9 are not currently planned to be drilled because McKenna (2004) did not show them to be in high-value locations. WTS-18 (planned replacement for WIPP-30 when that well has to be plugged and abandoned) and WTS-20 (planned replacement for H-7) will also likely never be drilled because of the presence of SNL-18 and SNL-17A, respectively. Final decisions on replacement of these wells and the wells designated as "Far Field" on Figure HYDRO-6 have not been made. In addition, use of the "WTS" designation has been abandoned—all wells at new locations are given "SNL" designations, while replacement wells will be given the original well name with an "R" appended (e.g., H-15R).

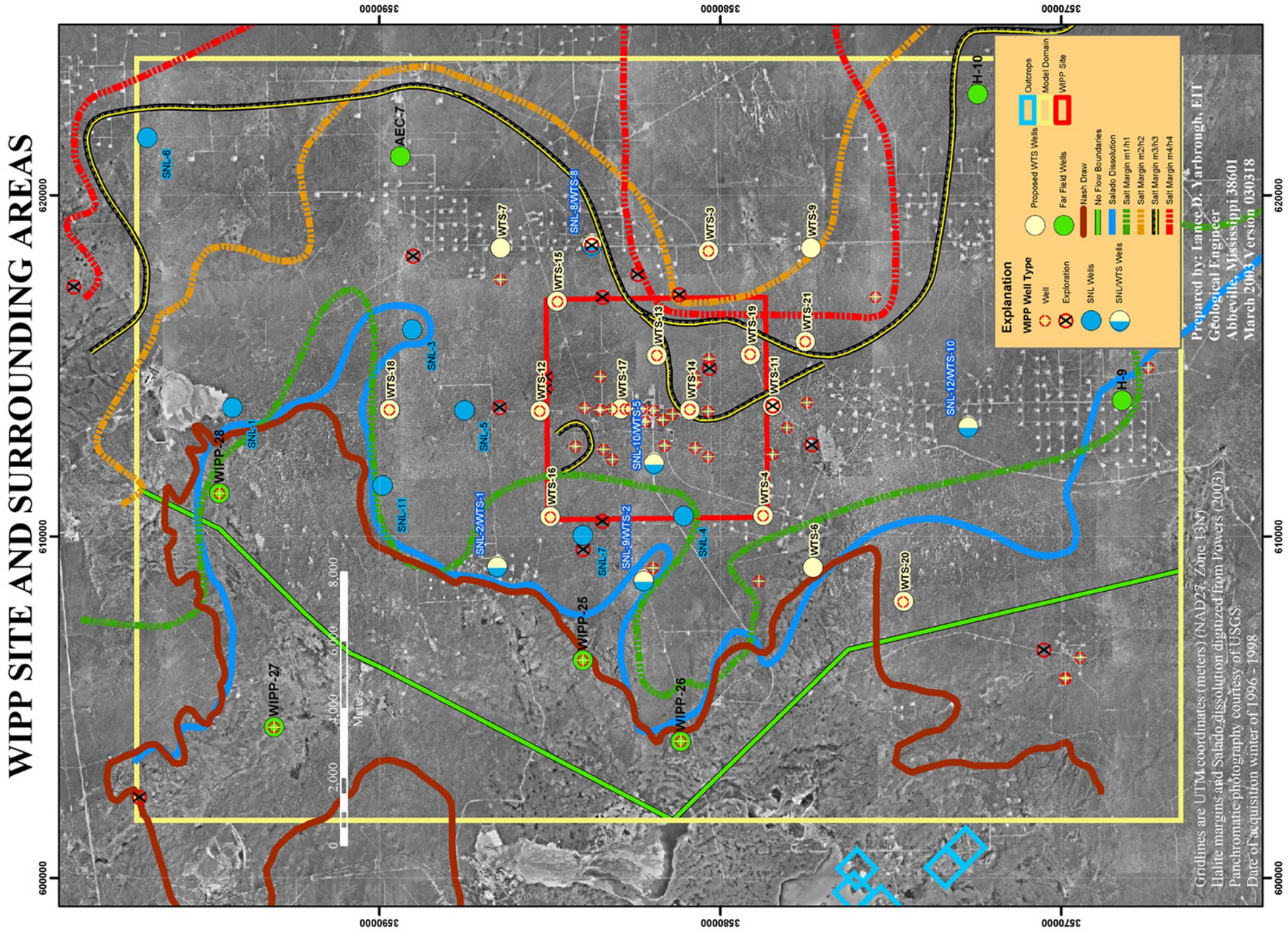

Figure HYDRO-6. Air-Photo Map From Sandia National Laboratories (2003, Figure 8) Showing Locations Proposed for SNL-and WTS-Series Wells

HYDRO-4.0 P&A and Recompletion of Old Wells

Until 1994, all wells installed for WIPP were constructed with steel well casing. Exposure to brine caused the steel casing to deteriorate, necessitating the P&A of many wells. In addition, having multiple Culebra wells on the same drilling pad (which were originally installed for now-completed testing purposes) is of little value for long-term monitoring. Hence, casing integrity was evaluated in all wells on the multiple-well drilling pads, and the most deteriorated wells were scheduled for P&A. Finally, the network optimization study performed by McKenna (2004) identified WIPP-12, WIPP-21, and WIPP-22 as being of little value to the monitoring network, and hence candidates for P&A.

Since the CRA-2004, 17 wells have been plugged and abandoned (Salness 2006 and 2007). Three other wells have been permanently recompleted to monitor different horizons (Salness 2005a, 2005b, and 2006). Eight wells monitoring the Magenta, but with the capability to also monitor the Culebra, were plugged back to provide simpler, and irreversible, Magenta completions (Salness 2006). In addition, the lower uncased Salado-Castile portion of AEC-7 was plugged back so that a bridge plug would no longer be required in the well to monitor the Culebra (Salness 2005c). Well H-7c, completed to the Culebra, and well H-8c, completed across the Rustler-Salado contact, were transferred to the Bureau of Land Management (BLM) for use in their range-management program. These well activities are summarized in Table HYDRO-3, and the well locations are shown in Figure HYDRO-7.

Table HYDRO-3. Wells Plugged and Abandoned or Recompleted from 2004 to 2006

Well	Interval(s) Previously Monitored	Activity	Date of Activity	Current Interval Monitored
AEC-7	Culebra	Plugback	Mar.-Apr. 2004	Culebra
AEC-8	Bell Canyon	P&A	April 2005	—
CB-1	Culebra and Bell Canyon	Recompleted	Jan.-Feb. 2004	Bell Canyon
DOE-1	Culebra	P&A	September 2006	—
DOE-2	Culebra and Magenta	Recompleted	Feb.-Mar. 2004	Bell Canyon
H-2a	Culebra	P&A	April 2005	—
H-2b1	Culebra and Magenta	Plugback	April 2005	Magenta
H-2c	Culebra	P&A	April 2005	—
H-3b1	Culebra and Magenta	Plugback	June 2005	Magenta
H-3b3	Culebra	P&A	June 2005	—
H-3d	Forty-niner and Dewey Lake	Recompleted	June 2005	Santa Rosa-Dewey Lake
H-4c	Culebra and Magenta	Plugback	May 2005	Magenta
H-5a	Culebra	P&A	June 2005	—
H-5c	Culebra & Magenta	Plugback/P&A	June 2005	(inadvertently plugged Magenta too)
H-6a	Culebra	P&A	May 2005	—
H-6c	Culebra and Magenta	Plugback	May 2005	Magenta

Table HYDRO-3. Wells Plugged and Abandoned or Recompleted from 2004 to 2006 (Continued)

Well	Interval(s) Previously Monitored	Activity	Date of Activity	Current Interval Monitored
H-7b2	Culebra	P&A	May 2005	—
H-7c	Culebra	Transferred to BLM	August 2005	—
H-8c	Rustler-Salado	Transferred to BLM	September 2005	—
H-11b1	Culebra	P&A	May 2005	—
H-11b2	Culebra and Magenta	Plugback	May 2005	Magenta
H-14	Culebra and Magenta	Plugback	April 2005	Magenta
H-18	Culebra and Magenta	Plugback	May 2005	Magenta
P-17	Culebra	P&A	August 2006	—
WIPP-12	Culebra	P&A	July 2005	—
WIPP-18	Culebra and Magenta	Plugback	May 2005	Magenta
WIPP-21	Culebra	P&A	May 2005	—
WIPP-22	Culebra	P&A	May 2005	—
WIPP-26	Culebra	P&A	October 2006	—
WIPP-27	Culebra	P&A	August 2006	—
WIPP-29	Culebra	P&A	May 2005	—

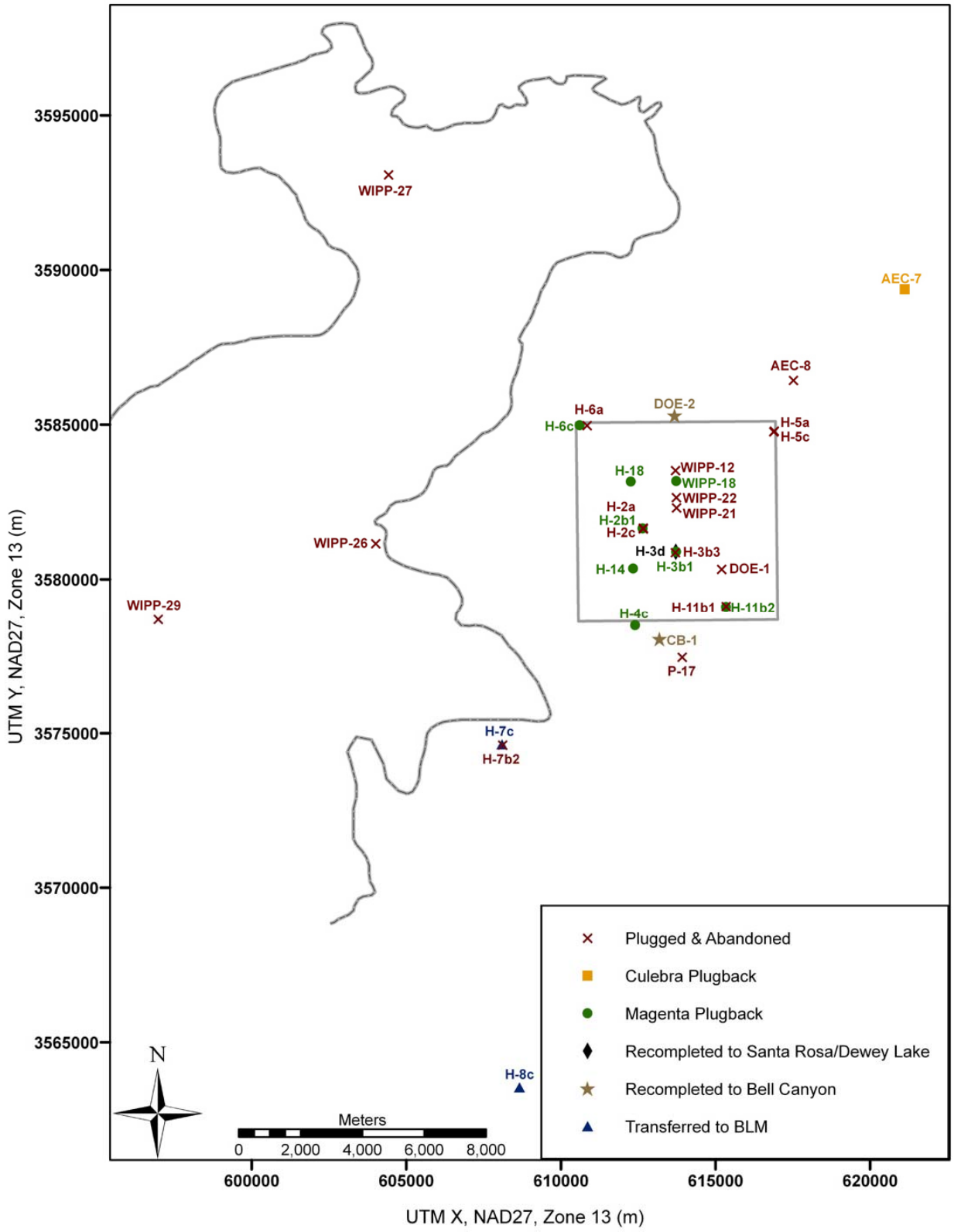

Figure HYDRO-7. Locations of Plugged and Abandoned and Recompleted Wells

HYDRO-5.0 Monitoring

Groundwater monitoring activities at the WIPP are carried out under the *Waste Isolation Pilot Plant Environmental Monitoring Plan* (U.S. Department of Energy 2004b) and under *Test Plan TP 06-01, Monitoring Water Levels in WIPP Wells* (Hillesheim 2007). The first monitoring program consists of monthly water-level measurements in all accessible wells, with results reported in the Annual Site Environmental Reports (ASERs) (U.S. Department of Energy, 2004c, 2005, 2006, 2007, and 2008). The second monitoring program involves both periodic water-level measurements and continuous measurement (typically at one-hour [hr] intervals) of fluid pressure in wells instrumented with downhole pressure gauges (TROLL®).

Water-level monitoring provides a general picture of the changes in hydraulic head occurring in the formations being monitored. Water levels are currently being monitored in the Culebra and Magenta Members of the Rustler, the Dewey Lake (Redbeds), and the Bell Canyon. The monitored well locations are shown in Figure HYDRO-8, Figure HYDRO-9, and Figure HYDRO-10. Wells in which monitoring has ceased since January 2004 are listed in Table HYDRO-3.

HYDRO-5.1 Culebra Monitoring

In addition to monitoring Culebra water levels, DOE monitors the fluid pressure in many wells with TROLL® gauges. The Culebra wells instrumented with TROLL® gauges are listed in Figure HYDRO-11, which shows the periods of time from October 2002 through 2007 during which the TROLL® gauges were installed. The continuous fluid-pressure measurements made using TROLL® gauges provide a clearer, more complete record of the changes in hydraulic head occurring in the wells than is provided by monthly water-level measurements.

Figure HYDRO-12 shows the TROLL® and water-level data from Culebra well WIPP-26 in Nash Draw from November 2003 through October 2006. The TROLL® pressure data show that what previously appeared to be random noise in the water-level data actually has a consistent underlying structure. Furthermore, the pressure data show a series of downward spikes and rapid recoveries, with the recoveries exceeding the prespike levels in many cases. Having a high temporal level of resolution in the head data is essential in understanding the causes of these head changes. By plotting daily rainfall measured at the WIPP rain gauge near the center of the WIPP site in parallel with the TROLL® pressure data from WIPP-26 (Figure HYDRO-13), it was discovered that the spikes in pressure correlate with rainfall events of approximately 10 millimeters (mm) (0.4 inches [in.]) or more in 24 hours (hrs). (Note that thunderstorms can be highly localized, and that any individual rain gauge may not always reflect rain that falls at remote wells.) It is hypothesized that rainfall accumulates in a localized area in Nash Draw, increasing the load on the Culebra at that location. The strata above the Culebra appear to act as a lever, with the increased load at the accumulation location causing a decreased load at WIPP-26. This effect seems to dissipate within approximately one day, usually followed by an increase in Culebra head related to the precipitation event, and then a gradual falloff in head. This phenomenon of precipitation causing an initial drop in pressure is also observed at well IMC-461 at approximately the same magnitude as at WIPP-26, and sometimes at WIPP-25 at a much smaller magnitude. No other wells show this response to rainfall.

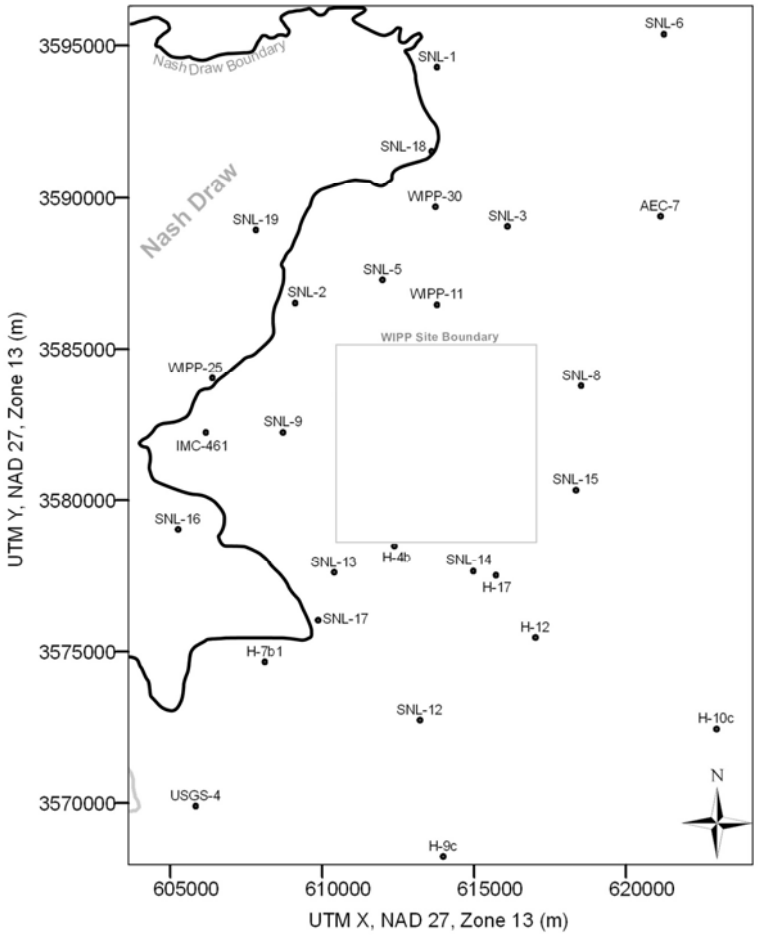

Figure HYDRO-8. Locations of Culebra Monitoring Wells Outside the WIPP Site as of 1/1/2008

The high-resolution TROLL® pressure data have shown that two other wells in Nash Draw, SNL-16 and SNL-19 (Figure HYDRO-14), respond rapidly to rainfall events without showing the initial pressure decrease evident at WIPP-26 and IMC-461. (Note that the measured pressure is relative to the position of a TROLL® in a well, which differs among wells.) Two wells on the edge of Nash Draw, SNL-1 and SNL-2, show more gradual responses to major storms (Figure HYDRO-15). Thus, the Culebra appears to be unconfined in at least parts of Nash Draw, probably because of a combination of dissolution, collapse, and fracturing of the overlying units that act as confining beds under Livingston Ridge. This is not to say, however, that present-day rainfall actually enters the Culebra wherever a pressure response to rainfall is observed. Rather, the rainfall reaches a water table in a higher stratigraphic unit that is in sufficient hydraulic communication with the Culebra to transmit a pressure response rapidly.

Once the head in the Culebra is increased in Nash Draw, a pressure transient propagates through the confined Culebra under Livingston Ridge and across the WIPP site over the following days to months (Hillesheim, Hillesheim, and Toll 2007), decreasing in magnitude as it goes. This can be seen in Figure HYDRO-16, which shows water levels measured in three wells with discrete rises associated with rainfall events becoming less distinct with increasing distance from Nash

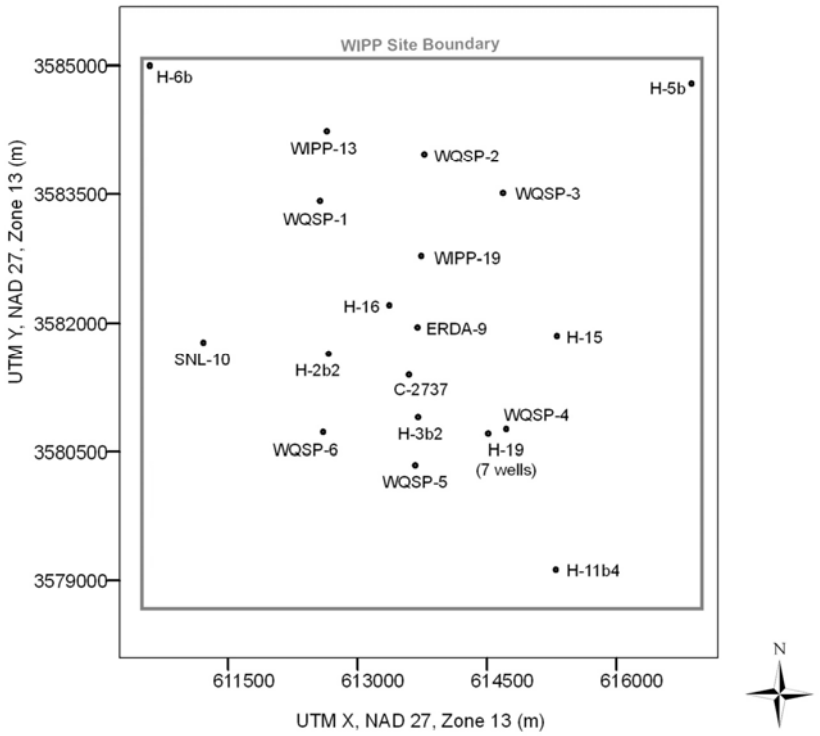

Figure HYDRO-9. Locations of Culebra Monitoring Wells Within the WIPP Site as of 1/1/2008

Draw (top to bottom in Figure HYDRO-16; see Figure HYDRO-8 and Figure HYDRO-9 for well locations). Unlike the responses seen in wells in Nash Draw, however, where the water level declines with time after rainfall-induced rises, the water levels in wells outside of Nash Draw show little decline but instead seem to show a sustained, long-term rise (compare Figure HYDRO-14 with Figure HYDRO-15 and Figure HYDRO-16). This may indicate that something in addition to rainfall in Nash Draw is affecting these wells. Section HYDRO-9.0 describes the modeling of different scenarios to explain this long-term rise in water levels.

Hillesheim, Hillesheim, and Toll (2007) evaluated the lag time between major rainfall events and water-level (or pressure) responses in wells around WIPP. They determined lag times for 34 wells after a large September 25, 2004, rainfall and for 27 wells after an August 15, 2006, storm, both of which occurred over extensive areas in and around Nash Draw, grouping them into five time ranges. Figure HYDRO-17 shows the spatial distribution of wells in the different lag-time ranges, along with the $\log_{10}$ transmissivity (square meters per second [m^2/s]) values for all Culebra wells. Also shown is a dashed line indicating the approximate contour of where the Culebra $\log_{10}$ transmissivity is -5.4, which is the approximate dividing line between fractured (double-porosity) and porous-medium hydraulic behavior in the Culebra (Holt, Beauheim, and Powers 2005). The lag-time ranges generally parallel this contour, and lag times are particularly long where the Culebra is unfractured and has a $\log_{10}$ transmissivity less than -5.4. This pattern is consistent with diffusive propagation of a pressure wave from Nash Draw to the east.

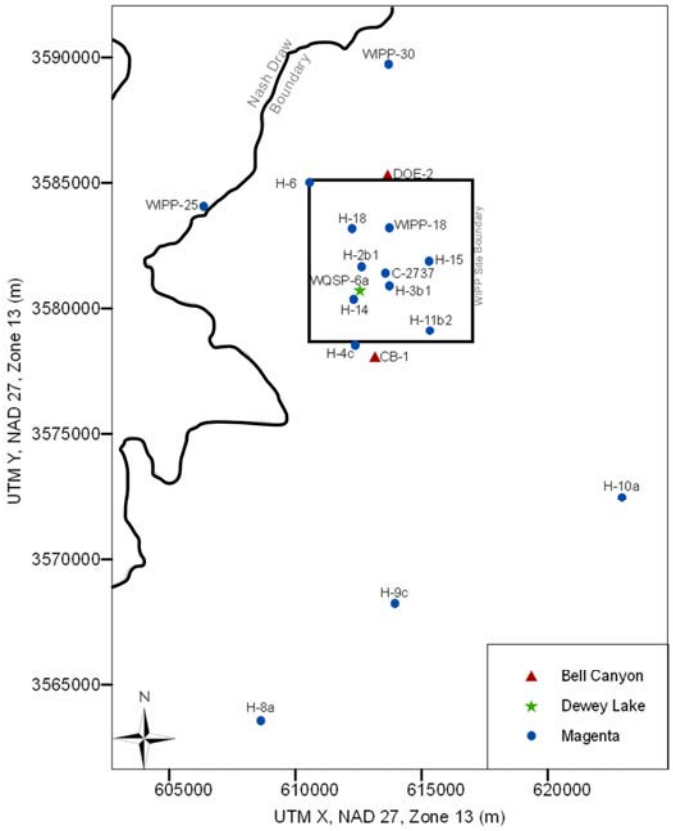

Figure HYDRO-10. Locations of Non-Culebra Monitoring Wells as of 1/1/2008

Figure HYDRO-18, Figure HYDRO-19, Figure HYDRO-20, Figure HYDRO-21, Figure HYDRO-22, Figure HYDRO-23, and Figure HYDRO-24 show the hydrographs from almost all Culebra wells monitored by the WIPP for the period from 2003 through 2007. No representative data were collected from AEC-7 over this period because of a leaking plug in the well, and H-15 was usually configured in such a way as to preclude Culebra water-level measurements. Figure HYDRO-18 and Figure HYDRO-19 show the hydrographs from seven Culebra wells north of the WIPP site and from seven Culebra wells in the northern portion of the WIPP site, respectively. The hydrographs from these 14 wells generally parallel one another, as well as the hydrograph from SNL-1 shown in Figure HYDRO-15. The seven wells with data going back to the beginning of 2003 show an early rise in 2003 followed by a decline that lasted until the second half of 2004, after which water levels again began to rise and generally showed more inflections than had been previously observed. These inflections are also seen in the hydrographs of the seven newer wells. The most pronounced of these inflections is the rise that occurred after the major rainstorms of mid-August and early September 2006. As discussed above, the inflections are more subtle in the wells farther from Nash Draw: WIPP-19 and H-2b2 (Figure HYDRO-19). Of the wells shown that existed at the time of the WIPP-11 19-day pumping test (February 1–20, 2005; see Section HYDRO-6.0), all but SNL-2 and H-2b2 showed drawdowns in response to the pumping. From late 2006 through 2007, SNL-2 (on the edge of Nash Draw) and SNL-19 (in Nash Draw) showed erratic behavior in contrast to the sustained water-level rise seen in the other wells (see also Figure HYDRO-14 and Figure HYDRO-15).

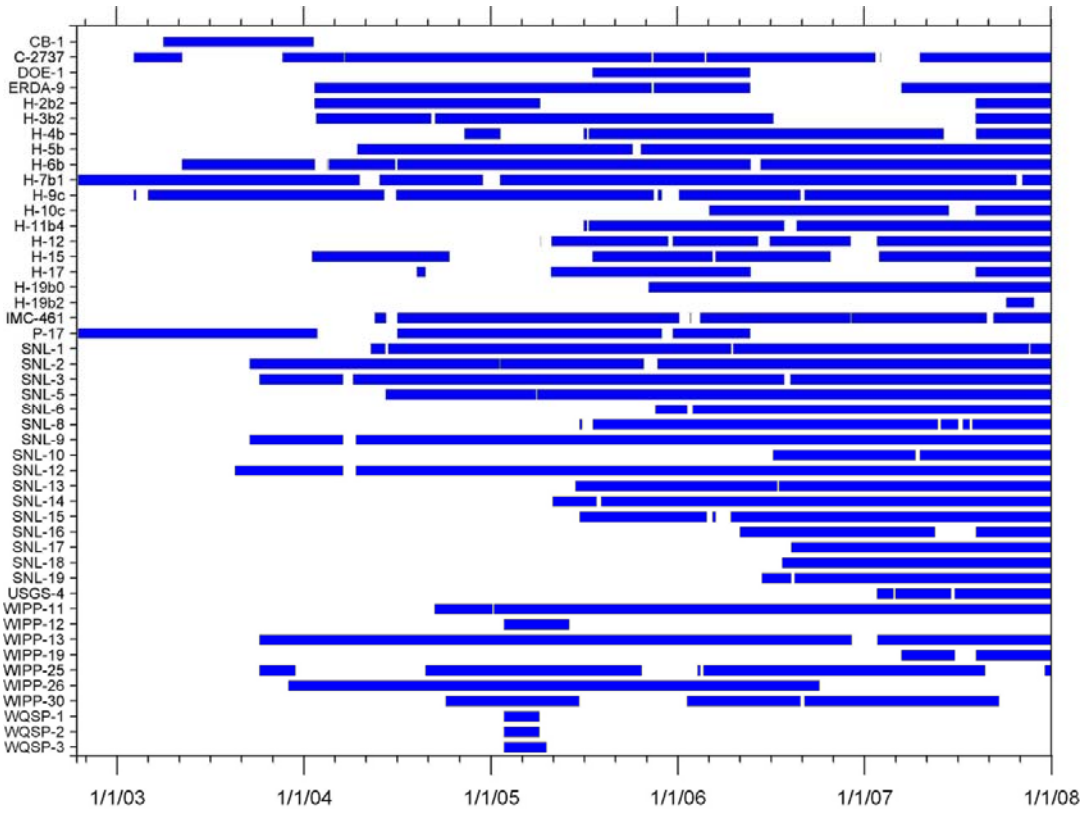

Figure HYDRO-11. Time Periods During Which Culebra Wells Have Been Monitored Using TROLL® Gauges

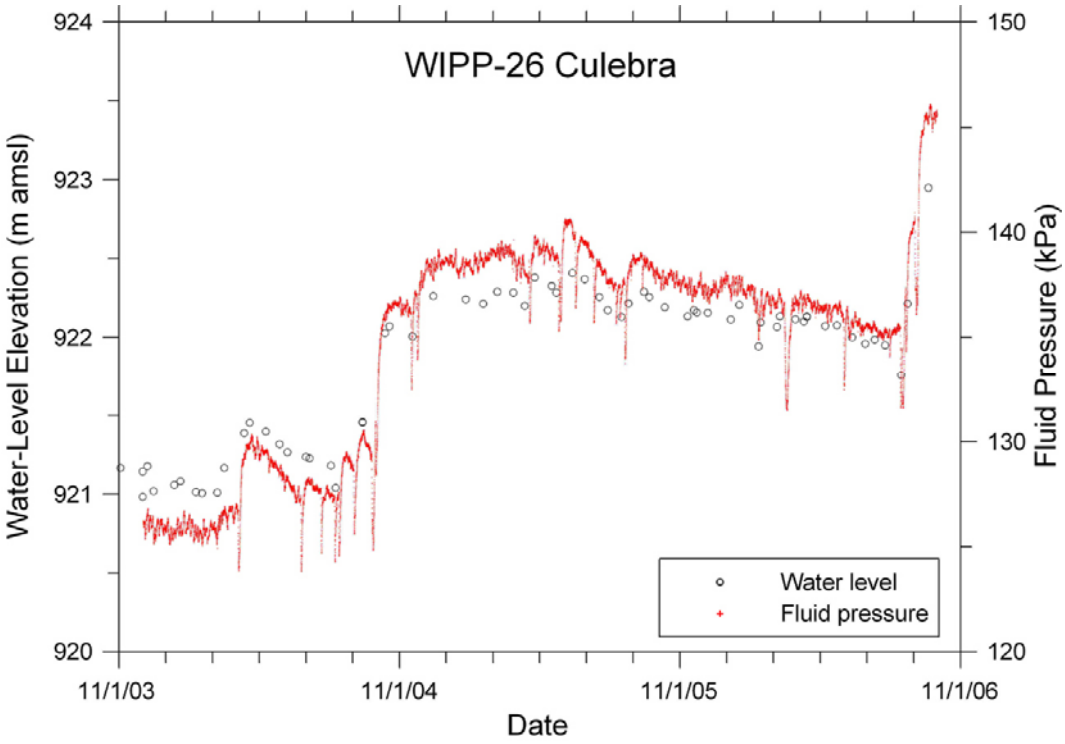

Figure HYDRO-12. WIPP-26 Culebra TROLL® and Water-Level Data

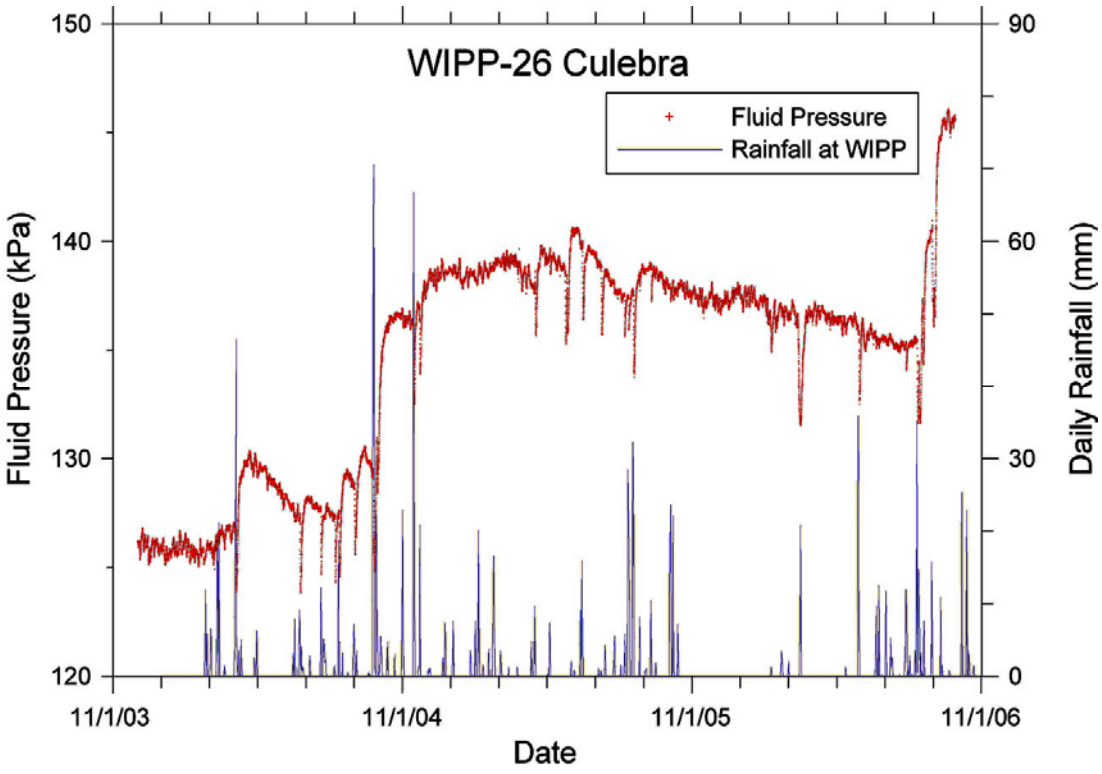

Figure HYDRO-13. WIPP-26 Culebra Fluid Pressure With Daily Rainfall Measured at the WIPP

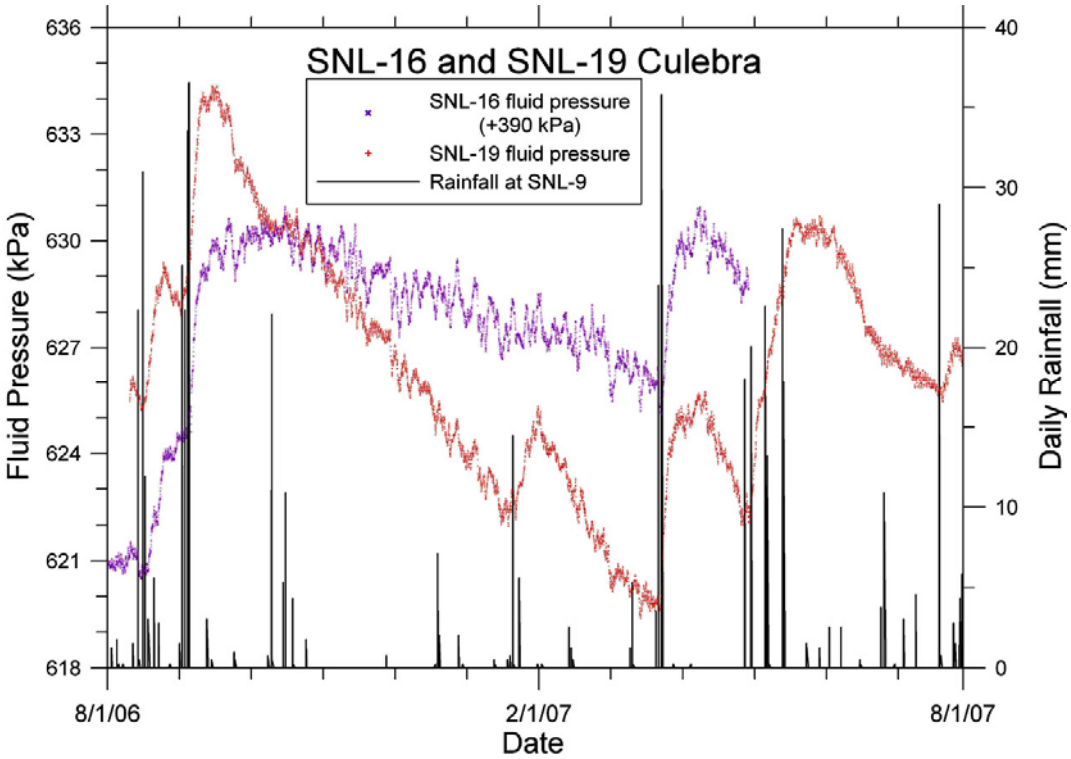

Figure HYDRO-14. SNL-16 and SNL-19 Culebra Fluid Pressures With Daily Rainfall Measured at SNL-9

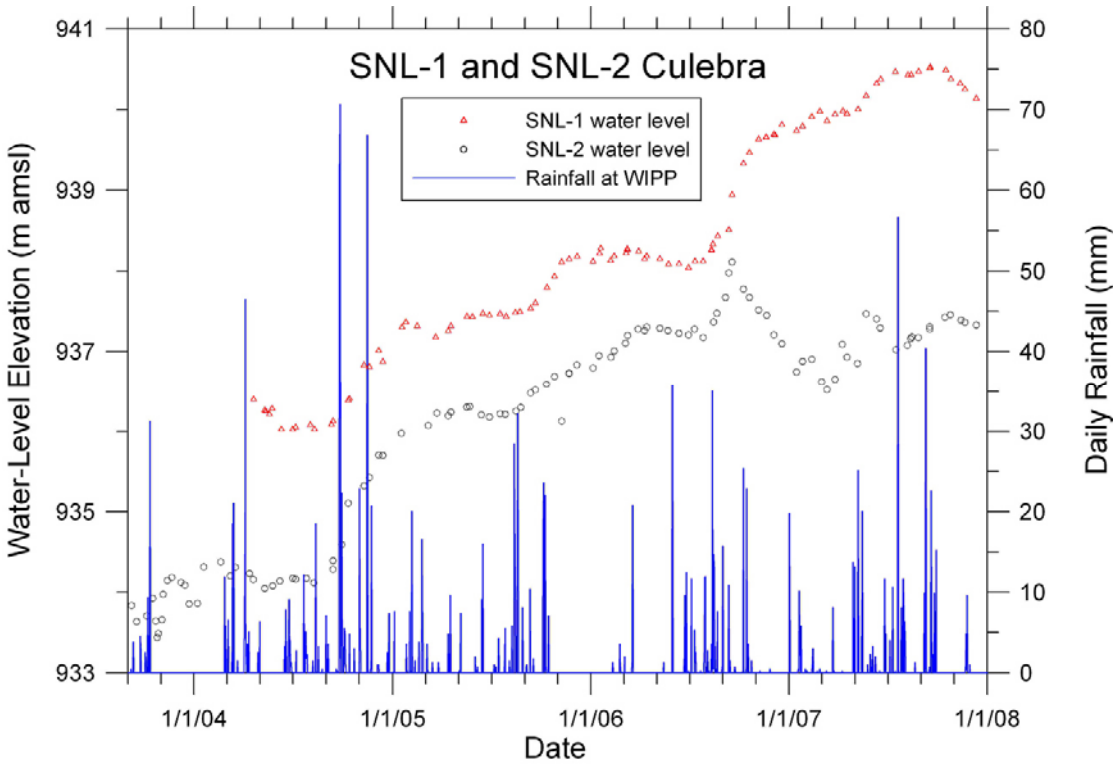

Figure HYDRO-15. SNL-1 and SNL-2 Culebra Water Levels With Daily Rainfall Measured at the WIPP

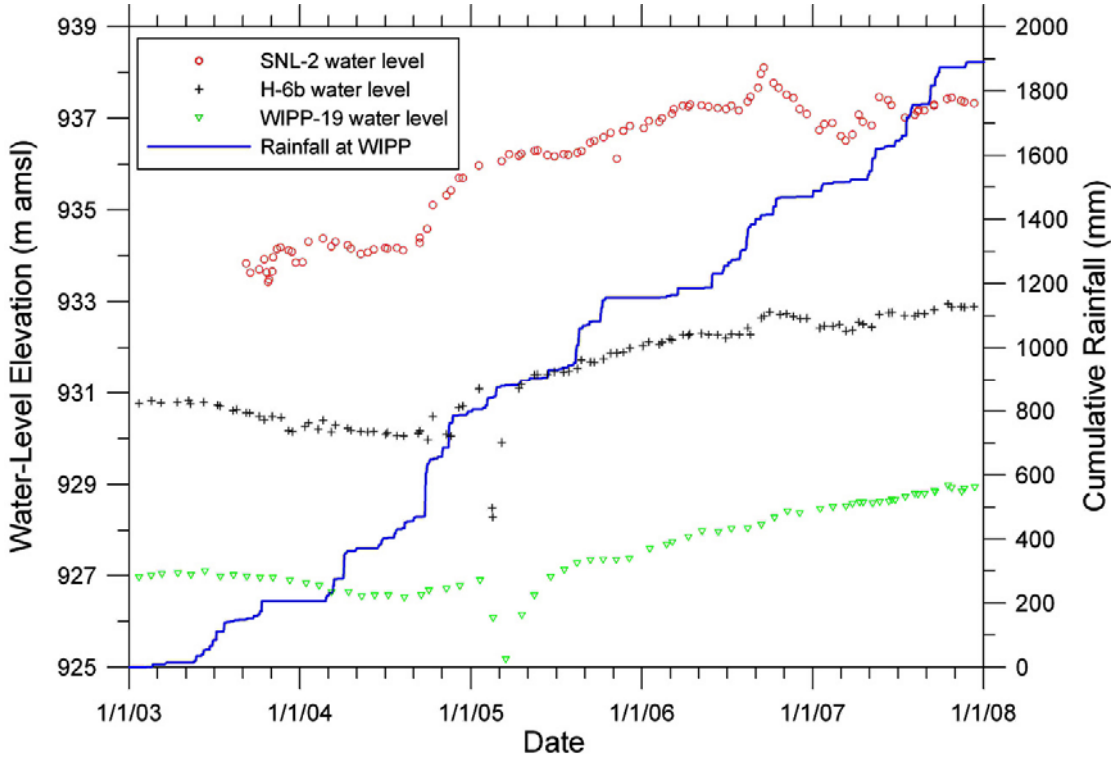

Figure HYDRO-16. SNL-2, H-6b, and WIPP-19 Culebra Water Levels With Cumulative Rainfall Measured at the WIPP

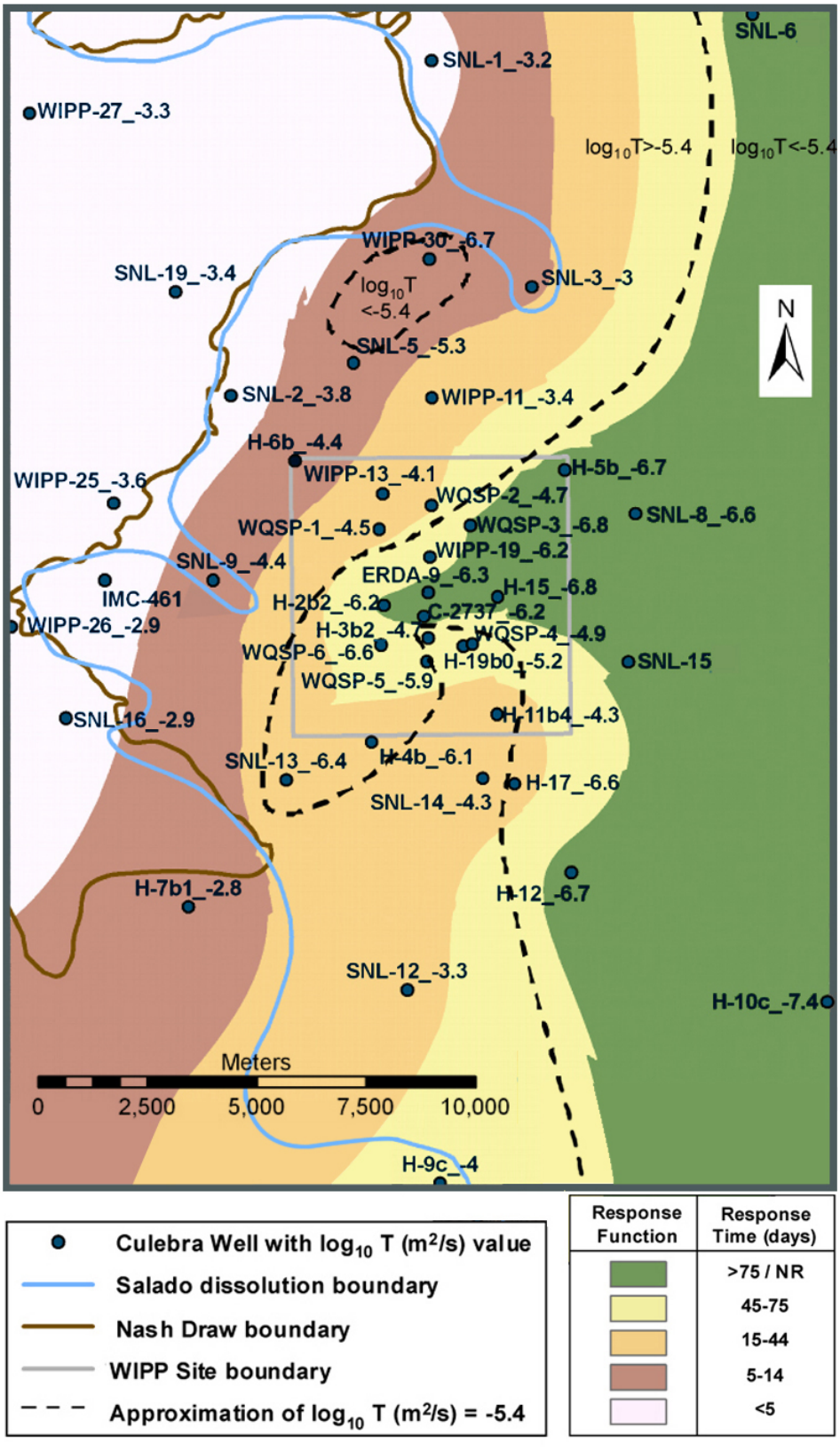

Figure HYDRO-17. Map of Culebra Lag-Time Response to Major Rainfall Events (from Hillesheim, Hillesheim, and Toll 2007). "NR" Denotes No Response.

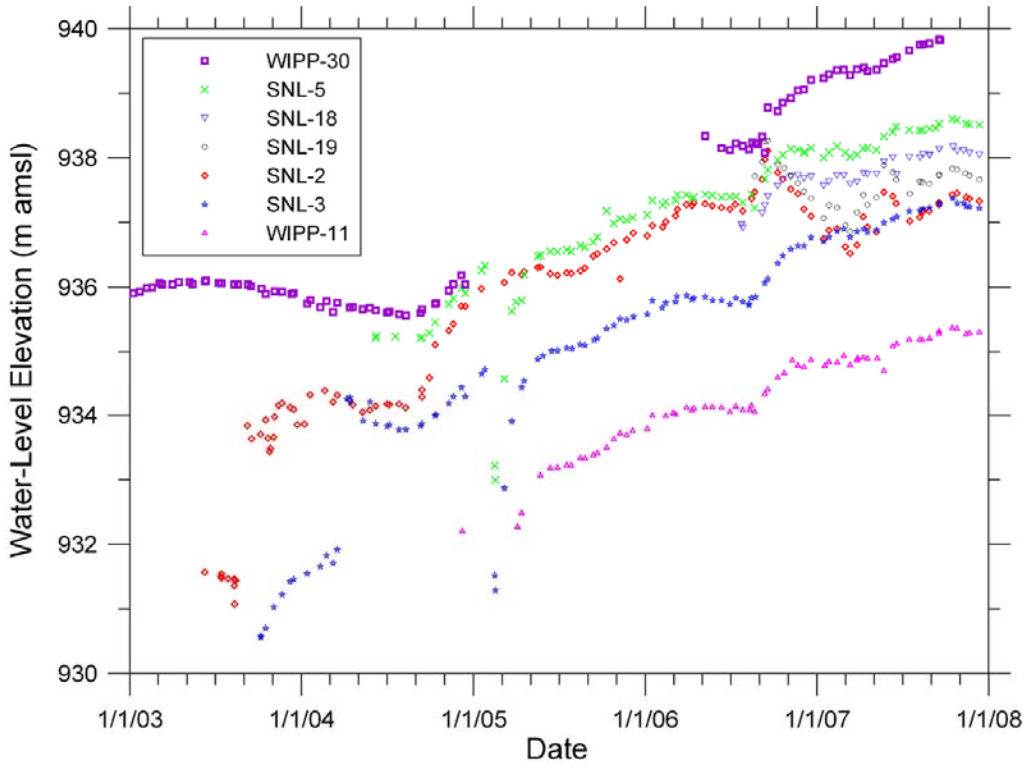

Figure HYDRO-18. Water Levels in Seven Culebra Wells North of the WIPP Site

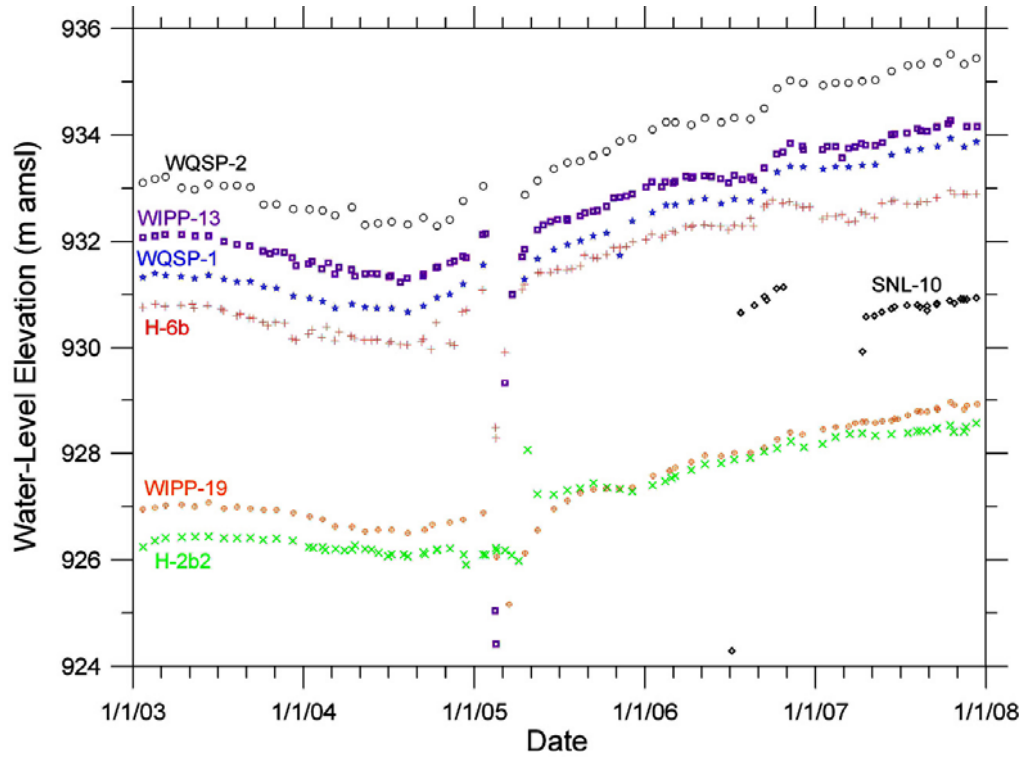

Figure HYDRO-19. Water Levels in Seven Culebra Wells in the Northern Portion of the WIPP Site

Figure HYDRO-20 and Figure HYDRO-21 show hydrographs from eight Culebra wells in the central portion of the WIPP site and six Culebra wells to the south of the WIPP site, respectively. The hydrographs from these 14 wells parallel one another, and are similar to the hydrograph for H-2b2 shown in Figure HYDRO-19. These wells did not respond to the WIPP-11 pumping test as the northern wells did, but (with the exception of WQSP-3) responded instead to the 22-day pumping test conducted at SNL-14 from August 4–26, 2005 (see Section HYDRO-6.0). Water levels in these 14 wells were generally more stable than the water levels in the northern wells, in particular showing less rise in 2006 and 2007.

Figure HYDRO-22 shows hydrographs from six Culebra wells in or near the southeastern arm of Nash Draw. With the exception of a possible rise in SNL-13, these wells show no consistent water-level trends. As described in the discussion of Figure HYDRO-14, SNL-16 responds to major rainfall events. The seemingly erratic behavior of H-9c in 2003 is ascribed to pumping of the nearby Engle stock well. Some sustained pumping appears to have occurred in that vicinity in the latter part of 2006 as well, seen most clearly in the H-9c hydrograph but also recognizable in the hydrographs from SNL-12, H-17, H-11b4, and H-4b (Figure HYDRO-21). SNL-12 and H-9c also responded to the August 2005 SNL-14 pumping test.

Figure HYDRO-23 shows hydrographs from three Culebra wells west of the WIPP site; IMC-461, SNL-9, and WIPP-25. The Culebra was not accessible for water-level measurements in WIPP-25 after January 2006 because of Magenta testing activities. The major upturns in water levels represent delayed responses to major rainfall events (see also Figure HYDRO-31 and Figure HYDRO-32 for WIPP-25). The general water-level trends are upward, but from late 2006 through 2007, water levels at IMC-461 and SNL-9 followed the pattern observed at SNL-2 and SNL-19 (Figure HYDRO-14 and Figure HYDRO-15) of rising after major storms followed by falloffs of similar magnitude.

Figure HYDRO-24 shows hydrographs from Culebra wells SNL-6 and SNL-15. These wells were drilled in areas where the Culebra contains halite cements (Powers et al. 2006a), and are recovering very slowly from well-development activities (and a March 30, 2007, slug test in SNL-15). At the rates at which these wells are recovering, water levels will not be representative of undisturbed Culebra conditions for many years. SNL-15 is on the old P-18 well pad. The Culebra water level in P-18 was monitored for 25 years (1977–2001) and rose from an elevation of approximately 741 m (2432 ft) above mean sea level (amsl) (Mercer and Orr 1979) to 964.4 m (3164 ft) amsl (Westinghouse TRU Solutions, LLC 2002) before the well was plugged and abandoned without the water level stabilizing.

Water levels are also locally affected by human activities around WIPP. For instance, water levels in well H-10c are affected by the drilling of nearby oil wells (Figure HYDRO-25). Invasion of drilling fluid as oil wells penetrate the Culebra briefly causes water levels at H-10c to rise. The water level then falls when the Rustler interval is cased and cemented. Similar responses have been observed in well H-6b (Hillesheim and Beauheim 2007). Water levels in H-5b were apparently affected by the P&A of H-5a and H-5c approximately 30 m away. The P&A activities caused the water level in H-5b to rise by nearly 2 m (6.7 ft) (Figure HYDRO-26). (Note that the subsequent sustained rise in water level is consistent with the water-level behavior observed in most other wells at the WIPP site, such as H-6b and WIPP-19 [Figure HYDRO-16], and is probably not, therefore, related to the P&A activities.) Water levels in other wells were

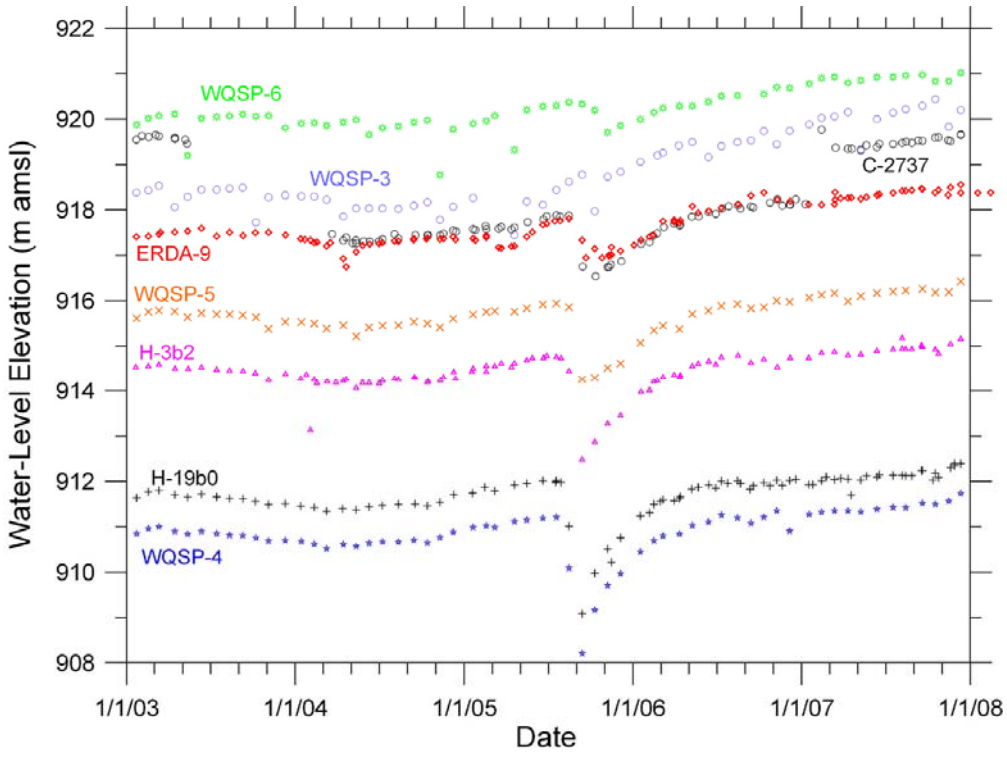

Figure HYDRO-20. Water Levels in Eight Culebra Wells in the Central WIPP Site

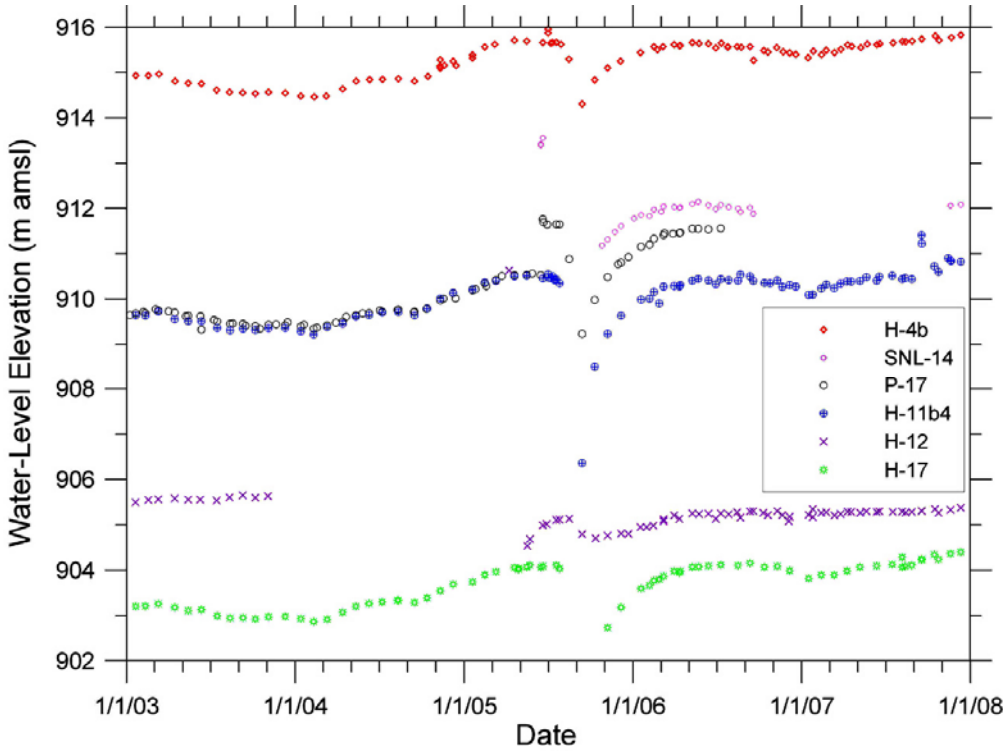

Figure HYDRO-21. Water Levels in Six Culebra Wells South of the WIPP Site

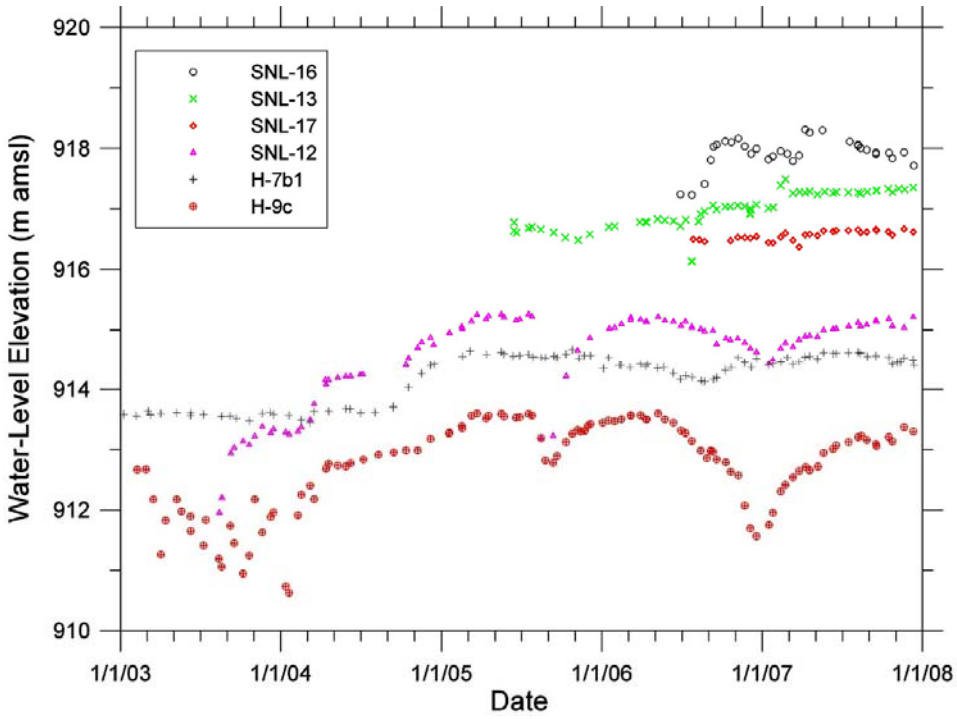

Figure HYDRO-22. Water Levels in Six Culebra Wells in and Near the Southeastern Arm of Nash Draw

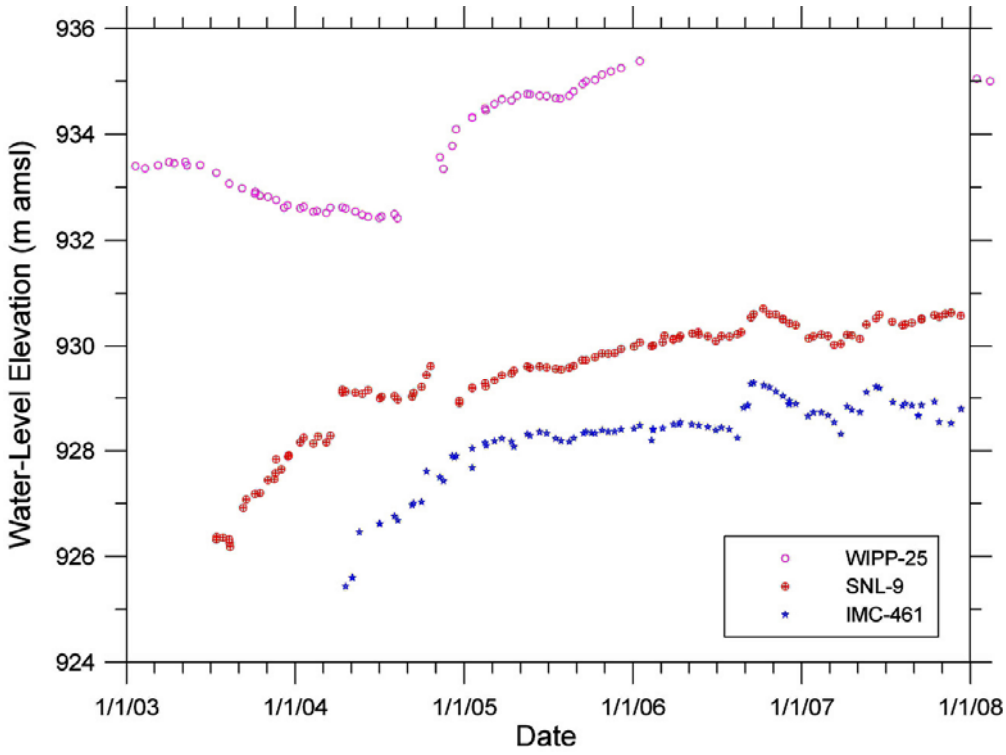

Figure HYDRO-23. Water Levels in Three Culebra Wells West of the WIPP Site

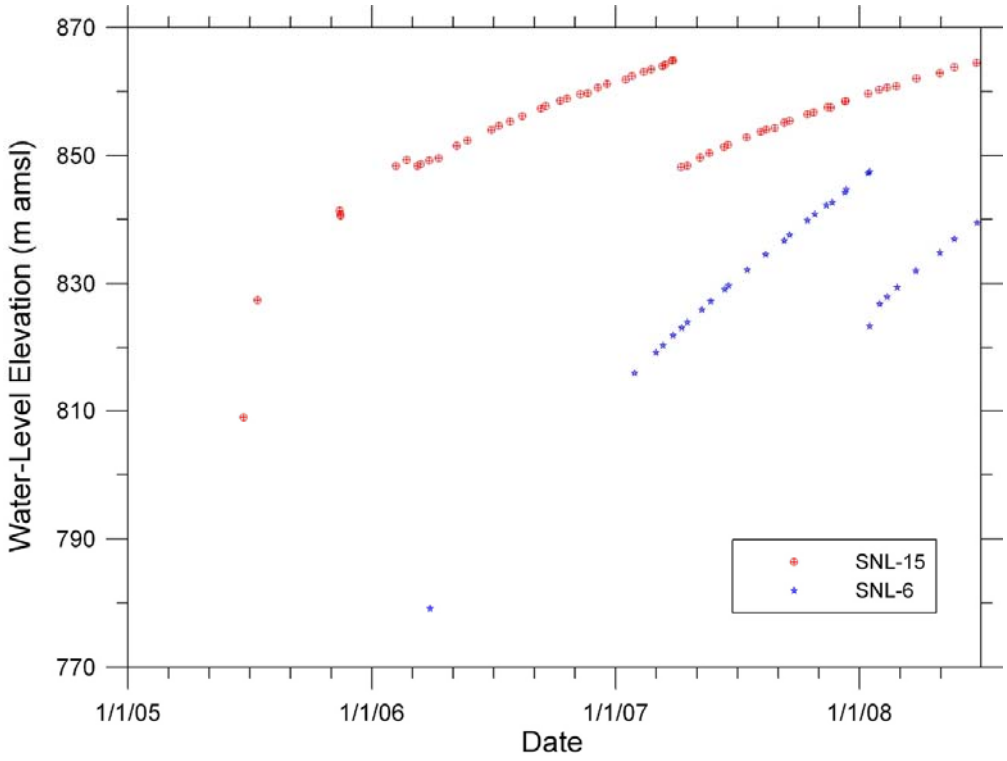

Figure HYDRO-24. Water Levels in Culebra Wells SNL-6 and SNL-15

affected by cleaning and rehabilitation activities (scraping scale from casing, removing sloughed materials from the bottom of a well, etc.).

HYDRO-5.2 Magenta Monitoring

Magenta water levels were monitored in 17 wells during some or all of the period from 2003 through 2007. The 15 wells still being monitored at the end of 2007 are shown in Figure HYDRO-10. The Magenta is no longer being monitored in DOE-2 and H-5c (see Table HYDRO-3). Water levels in most of the Magenta wells were significantly disrupted by a variety of activities at one time or another between 2003 and 2007.

Figure HYDRO-27 shows hydrographs from nine of the Magenta wells. Of these wells, H-9c was disturbed the least over the period shown, as the only activity in the well was the replacement of a bridge plug set below the Magenta with a production-injection packer (PIP) on tubing to allow simultaneous monitoring of the Magenta and Culebra in March 2003. Over the 5-yr period shown, the Magenta water level in H-9c rose by approximately 1 m (3.2 ft). C-2737 and H-15 are also dual-completion (Magenta and Culebra) wells that were disrupted by removing or replacing bridge plugs and PIPs for a variety of testing and water-quality sampling exercises. Changes in fluid density are often associated with replacement of bridge plugs and PIPs. The Magenta water level in C-2737 appeared to be rising slightly, while that in H-15 declined in 2007. A variety of activities occurred in WIPP-30 from 2003 through early 2006 preventing measurement of Magenta water levels. When monitoring resumed, water levels rose slightly until mid-2007.

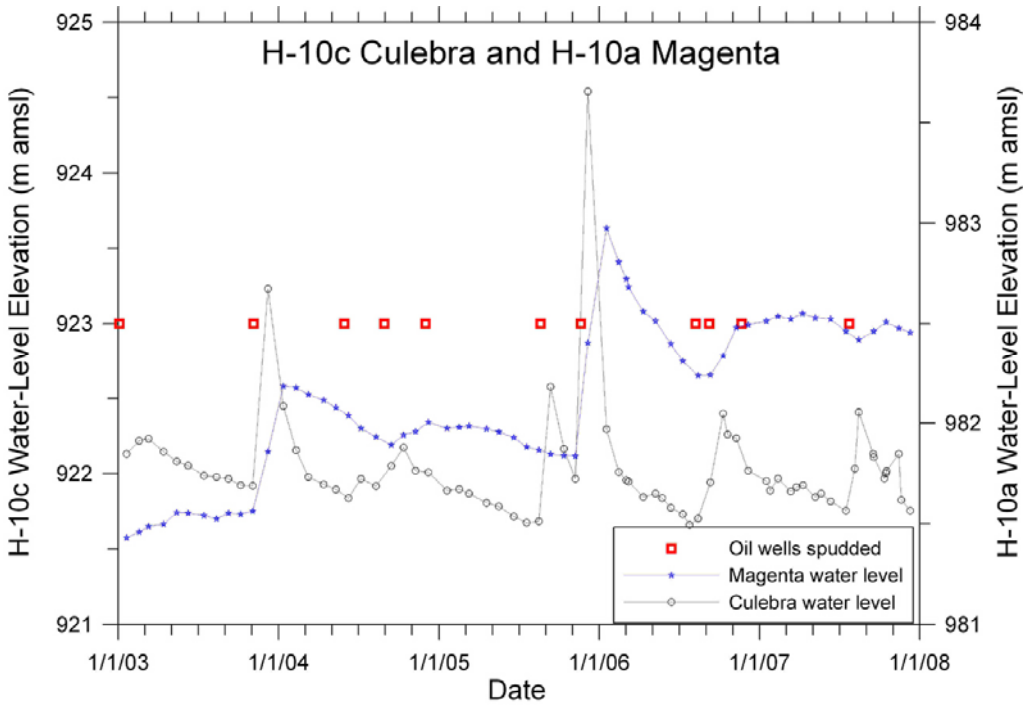

Figure HYDRO-25. H-10c Culebra and H-10a Magenta Water Levels With Spud Dates for Oil Wells Within 1.0 km

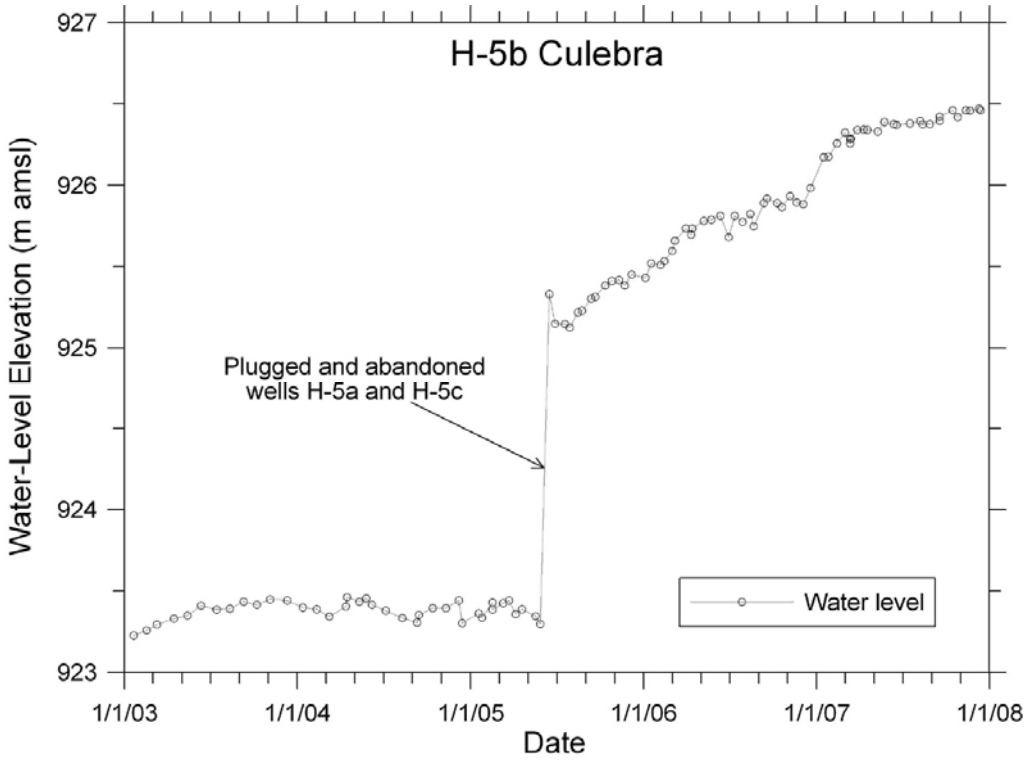

Figure HYDRO-26. H-5b Culebra Water Levels

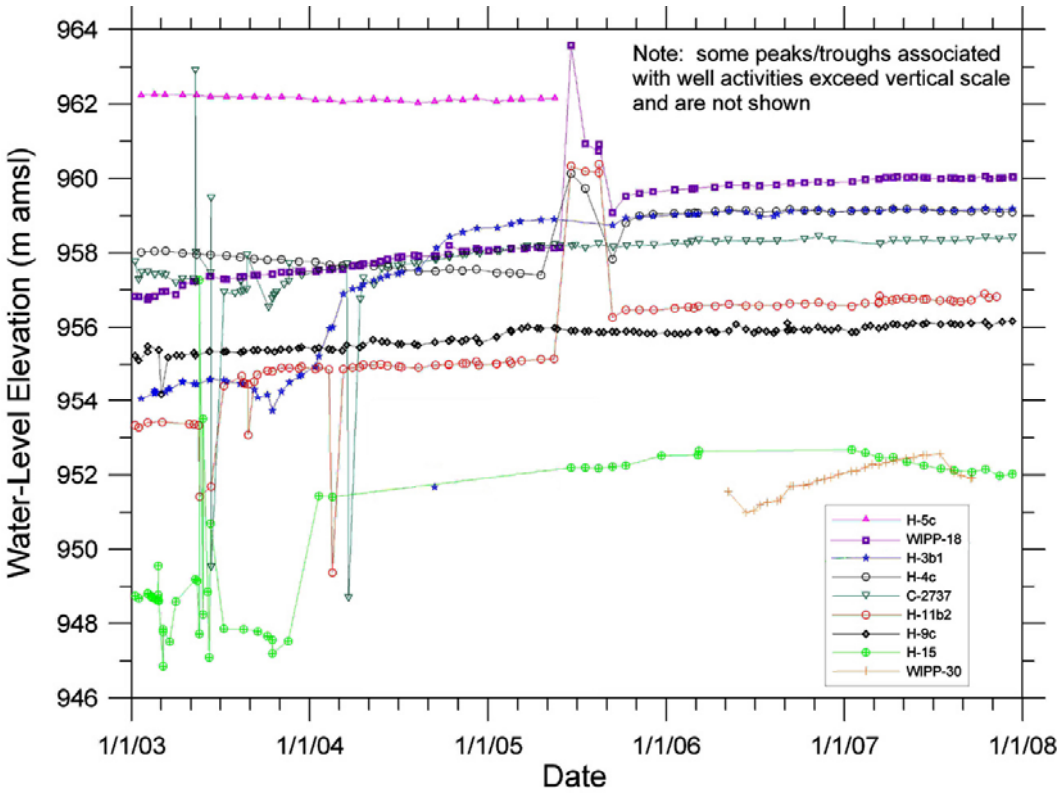

Figure HYDRO-27. Water Levels in Nine Magenta Wells

H-3b1, H-4c, H-5c, H-11b2, and WIPP-18 had similar configurations in 2003—they had all been drilled past the Magenta, were open to both the Magenta and Culebra (and also the Rustler-Salado contact in the case of H-3b1, H-4c, and H-5c), and had bridge plugs set below the Magenta to isolate the interval(s) below. In mid-2005, the bridge plugs were removed from these wells, and the lower portions of the holes were cemented up to depths 3.7 to 8.5 m (12 to 28 ft) below the Magenta (Salness 2006). (In the case of H-5c, the entire Magenta interval of the well was also cemented by mistake, ending its usefulness as a monitoring well.) The cementing operations displaced the water in the wells to higher levels. This caused water to enter the Magenta thereby dissipating the excess head. Several months later, before pressure equilibration was reached, the wells were bailed to remove the cement-contaminated water, and water flowed back out of the Magenta to reestablish equilibrium. For H-4c, H-11b2, and WIPP-18, the water flowing into the well had a lower specific gravity than the water that had been in the well previously, causing the water level to stabilize at a higher elevation. All four of the plugged-back wells showed slight increases in Magenta water levels in 2006 and 2007.

Figure HYDRO-28 shows hydrographs of Magenta water levels in H-2b1, H-14, and H-18. These wells were plugged back and then bailed in a similar fashion to the five wells discussed above (Salness 2006). In H-2b1 and H-14, the recovery from bailing took over a year to complete, reflecting the low-T of the Magenta. The postplugback water-level behavior in H-18 was quite different from the preplugback behavior. Postplugback, the water level quickly reached a level ~16 m (53 ft) higher than it was preplugback, and then continued to rise steadily through 2006 and 2007. A 16-m (53 ft) change in water levels cannot be explained by a change in the specific gravity of the water in the well. The most likely explanation for the change is that

the inflatable bridge plug set in the well in 2001 to isolate the Culebra from the Magenta was leaking, allowing Magenta head to bleed into the Culebra. Magenta water levels from 2001 through 2004 were within 6 m (20 ft) of the last water level measured in the Culebra in 2001, an unusually small difference between Magenta and Culebra water levels. The difference between the Magenta water levels observed since the Culebra portion of the hole was plugged with cement and the 2001 Culebra water level is much more consistent with the differences typically observed at locations such as the H-2 hydropad or WIPP-18. Hence, water levels representative of the Magenta at H-18 may only now be measured.

Figure HYDRO-29 shows Magenta water levels in DOE-2, H-6c, H-8a, and WIPP-25. The period of record in DOE-2 is short, and shows only a rising trend. Water levels in H-6c show a steady rising trend, little affected by the plugback and subsequent bailing that occurred in 2005. The Magenta water level in H-8a was stable for the entire period shown. Measurement of Magenta water levels in WIPP-25 was repeatedly interrupted by various activities in the well. Water levels rose steadily through 2005, the longest continuous period of measurement.

Magenta water levels measured in well H-10a are shown in Figure HYDRO-25. Water levels clearly increased in response to drilling of nearby oil and gas wells.

TROLL® downhole pressure gauges were installed in 13 of the Magenta wells during the periods shown in Figure HYDRO-30. The TROLL® data are consistent with the water-level measurements made in those wells. The TROLL® data provide a more complete record of pumping, water-quality sampling, and other activities in the wells than the water-level data alone.

In WIPP-25, the TROLL® data also show that the Magenta there responds to some major rainfall events. Figure HYDRO-31 and Figure HYDRO-32 show the TROLL® records from both the Magenta and Culebra in WIPP-25 from October 2004 through January 2006 and March 2006 through January 2007, respectively, along with daily rainfall measured at the WIPP and at the SNL-9 pad (Figure HYDRO-32 only). (Note that the pressures measured are relative to the TROLL® positions and do not imply anything about the hydraulic gradient between the Culebra and Magenta.) Whereas the Culebra clearly responded to the rainfall events in November 2004 (which occurred when the Culebra was being drawn down by the 32-day pumping test at SNL-9; see Section HYDRO-6.0) and August 2005 (Figure HYDRO-31), the Magenta showed only delayed increases in the rate of pressure rise. The Magenta pressure clearly responded, however, to the rainfall events that occurred in mid-August 2006 and the first four days of September 2006, as did the Culebra pressure (Figure HYDRO-32). Neither zone, however, appears to have responded to the storm on June 1, 2006, and the Magenta appears to have responded little if at all to the series of rainfall events beginning on October 9, 2006, and to the rainfall on July 31, 2006. This may indicate that less rain fell near WIPP-25 than at the measurement locations. No other TROLL® data from Magenta wells indicate a response to rainfall.

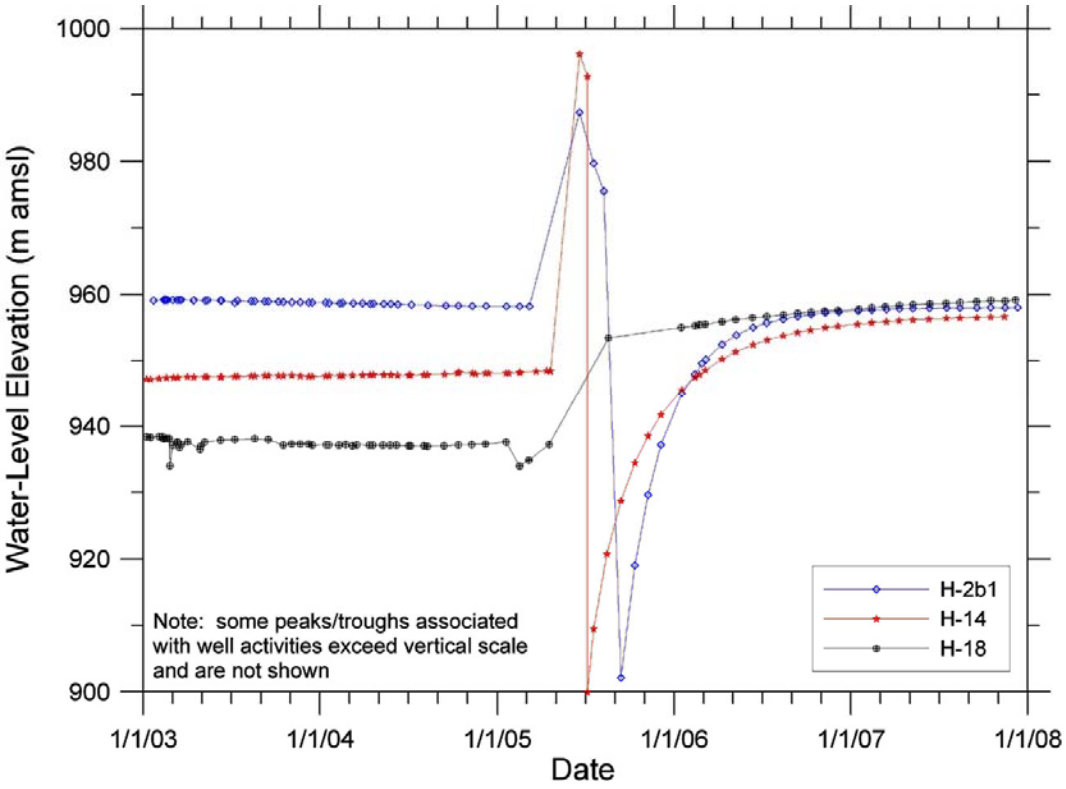

Figure HYDRO-28. Magenta Water Levels in Wells H-2b1, H-14, and H-18

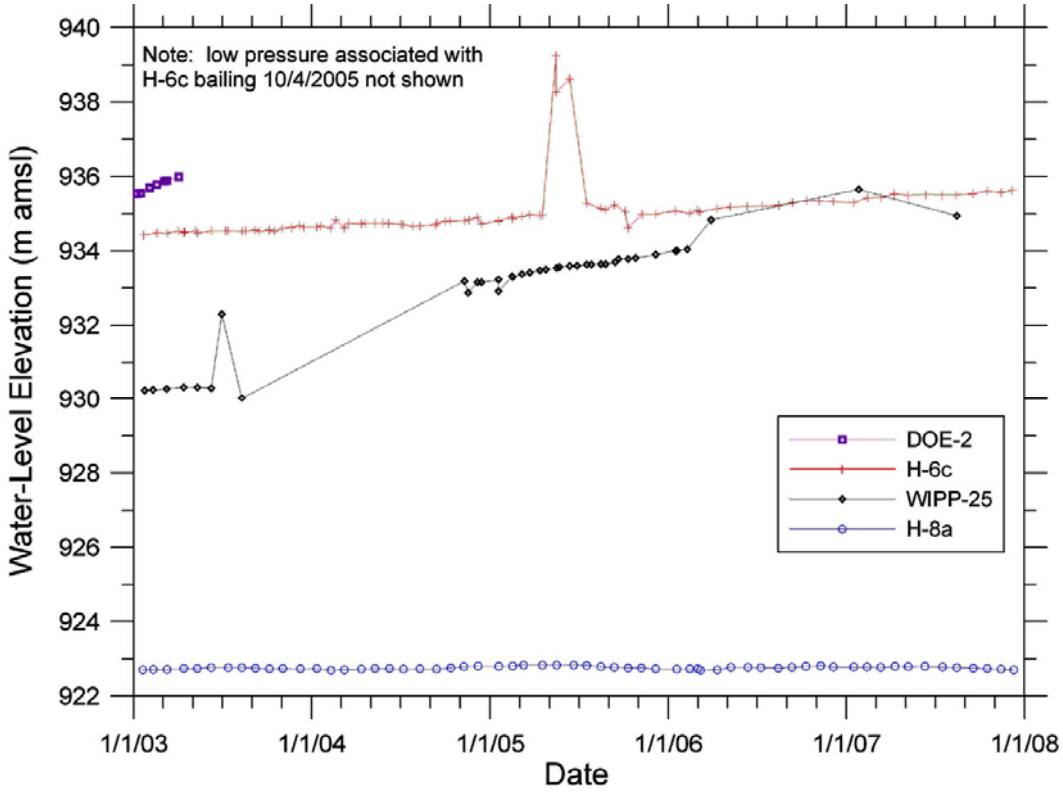

Figure HYDRO-29. Magenta Water Levels in Wells DOE-2, H-6c, H-8a, and WIPP-25

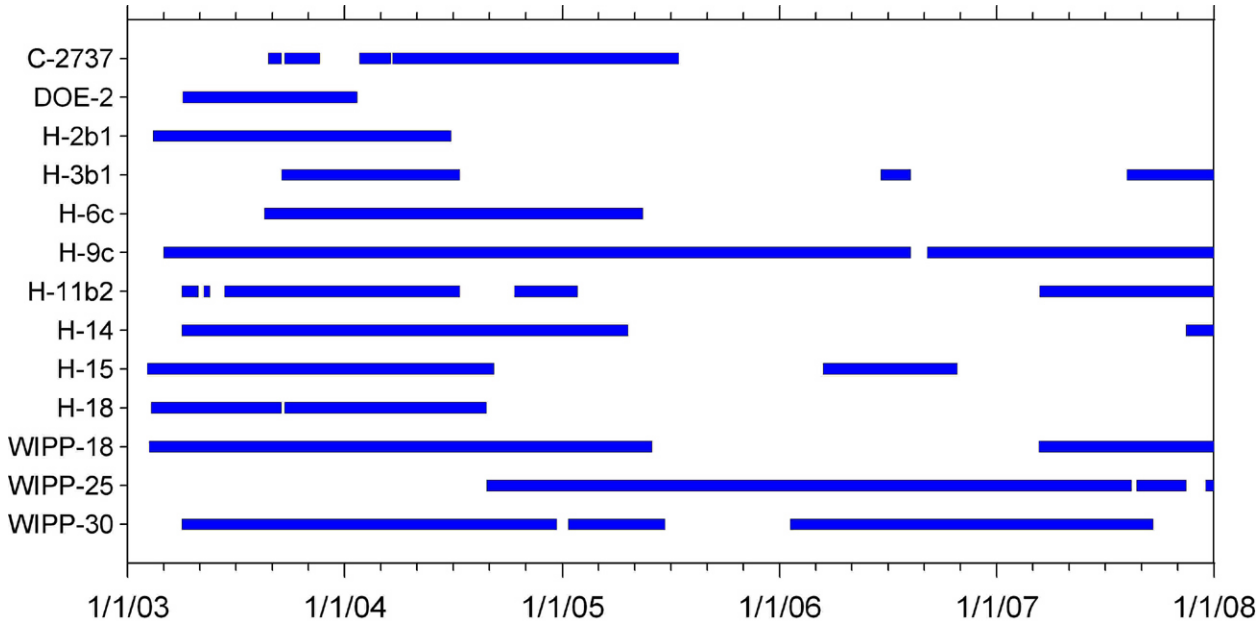

Figure HYDRO-30. Time Periods During Which Magenta Wells Have Been Monitored Using TROLL® Gauges

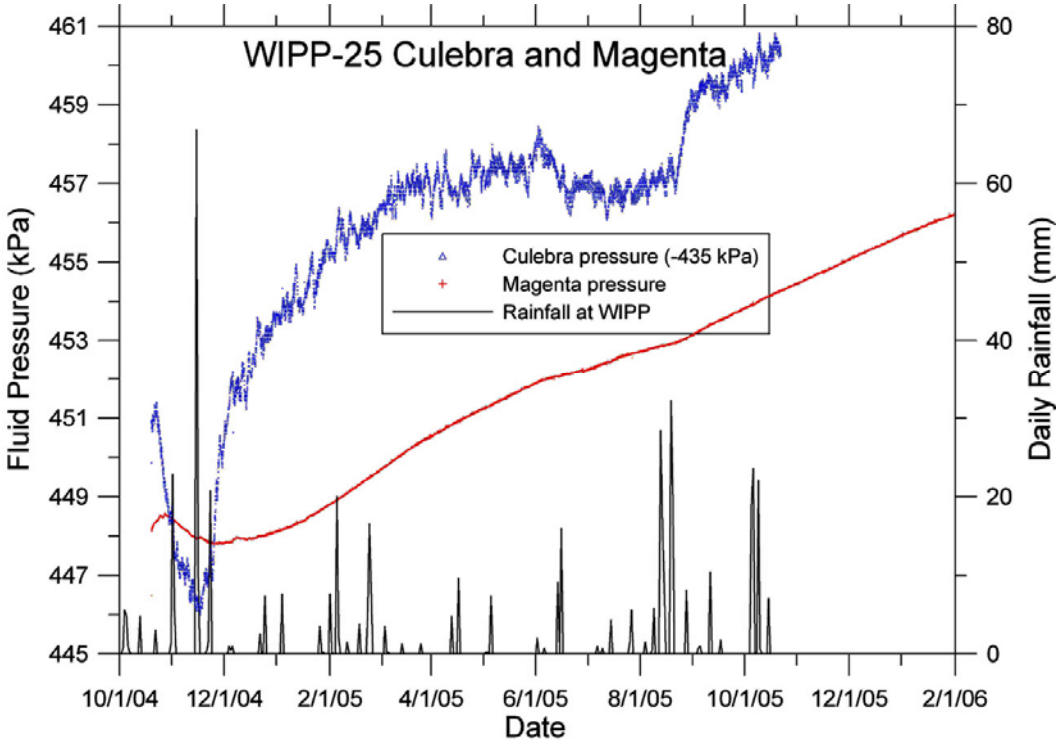

Figure HYDRO-31. WIPP-25 Culebra and Magenta Fluid Pressures from October 2004 Through January 2006 with Daily Rainfall Measured at the WIPP

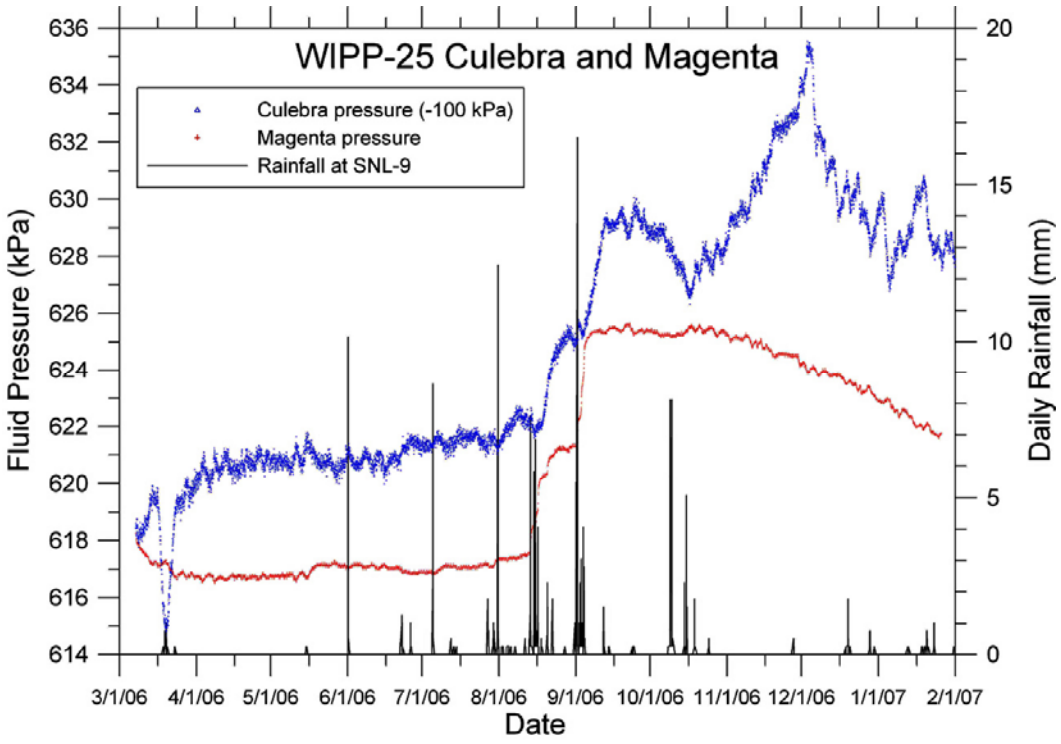

Figure HYDRO-32. WIPP-25 Culebra and Magenta Fluid Pressures from March 2006 Through January 2007 with Daily Rainfall Measured at SNL-9

HYDRO-5.3 Dewey Lake Monitoring

The DOE monitors Dewey Lake water levels in only one well, WQSP-6A (Figure HYDRO-10). Figure HYDRO-33 is a hydrograph of Dewey Lake water levels in WQSP-6A from 2003 through 2007. The hydrograph shows that water levels were stable within an approximately 20-centimeter (cm) (8-in.) band over that period, with perhaps a slight downward trend. Note that some of the fluctuations in the water levels are probably related to the water-quality sampling performed in the well twice a year (e.g., U.S. Department of Energy 2007).

HYDRO-5.4 Bell Canyon Monitoring

Bell Canyon monitoring wells are situated at the northern (DOE-2) and southern (Cabin Baby [CB]-1) WIPP site boundaries (see Figure HYDRO-10). The primary purpose of this monitoring is to determine if oil production, secondary recovery, and/or brine-disposal activities in the Bell Canyon are affecting the hydraulic head of the Bell Canyon at the WIPP site. Bell Canyon water levels had been monitored in DOE-2 between August 1985 and March 1986 through tubing attached to a PIP set at the base of the Castile Formation (Beauheim 1986) before the well was recompleted as a Culebra monitoring well. After swabbing ~22 m^3 (775 ft^3) of brine from the tubing to develop the open Bell Canyon interval, the Bell Canyon fluid specific gravity was approximately 1.1 and the water level stabilized at approximately 925 m (3033 ft) amsl. DOE-2 was converted to a single-completion Bell Canyon well in February and March 2004 (Salness 2005b), and water-level monitoring began in July 2004. Figure HYDRO-34 shows the water-

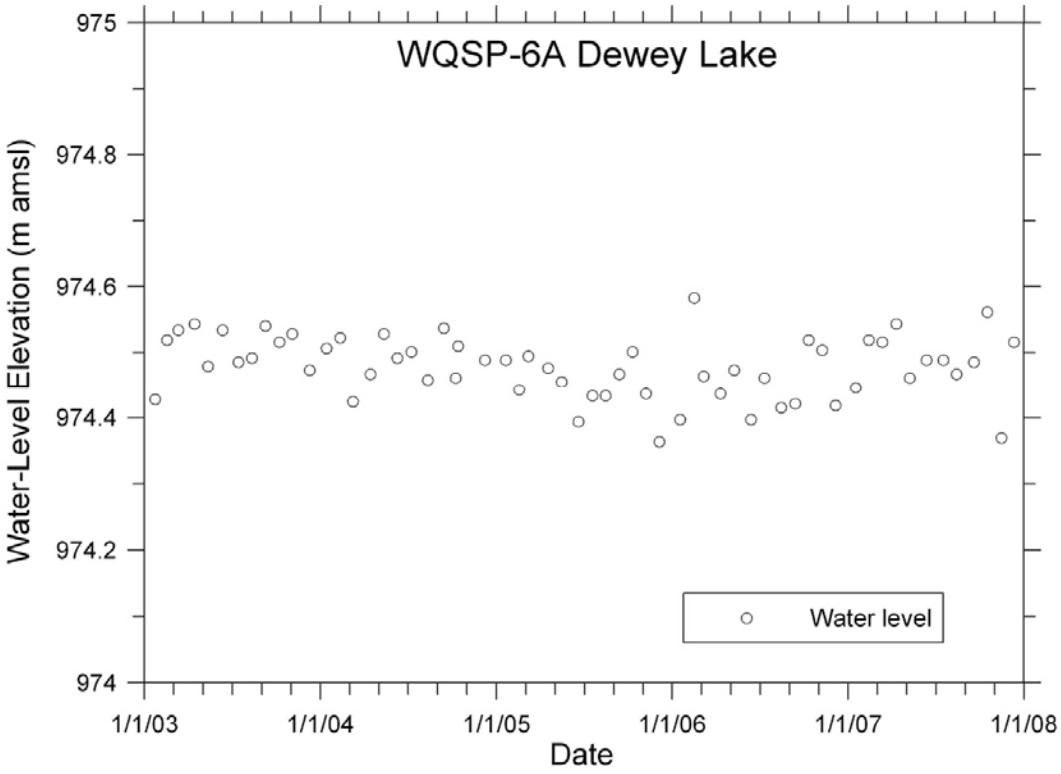

Figure HYDRO-33. WQSP-6A Dewey Lake Water Levels

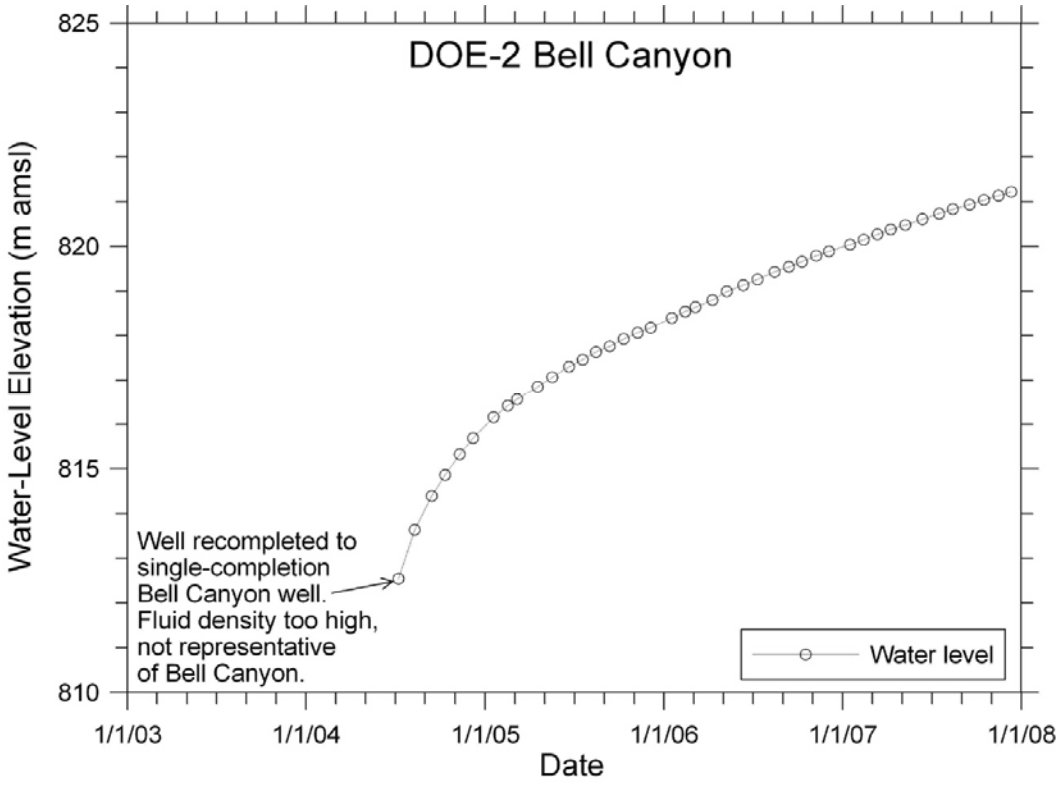

Figure HYDRO-34. DOE-2 Bell Canyon Water Levels

level data collected since that time. Although some of the water left in the well after recompletion was removed by bailing, the remaining water in the well was drilling brine having a specific gravity of approximately 1.2. Consequently, the water levels shown in Figure HYDRO-34 are not comparable to those measured between 1985–1986. Fluid-density issues notwithstanding, the Bell Canyon water level is steadily rising. Whether this is caused by gradual dilution of the heavy brine in the bottom of the hole by flowing groundwater or by some other factor cannot be determined until all of the water in the well is more nearly representative of Bell Canyon fluid. DOE-2 will be developed in 2008 to establish a specific gravity and water levels more representative of the Bell Canyon.

CB-1 was temporarily completed to the Bell Canyon shortly after drilling in September 1983 by setting a PIP on tubing in the lower anhydrite of the Castile Formation. After swabbing 16.8 m^3 (595 ft^3) of brine from the tubing to develop the open Bell Canyon interval, the Bell Canyon fluid-specific gravity was approximately 1.128 (Beauheim, Hassinger, and Klaiber 1983). Bell Canyon water levels were monitored in CB-1 through September 1986, and the water level stabilized at ~920 m (3020 ft) amsl (Intera Technologies, Inc. 1986). Monitoring of the Bell Canyon was suspended in late 1986 when CB-1 was converted to a Culebra monitoring well. In August 1999, a double-packer assembly was installed in the well to allow simultaneous monitoring of the Bell Canyon and Culebra (Beauheim 1999). After swabbing ~22 m^3 (775 ft^3) of fluid from the tubing connected to the Bell Canyon, the specific gravity stabilized at 1.126 and the water level subsequently stabilized at ~919 m (3015 ft) amsl. In January and February of 2004, CB-1 was reconfigured as a single-completion Bell Canyon monitoring well (Salness 2005a). As at DOE-2, some of the water left in the well after recompletion was removed by bailing, but the remaining water in the well was drilling brine with a specific gravity of approximately 1.2. Consequently, the water levels measured since that time are not comparable to those measured previously (Figure HYDRO-35). Like DOE-2, the Bell Canyon water level in CB-1 is steadily rising, albeit more slowly. Whether this is caused by gradual dilution of the heavy brine in the bottom of the hole by flowing groundwater or by some other factor cannot be determined until all of the water in the well is more nearly representative of Bell Canyon fluid. CB-1 will be developed in 2008 to establish a specific gravity and water levels more representative of the Bell Canyon.

HYDRO-5.5 Monitoring Summary

Water-level monitoring provides a general picture of the changes in hydraulic head occurring in the formations being monitored. Water levels are currently being monitored in the Culebra, Magenta, Dewey Lake, and Bell Canyon. From 2003 through 2007, Culebra water levels generally rose by 1 to 3 m (3 to 10 ft), with most of the rise occurring between late 2004 and the end of 2007. Water levels rose more in Nash Draw and north of the WIPP site than they did elsewhere. Water levels in most Magenta wells generally rose over the same period, although only by ~1 m (3 ft) or less. The Dewey Lake water level (measured only in well WQSP-6A) was stable within a ~20-cm (8-in.) band over the 5-yr period. Bell Canyon water levels rose steadily as a recovery response to well recompletion, and were well below historic levels because the water left in the wells after recompletion was much denser than the native Bell Canyon water.

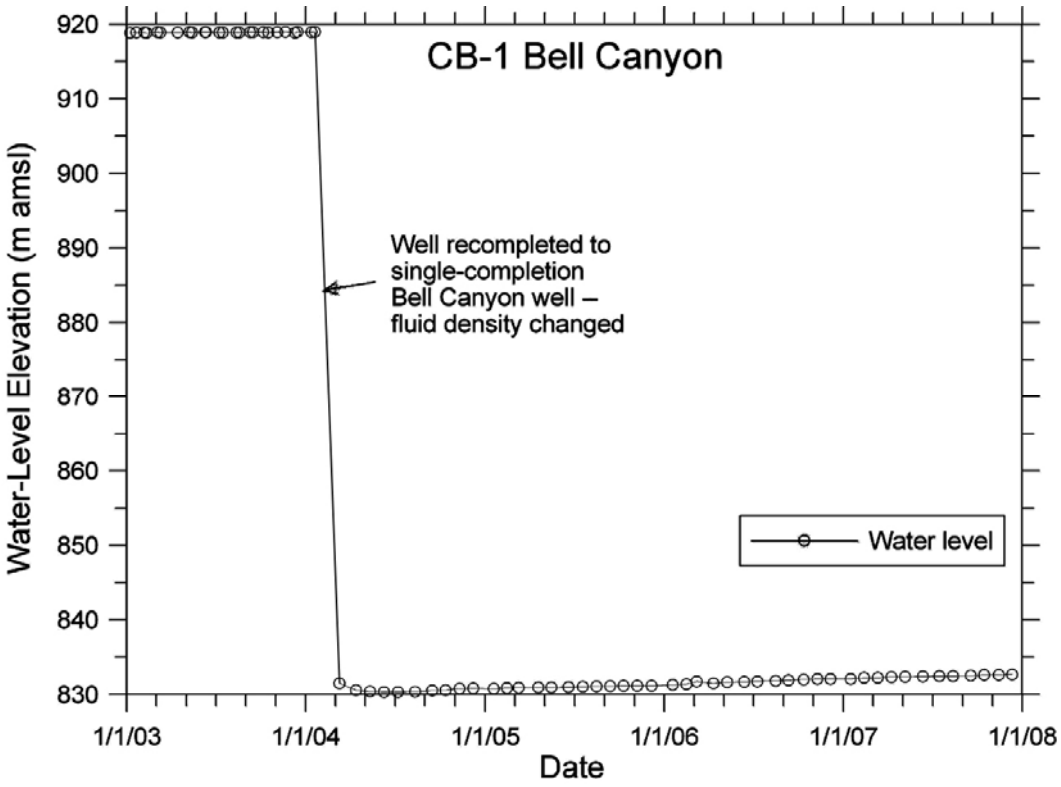

Figure HYDRO-35. CB-1 Bell Canyon Water Levels

In addition to monitoring water levels, fluid pressures in most Culebra and Magenta wells were monitored on an hourly basis using TROLL® gauges. These continuous fluid-pressure measurements provide a clearer, more complete record of the changes in hydraulic head occurring in the wells than that provided monthly water-level measurements. When coupled with rainfall data, the TROLL® data show that wells in and on the edge of Nash Draw respond to rainfall events of ~10 mm (0.4 in.) or more in 24 hr. Wells more distant from Nash Draw show smaller responses delayed by days to months for rainfall events of several cm, reflecting pressure propagation from Nash Draw to the east.

HYDRO-6.0 Hydraulic Testing

Hydraulic testing provides data to generate Culebra T fields for performance assessment (PA). Between the September 2002 data-cutoff date for the CRA-2004 and January 2008, hydraulic testing was performed in 20 Culebra wells. The wells tested, the types of tests performed, the dates of the tests, and the pumping rates during pumping tests are summarized in Table HYDRO-4. The testing was performed under *TP 03-01, Test Plan for Testing of Wells at the WIPP Site* (Chace and Beauheim 2006) and is documented in Johnson (2008).

Table HYDRO-4. Hydraulic Testing in Culebra Wells from December 2003 through January 2008

Well	Test Type	Test Date(s)	Pumping Rate (L/s)	Transmissivity (m^2/s)
C-2737	Pumping	3/4-5/2004	0.019	6.6×10^{-7}
IMC-461	Slug	1/25-26/2005	Not applicable	1.9×10^{-4}
SNL-1	Pumping	5/25-29/2004	0.69	Not calculated
	Pumping	3/7-10/2005	2.2	6.2×10^{-4}
SNL-2	Pumping	1/13-17/2004	0.047	Not calculated
	Pumping	1/20-24/2005	0.76	1.1×10^{-4}
SNL-3	Pumping	4/14-16/2004	0.63	9.9×10^{-4}
SNL-5	Pumping	7/20-24/2004	0.22	4.9×10^{-6}
SNL-6	Slug	1/16/2008	Not applicable	8.7×10^{-12}
SNL-8	Slug	12/14/2006	Not applicable	2.4×10^{-7}
SNL-9	Pumping	12/2-6/2003	0.79	3.9×10^{-5}
	Pumping	10/22-11/23/2004	1.0	Not calculated
SNL-10	Pumping	10/30-11/3/2006	0.016	3.3×10^{-7}
SNL-12	Pumping	8/10-14/2004	1.3	5.0×10^{-4}
SNL-13	Pumping	7/17/2006	Variable	3.8×10^{-7}
SNL-14	Pumping	8/4-26/2005	1.9	4.9×10^{-5}
SNL-15	Slug	3/30/2007	NA	1.4×10^{-13}
SNL-16	Pumping	6/5-9/2006	1.6	1.3×10^{-3}
SNL-17A	Pumping	9/11-15/2006	2.0	3.4×10^{-4}
SNL-18	Pumping	8/14-18/2006	1.9	1.4×10^{-4}
SNL-19	Pumping	7/24-28/2006	1.9	4.3×10^{-4}
WIPP-11	Pumping	2/1-20/2005	2.2	4.3×10^{-4}
WIPP-25	Pumping	9/22/2004	1.9	2.5×10^{-4}

The initial attempts at pumping SNL-1, SNL-2, and WIPP-11 revealed that the wells were poorly connected to the Culebra. Subsequently, the wells were acidized to improve the connections. SNL-1 was acidized on March 3, 2005, by injecting 7.6 m^3 (270 ft^3) of a 15% hydrochloric (HCl) acid solution followed by 7.6 m^3 (270 ft^3) of fresh water into the well. SNL-2 was acidized in a

similar fashion on January 19, 2005. WIPP-11 was acidized on January 5, 2005, by injecting 6.8 m^3 (241 ft^3) of a 15% HCl acid solution charged with liquid nitrogen followed by 9.2 m^3 (326 ft^3) of fresh water into the well. All three wells could sustain much higher pumping rates after acidization.

The Culebra hydraulic-test data have been analyzed by Roberts (2006 and 2007) and Bowman and Roberts (2009) under *AP-070, Analysis Plan for Non-Salado Hydraulic-Test Interpretations* (Beauheim 2004a) using techniques described in Beauheim and Roberts (2004). The transmissivity values inferred by Roberts (2006 and 2007) and Bowman and Roberts (2009) from the tests are also listed in Table HYDRO-4.

HYDRO-6.1 Qualitative Analysis of Diagnostic Plots

In addition to the quantitative information on transmissivity obtained from the Culebra pumping tests, qualitative information on Culebra heterogeneity can also be inferred. A log-log plot of pressure change and the derivative of the pressure change with respect to log time during a pumping or recovery period is the standard "diagnostic" plot used by the petroleum industry to develop a conceptual model of the formation being tested (Bourdet, Ayoub, and Pirard 1989). At early time, both the pressure change and pressure derivative curves have a unit slope (Figure HYDRO-36), indicating that water is coming predominantly from storage in the wellbore rather than the formation. The duration of this wellbore-storage period is increased if the formation is poorly connected to the well, as can result from drilling mud buildup on the wall of the hole or mud invasion of the formation (referred to as a positive "skin"). If the formation is directly connected to the well by open fractures, very little wellbore storage may be observed and the well may have a negative skin. A minimum observed in the derivative after the wellbore-storage period is indicative of double-porosity (fractured) conditions, with the amplitude of the minimum increasing if flow between the fractures and rock matrix is inhibited by mineralization or some other coating on the fracture surface. In a homogeneous, isotropic system (whether single or double porosity), flow to a pumping well is radial and the pressure derivative takes on a constant value at late time, forming a horizontal line on the diagnostic plot. A decline in the derivative at late time indicates that transmissivity is increasing with distance from the pumping well or that some higher-T region (in the extreme, a constant-pressure boundary) has been encountered by the expanding pressure transient from the test. A rise in the derivative indicates that transmissivity is decreasing or that flow is being constrained by a lower-T region (in the extreme, a no-flow boundary). Referring to these basic characteristics of the pressure derivative on a diagnostic plot, information on Culebra heterogeneity can be inferred from the diagnostic plot of each pumping test.

Figure HYDRO-37 shows the diagnostic plot of the pressure recovery following the C-2737 pumping test. Wellbore storage and single-porosity, radial flow are readily apparent in the derivative. Note that the late-time derivative is erratic because the signal-to-noise ratio decreases as the rate of pressure change decreases. The diagnostic plot shows that the transmissivity of the Culebra varies little within the area interrogated by the 10.4-hr pumping test. Similar uniform transmissivity conditions were found from the SNL-9, SNL-10, SNL-13, SNL-16, and WIPP-25 pumping tests, with SNL-9 and SNL-16 also providing clear indications of double-porosity conditions (Roberts 2006 and 2007).

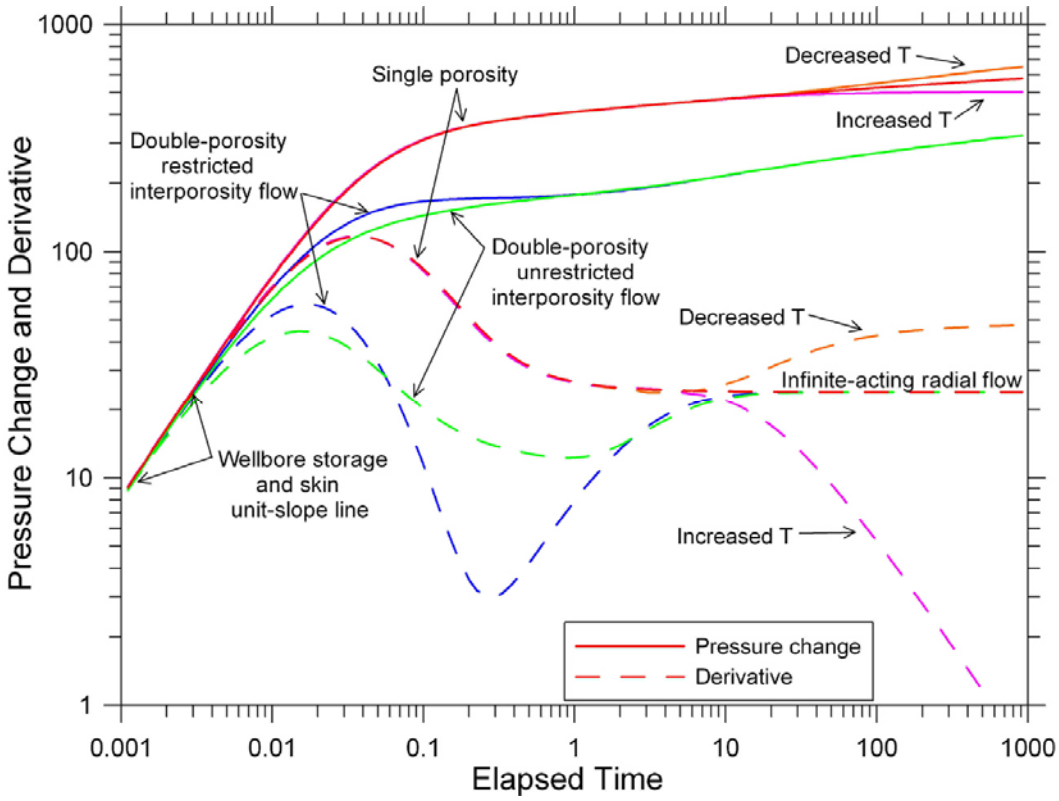

Figure HYDRO-36. Log-Log Diagnostic Plot Showing Different Aquifer Conditions

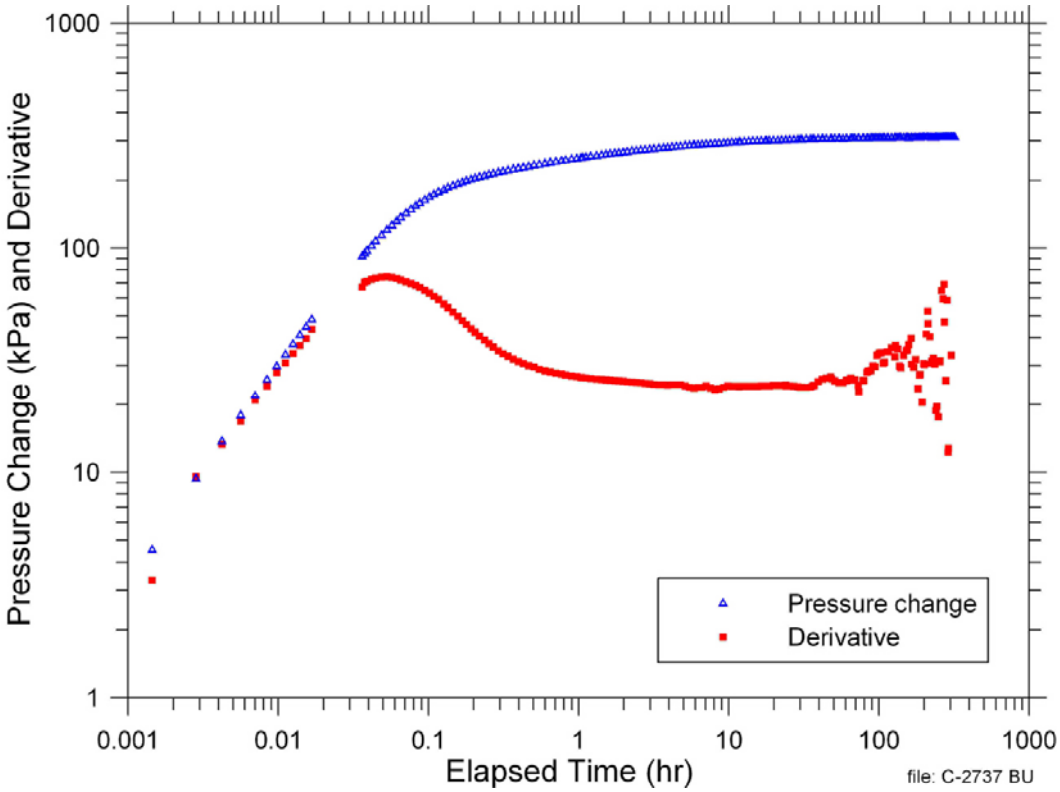

Figure HYDRO-37. Log-Log Diagnostic Plot of C-2737 Recovery

Figure HYDRO-38 shows the diagnostic plot from the pressure recovery following the SNL-3 pumping test. The SNL-3 response shows much more wellbore storage and (positive) skin effect than the C-2737 response shown in Figure HYDRO-37. The minimum in the derivative may reflect either double porosity or simply a highly positive skin. In either case, the minimum is not followed by a stabilized derivative representing radial flow through a region of uniform transmissivity. Instead, the derivative steadily climbs, which reflects either decreasing transmissivity or channelization of flow through a quasi-linear region with higher T than the surrounding rock. Similar, steadily rising late-time derivatives were observed in the tests of SNL-1 and SNL-12 (Roberts 2006). The SNL-12 diagnostic plot also showed apparent double-porosity effects.

The log-log diagnostic plot of the recovery from the WIPP-11 pumping test (Figure HYDRO-39) shows a more complicated pattern of heterogeneity. After a brief period of wellbore storage, the derivative appears to stabilize for nearly one log cycle of time, then rises for another log cycle, stabilizes (or drops slightly) for another log cycle, and then begins a final sustained rise. This pattern could indicate a series of rings around WIPP-11 with progressively lower T or, more likely, regions of lower T encountered at different distances in different directions. A similar derivative was seen in the diagnostic plot for the SNL-14 pumping test with the addition of apparent double-porosity effects (Roberts 2006).

The log-log diagnostic plot of the recovery from the SNL-5 pumping test (Figure HYDRO-40) shows yet another type of heterogeneity. After the wellbore storage and skin period, the derivative hints at a radial-flow stabilization at ~2-3 hr elapsed time, but then begins a steady decline. This decline indicates that the transmissivity of the Culebra increases with distance from SNL-5. Similar late-time declines were observed in the pressure derivatives from the tests at SNL-2, SNL-18, and SNL-19 (Roberts 2006 and 2007). The SNL-18 diagnostic plot also showed apparent double-porosity effects.

The log-log diagnostic plot of the recovery from the SNL-17A pumping test (Figure HYDRO-41) provides a final example of the heterogeneity observed in Culebra testing. After a brief wellbore-storage period, the derivative displays a double-porosity minimum, rises and begins to stabilize, then rises again before rolling over into a sustained decline. This behavior is indicative of a double-porosity system with homogeneous properties in the near-well region and then lower T at some distance in one direction followed by much higher T in another direction.

HYDRO-6.2 Distribution of Transmissivity and Correlation with Depth

The changes in transmissivity implied by the Culebra pumping test diagnostic plots are consistent with knowledge of the Culebra transmissivity distribution. Figure HYDRO-42 shows the $\log_{10}$ transmissivity (m^2/s) values for all of the Culebra wells around the WIPP site. Those wells at which the Culebra was observed to be fractured and/or where double-porosity hydraulic responses were observed are shown as red dots, while those wells at which few (or no) open fractures were observed and only single-porosity hydraulic responses were observed are shown as blue stars. C-2737 is seen to be at the southern end of an area with $\log_{10}$ transmissivity values between -7 and -6. The effects of the short (10.4-hr), low-rate (0.019 liters per second [L/s] [0.3 gallons per minute (gpm)]) pumping test conducted at C-2737 appear to have been confined

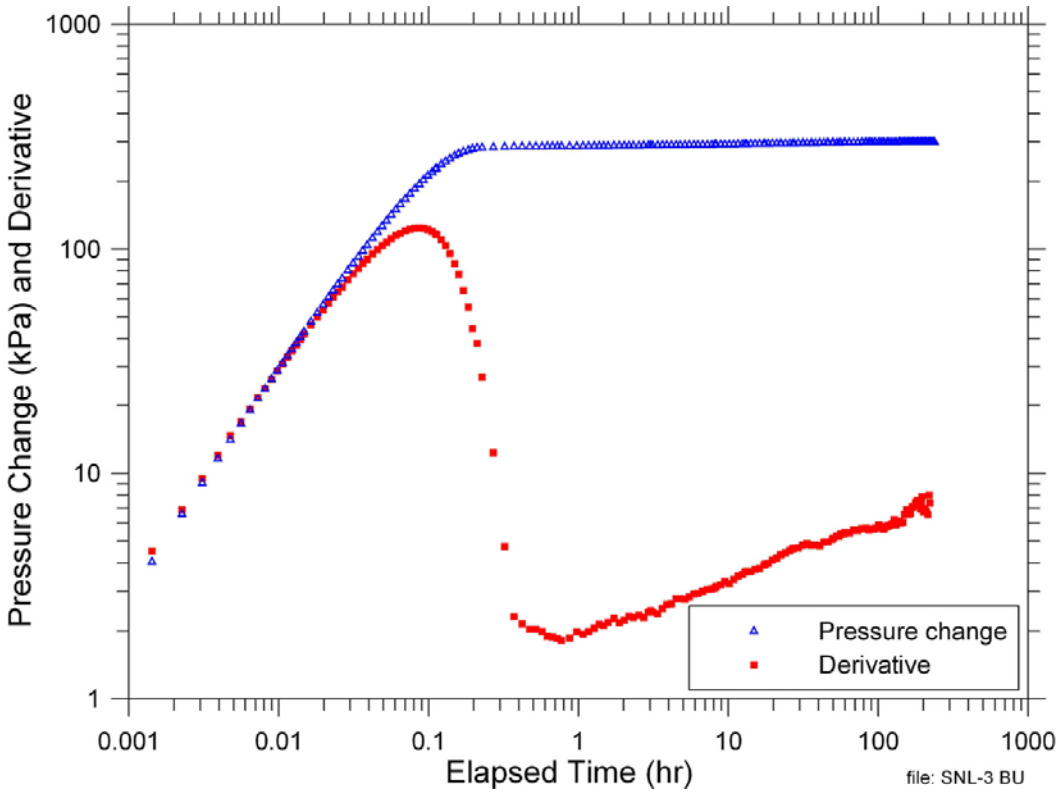

Figure HYDRO-38. Log-Log Diagnostic Plot of SNL-3 Recovery

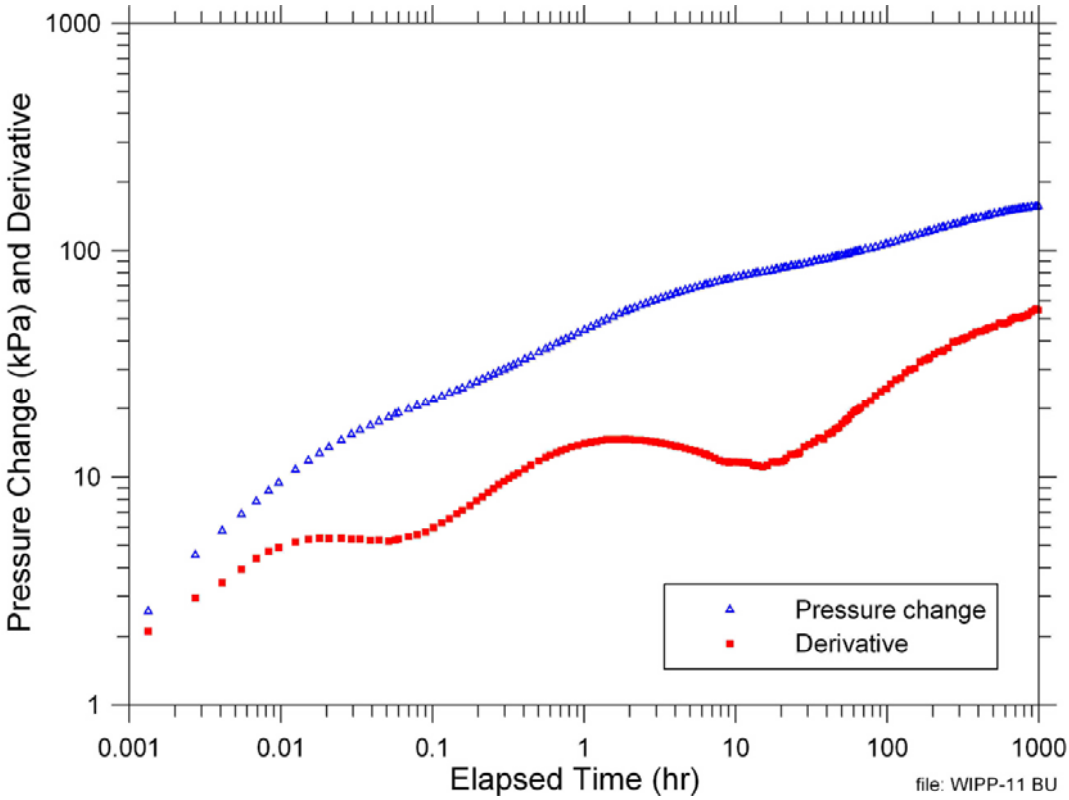

Figure HYDRO-39. Log-Log Diagnostic Plot of WIPP-11 Recovery

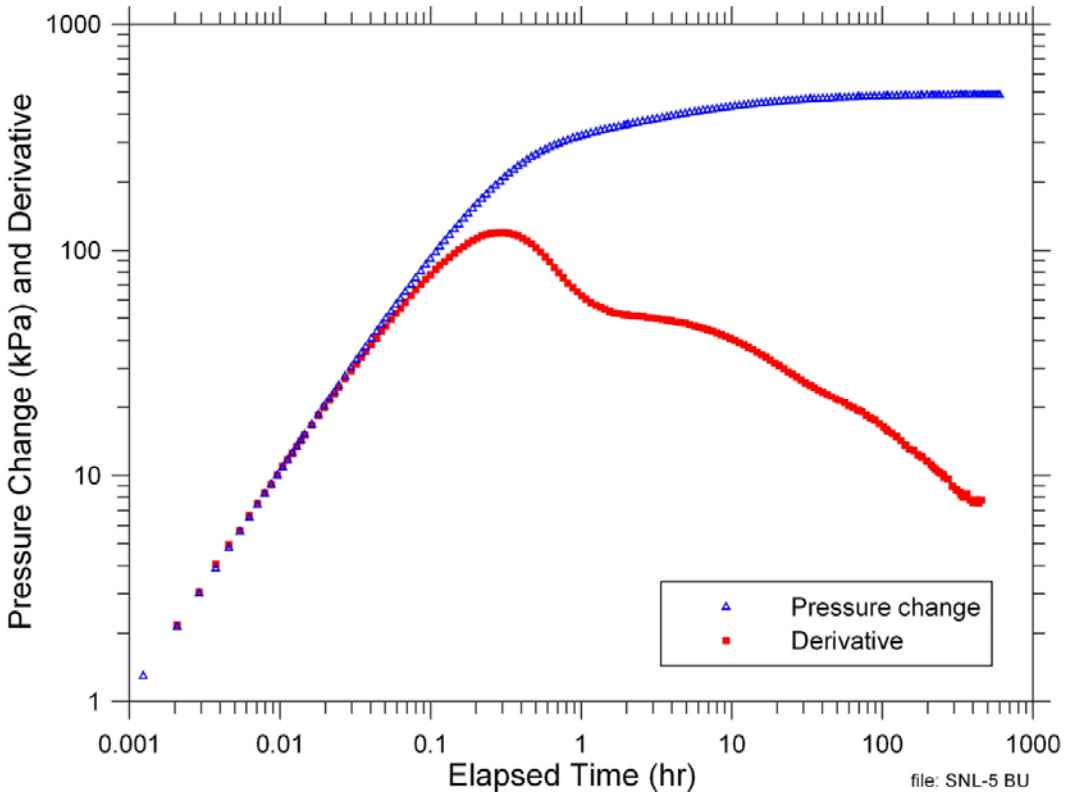

Figure HYDRO-40. Log-Log Diagnostic Plot of SNL-5 Recovery

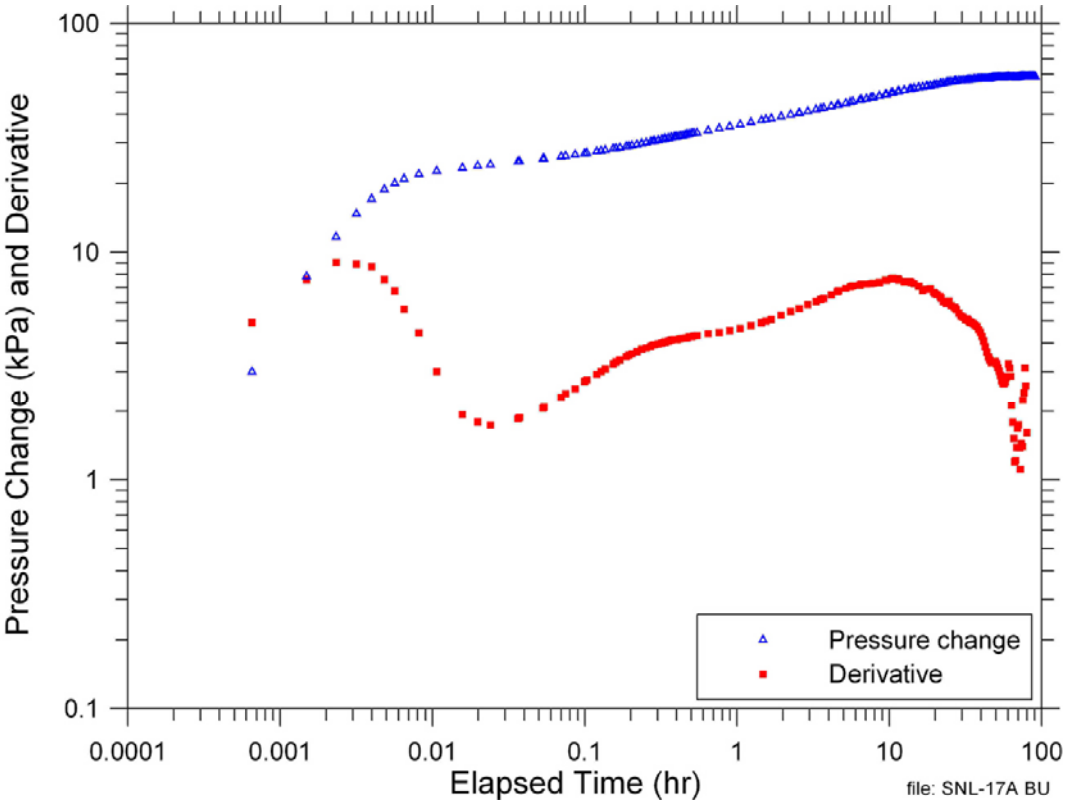

Figure HYDRO-41. Log-Log Diagnostic Plot of SNL-17A Recovery

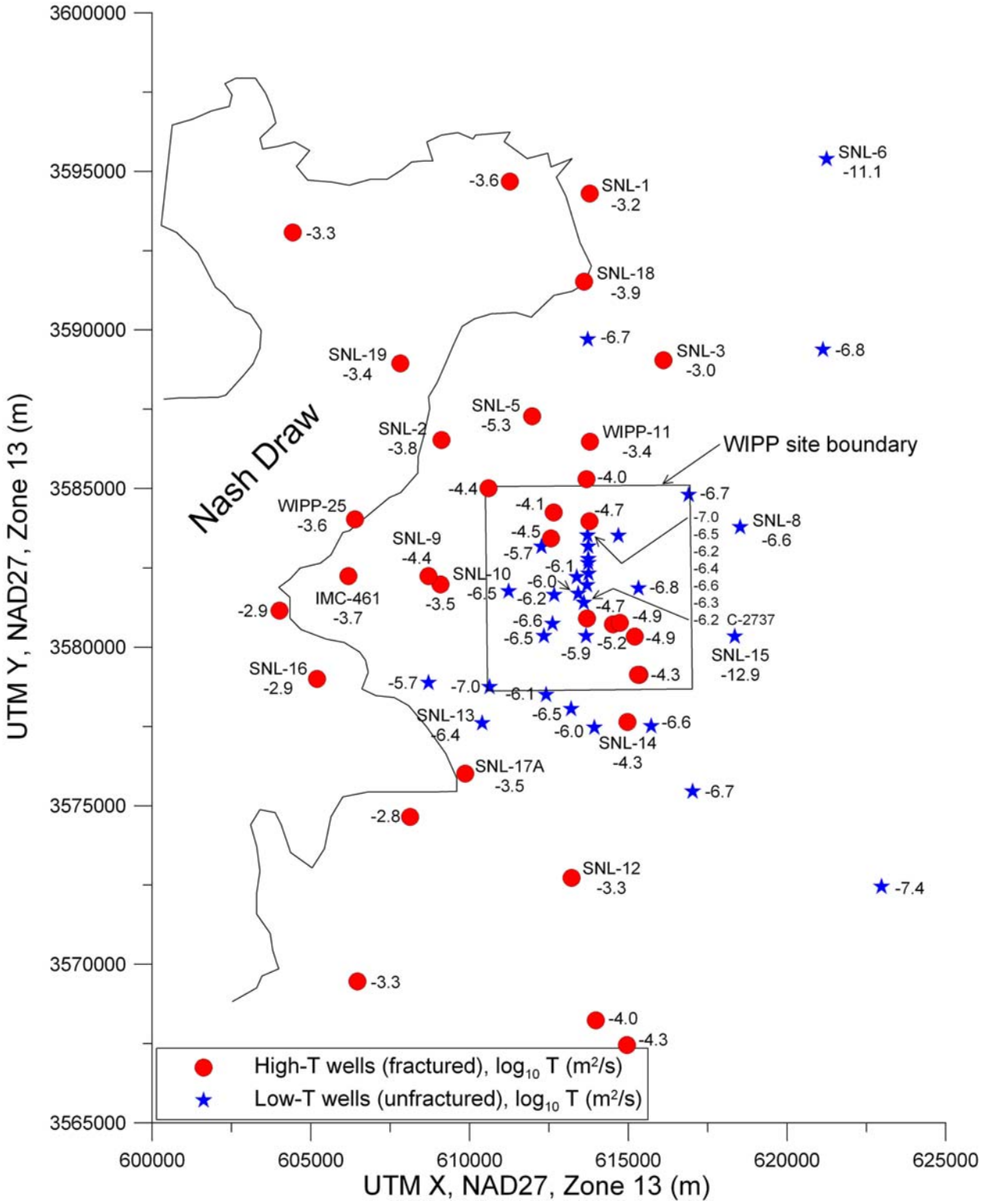

Figure HYDRO-42. log_{10} Transmissivity (m^2/s) Values of Culebra Wells Around the WIPP Site

to this low-T region. A longer test would be expected to show the effects of the higher T (log_{10} transmissivity = -4.7) seen at H-3 to the south. SNL-3 can be seen to be in a region with lower T to both the east and west, leading to the derivative behavior seen in Figure HYDRO-38. The derivative behavior seen at the other tested Culebra wells can be similarly explained by referring to Figure HYDRO-42.

The transmissivity values inferred from the hydraulic tests listed in Table HYDRO-4 are generally consistent with a correlation between Culebra transmissivity and overburden thickness, taking other geologic factors into consideration. This correlation was developed by Holt and Yarbrough (2002) and was used to generate the CRA-2004 T fields. Figure HYDRO-43 shows the results listed in Table HYDRO-4 added to the data and correlation of Holt and Yarbrough (2002). The data are divided into three categories: wells where upper Salado dissolution has occurred, wells where no Salado dissolution has occurred and log_{10} transmissivity (m^2/s) is greater than -5.4, and wells where no Salado dissolution has occurred and log_{10} transmissivity is less than -5.4. log_{10} transmissivity = -5.4 is the cutoff used by Holt and Yarbrough (2002) to differentiate wells showing double-porosity hydraulic behavior indicative of fractures from wells showing single-porosity (porous medium) hydraulic behavior. SNL-5 (log_{10} transmissivity = -5.3, single porosity) had not yet been drilled at the time of this demarcation. Not shown are the results from SNL-6 and SNL-15, which are from a different geologic domain (Culebra bounded by and containing halite [see Section HYDRO-7.1]) than the data shown on the plot and have much lower transmissivities.

Most of the new transmissivity data are in good agreement with the correlation of Holt and Yarbrough (2002). SNL-12 and WIPP-11 have higher transmissivities than would have been expected. The evidence for upper Salado dissolution at SNL-9 is tenuous (Powers and Richardson 2003b), and SNL-9 might be more properly assigned to the middle population (shown in green) on Figure HYDRO-43. SNL-5 is shown as belonging to the middle (green) group only because its log_{10} transmissivity value falls above the cutoff used by Holt and Yarbrough (2002). Some fracturing was observed in the core from SNL-5 (Powers and Richardson 2004d), but no indication of double-porosity hydraulic behavior is seen in the diagnostic plot of the pumping test recovery (Figure HYDRO-40). The cutoff could perhaps be redefined (as was done in Beauheim 2007) and SNL-5 assigned to the lower (blue) group. In either category, it would represent an end member.

HYDRO-6.3 Large-Scale Tests with Distant Observation Wells

Most of the tests performed since 2003 were single-well tests, meaning that the test was only intended to produce a response in the well being tested. Three longer-term pumping tests were conducted in 2004 and 2005, however, that were designed to produce responses in surrounding observation wells that could be used to calibrate the groundwater-flow model of the Culebra. Total production from these tests was limited to the 3700 m^3 (3 acre-feet [acre-ft]) the New Mexico Office of the State Engineer specifies as the maximum amount that can be pumped from a well in a calendar year without obtaining additional water rights. These tests were conducted at SNL-9, WIPP-11, and SNL-14, and lasted 32 days, 19 days, and 22 days, respectively (Table HYDRO-4). The observation wells that responded to these tests are shown in Figure HYDRO-44.

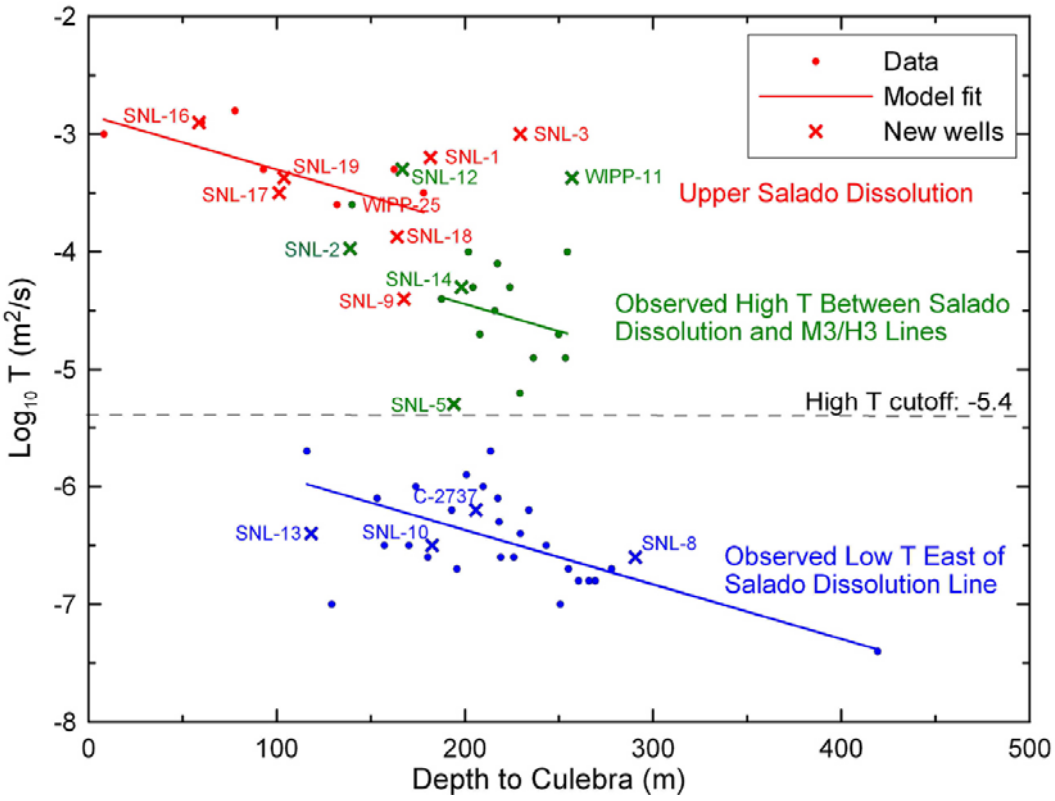

Figure HYDRO-43. New Transmissivity Data Added to Correlation of Holt and Yarbrough (2002)

HYDRO-6.4 Evidence for Fracture Interconnections from Diffusivity Analysis

Beauheim (2007) compiled hydraulic diffusivity data from observation-well responses to 15 Culebra pumping tests to identify the areas that are, and are not, interconnected by fractures. In a highly heterogeneous medium such as the Culebra, only hydraulic diffusivity, the ratio of transmissivity and storativity (S), can be determined from the responses of observation wells to pumping tests. Independent estimation of transmissivity and S requires knowledge of the areal distribution of flow during pumping, which is not known in a heterogeneous system. Generally speaking, higher values of diffusivity reflect higher degrees of connectivity between wells.

The diffusivity data represent tests in which the observation-well-to-pumping-well distances ranged from 398 m (1304 ft) to 9472 m (31075 ft) (Beauheim 2007). All Culebra pumping tests that have produced observable responses at wells over 100 m (330 ft) away were performed at wells showing high T ($\log_{10}$ T $\geq$ -5.4) and evidence of fracturing. (Indeed, lower-T locations typically cannot sustain pumping rates of at least 0.25 L/s (4 gpm) required to produce observable responses over great distances in the Culebra.) Thus, the pressure responses observed at distant wells all involve some amount of propagation through fractures before, perhaps, encountering unfractured dolomite. The objective, therefore, was to distinguish pressure-transient propagation entirely through fractures from that which starts in fractures but ends in unfractured rock (Beauheim 2007). This was accomplished by comparing the diffusivities (D)

calculated for each pumping well/observation well pair in the context of the other information available about fracturing in the Culebra.

Beauheim (2007) found that all of the well pairs showing $\log_{10}$ D (m^2/s) values of 1.0 or greater involve wells already known to have high-T ($\log_{10}$ T $\geq$ -5.4) and other evidence of fracturing. Thus, these wells are likely directly interconnected by fractures. At the other extreme, all well pairs showing $\log_{10}$ D values less than 0 involve an observation well known to have low-T and no evidence of fracturing. Thus, these wells are probably not directly interconnected by fractures. The well pairs showing $\log_{10}$ D values between 0 and 1 required more detailed attention because they involved wells with and wells without evidence of fracturing. Based largely on the response of H-15 to the H-11b1 pumping test, which produced a $\log_{10}$ D estimate of 0.21 (Beauheim 1989), Beauheim (2007) concluded that a $\log_{10}$ D value of approximately 0.20 appears to represent the cut-off between well pairs connected by fractures from those that are not. H-15 encountered little fracturing in the Culebra, with most fractures filled with gypsum (Mercer and Snyder 1990) but, as suggested by Beauheim (1989), it must be near to hydraulically significant fractures to have responded to the pumping at H-11b1 (and later at SNL-14) as it did.

The spatial pattern of estimated Ds is shown in Figure HYDRO-45. A red line shows the separation between regions with $\log_{10}$ D values greater and less than 0.20. The regions containing high-T wells show $\log_{10}$ D values greater than 0.20, reflecting fracture interconnections. The high-T region in the southeastern part of the WIPP site clearly seems to be interconnected to high Ts farther to the south. The swath of Culebra running roughly NE to SW across the WIPP site that encompasses only low-T wells generally shows $\log_{10}$ D values less than 0.20. Combining this information with the fact that no responses to pumping in a high-T well on one side of this swath have ever been observed in high-T wells on the other side of the swath, Beauheim (2007) inferred that a continuous band of low-T Culebra lacking hydraulically significant fractures separates the high-T Culebra found in the northwestern part of the WIPP site from the high-T Culebra found in the southeastern part of the site.

HYDRO-6.5 Other Testing

Hydraulic testing of Magenta wells was performed under *TP 00-03, Compliance Monitoring Program: Recompletion and Testing of Wells for Evaluation of Monitoring Data from the Magenta Member of the Rustler Formation at the WIPP Site* (Chace 2003). Slug tests of the Magenta were performed in well C-2737 in January 2007. Bowman and Roberts (2009) inferred a transmissivity of 1.5×10^{-7} m^2/s (0.14 square feet (ft^2)/day) from these tests.

Tests of the Magenta were also attempted in WIPP-25, where Mercer (1983) reported the transmissivity of the Magenta to be 4.0×10^{-4} m^2/s (375 ft^2/day), higher than the 2.9×10^{-4} m^2/s (270 ft^2/day) reported for the Culebra at that location. Lambert and Robinson (1984) reported maintaining a pumping rate of 2.1 L/s (33 gpm) when they sampled the Magenta at WIPP-25 in 1980. Two attempts were made to pump the well in February 2006 and September 2007, but even a pumping rate of 0.08 L/s (1.25 gpm) was more than the well could sustain, and the well was rapidly dewatered. Pressure recovery to the prepumping level then took several months. Video inspection inside the well showed that the casing perforations across the Magenta interval

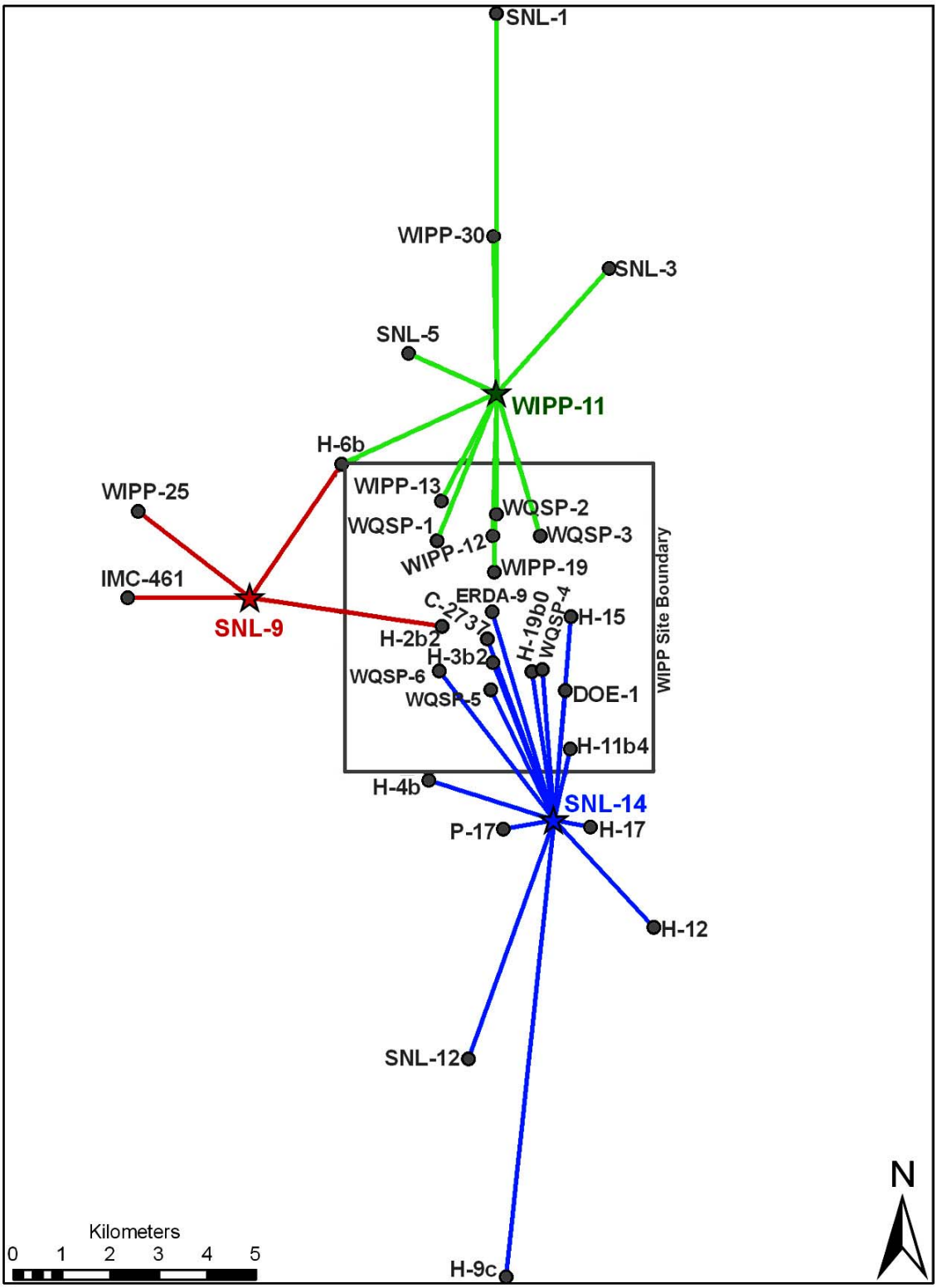

Figure HYDRO-44. Observation Wells Responding to 2004–2005 Long-Term Pumping Tests

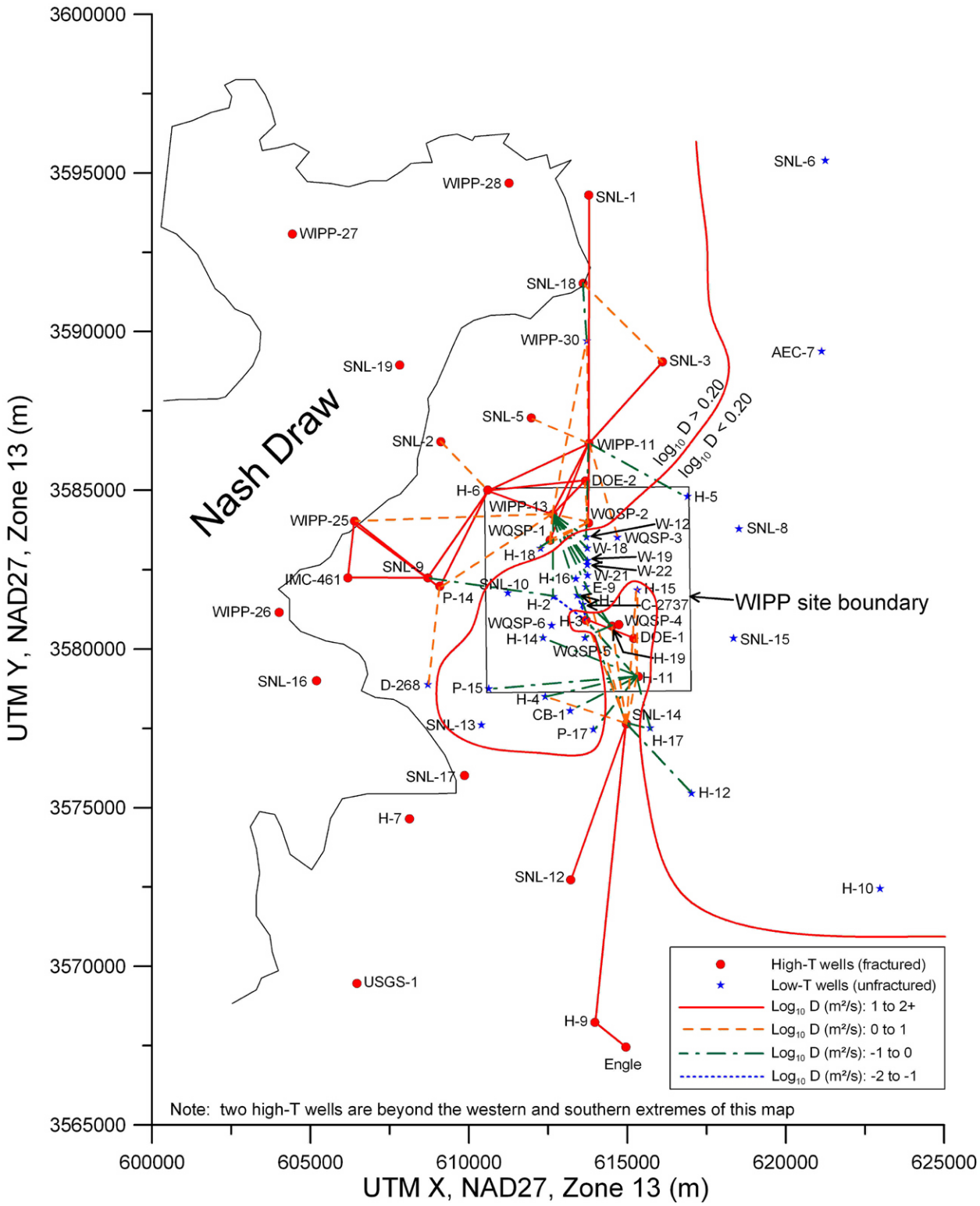

Figure HYDRO-45. log_{10} D Values Observed for Pumping Well-Observation Well Pairs (modified from Beauheim 2007)

were open. It is surmised that the packer separating the Culebra and Magenta in WIPP-25 was leaking when Lambert and Robinson (1984) sampled the well, because they reported virtually identical water chemistries for the Culebra and Magenta. The Magenta transmissivity

value reported by Mercer (1983) was derived from the same pumping test as the water-quality samples; hence, the transmissivity value is not representative of the Magenta. Based on the rapid dewatering and slow recovery observed in 2006 and 2007, the true Magenta transmissivity value at WIPP-25 may be two or more orders of magnitude lower than the value reported by Mercer (1983).

As a historical note, the U.S. Geological Survey (USGS) performed hydraulic tests in wells H-1, H-2a, H-2b, H-2c, and H-3 (later referred to as H-3b1) in 1979 and 1980 that provided data for transmissivity estimates for the Magenta, Culebra, and Rustler-Salado contact interval reported in Mercer (1983). However, the data from those tests were not published at that time. The USGS completed documentation of the data from those tests in Huff and Gregory (2006).

HYDRO-6.6 Summary

Extensive hydraulic testing has been performed in the new wells. This testing has involved both single-well tests, which provide information on local transmissivity and heterogeneity, and long-term (19 to 32 days) pumping tests that have created observable responses in wells up to 9.5 km (5.9 mi) away. The transmissivity values inferred from the single-well tests support the correlation between geologic conditions and Culebra transmissivity developed by Holt and Yarbrough (2002) and elucidated by Holt, Beauheim, and Powers (2005). The types of heterogeneities indicated by the diagnostic plots of the pumping-test data are consistent with the known spatial distribution of transmissivity in the Culebra. Mapping of diffusivity values obtained from analysis of observation-well responses to pumping tests shows areas north, west, and south of the WIPP site connected by fractures, and also a wide area that includes a NE-to-SW swath across the WIPP site where hydraulically significant fractures are largely absent (Beauheim, 2007). This mapping, combined with the responses observed to the long-term SNL-14 pumping test, has confirmed the presence of a high-T area extending from the SE quadrant of the WIPP site to at least 10 km (6.2 mi) to the south.

The data from hydraulic testing provide the basis for developing T fields that are used for PA to describe radionuclide transport in the Culebra. However, the T fields for the CRA-2009 PA are the same T fields as were used for the CRA-2004 PABC. New T fields based on the data presented in Section HYDRO-6.0 are undergoing peer review.

HYDRO-7.0 Geological Investigations

Geological investigations conducted from 2003 through 2007 focused on two major topics: delineation of halite margins in the nondolomite members of the Rustler and karst. Separate karst studies were performed to (1) evaluate the potential for karst at the WIPP site, and (2) increase understanding of karst in Nash Draw.

HYDRO-7.1 Halite Margins

A reexamination of Rustler halite margins using geophysical log data from new and/or additional oil and gas wells and other boreholes around the WIPP was performed under *AP-114, Analysis Plan for Evaluation and Recalibration of Culebra Transmissivity Fields* (Beauheim 2004b), as part of refining the WIPP conceptual hydrology model and Culebra T fields. Mudstone and halite are lateral facies equivalents in the nondolomite members of the Rustler (Powers and Holt 2000). Holt and Powers (1988) recognized the facies equivalency, and defined the informal stratigraphic nomenclature for the Rustler shown in Figure HYDRO-3. Powers (2002) delineated the halite margins based on the then-available data for CRA-2004.

As described by Holt, Beauheim, and Powers (2005), deposition (and preservation) of halite in units adjacent to the Culebra is related to the hydraulic properties of the Culebra in several ways. First, when halite was deposited above the Culebra, high-salinity fluids circulated through the Culebra, depositing halite in Culebra pores as well, resulting in extremely low-T. Second, if the Culebra is fractured, allowing high flux, halite immediately below or above the Culebra would probably not survive for millions of years. Therefore, the presence of halite below or above the Culebra can indicate the lack of open fractures in the Culebra. Third, if halite is dissolved from below the Culebra, it could cause fracturing of the Culebra (as Salado dissolution has caused in Nash Draw). As halite is most likely to be dissolved along its depositional margin, the M2-H2 margin below the Culebra should be evaluated as a potential location of high Culebra transmissivity.

Thus, mapping the occurrence of halite in the Rustler members allows inferences about Culebra transmissivity in areas where there are no Culebra wells. Powers (2007) completed this investigation and produced the revised halite-margin map shown in Figure HYDRO-46. The revised map shows more detail and complexity than the previous version, made possible by the data available from newly drilled oil and gas wells. The revised halite margins will be used in developing new Culebra T fields.

HYDRO-7.2 Karst

In response to WIPP stakeholder comments about the potential effects of karst on WIPP regulatory compliance and a request from EPA (U.S. Environmental Protection Agency 2006, p. 18015), the DOE initiated a comprehensive review of all claims and information pertaining to karst in the WIPP vicinity. This review (Lorenz 2006a and 2006b) supported the previous DOE position on karst, concluding that most of the geological evidence offered for the presence of karst in the subsurface at the WIPP site "has been used uncritically and out of context, and

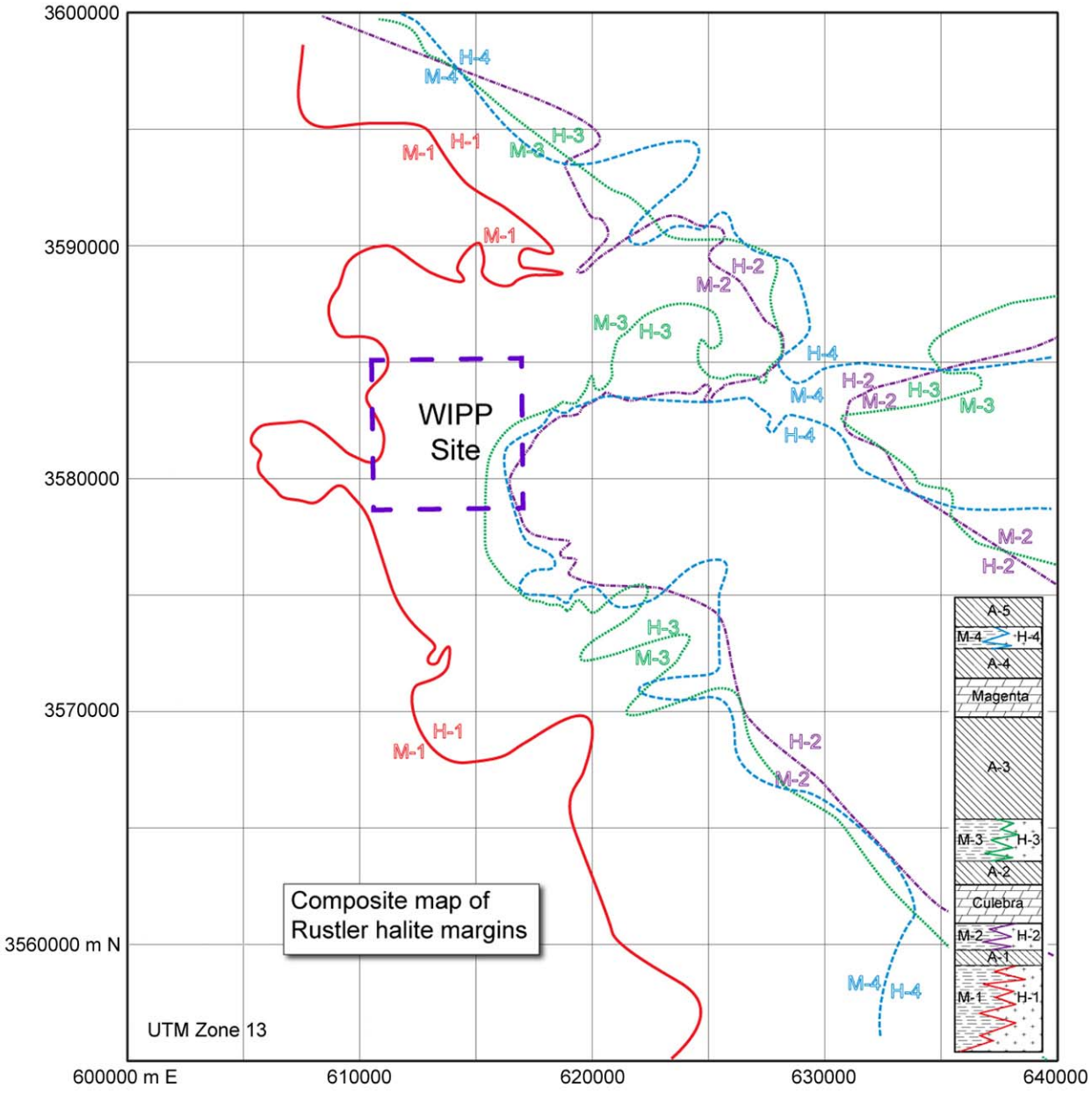

Figure HYDRO-46. Revised Rustler Halite Margins

does not form a mutually supporting, scientifically defensible framework. …The remaining evidence is more readily interpreted as primary sedimentary features" (Lorenz 2006b, p. 243). Lorenz (2006b, p. 250) summarized his findings as follows:

> Analysis of primary data suggests that the overwhelming majority of data support an interpretation of unkarsted strata in the Rustler Formation at and near the WIPP site. There is some evidence for local dissolution at the top of the Magenta horizon in the WIPP-33 drillhole, but extrapolation of the known karst features in Nash Draw eastward to the WIPP site is unwarranted. The arguments offered for karst in the Rustler Formation at the WIPP site are speculative, and what evidence

> exists for karst is inconsistent and contradictory, and subject to other, more plausible interpretations.
>
> Interpretations of 'insoluble residues' in the cores were based on undeveloped theory, faulty analogy, and severely limited exposures. These early interpretations have been erroneously cited as evidence for karst in the Rustler Formation. More recently, better exposures of these strata, and their interpretation by analogy to modern depositional environments, have documented the presence of primary sedimentary structures including the disruption of bedding related to syndepositional desiccation and cracking, proving that they are primary deposits that have not been subjected to post-burial dissolution.
>
> Topographic depressions near the WIPP site that have been cited as being the probable locations of sinkholes are few, and the data that have been cited to interpret these depressions as sinkholes have been taken out of context and have other, more scientifically valid and better supported interpretations. The characteristics of these depressions are not similar to the characteristics of the unambiguous sinkholes which pirate drainage systems in Nash Draw to the west. The stratigraphic thinning commonly cited as evidence of dissolution of the Rustler Formation at the WIPP site is in fact related to dissolution only in the immediate vicinity of Nash Draw. This dissolution-related thinning overlaps with and obscures the depositional thinning and thickening that is common to the Rustler Formation across the Delaware Basin. Rustler halites were deposited in shallow depressions at the same time that muddy deposits were accumulating at the margins of the pans, and this lateral facies equivalency, a well-documented and founding principle of stratigraphy, caused most of the sedimentary patterns that are mistakenly cited as evidence for post-depositional dissolution and removal of halite from the thinner parts of the Rustler Formation in the vicinity of the WIPP site. The laterally extensive and uniform dolomite layers are not evidence for the original extents of the halite layers. Finally, it would be impossible to obtain the observed thicknesses of the muddy and silty deposits that have been called "residues" by dissolving the limited available volumes of muddy and silty halite.

While Lorenz (2006a and 2006b) focused on evidence for karst at the WIPP site, Powers et al. (2006b) provided new details on karst in Nash Draw. Quoting from their discussion,

> Nash Draw is a complicated geological feature whose origins, history, and processes have been broadly outlined by previous investigations. Powers and Owsley (2003) provided additional details of karst features in the southeastern arm of Nash Draw, and many of the features reported there are discussed or described further here. Some of the approaches taken here will be extended elsewhere in the draw.
>
> Upper Salado halite was dissolved to form a distinct margin along Livingston Ridge and the eastern margin of Nash Draw. Drillhole control is not as dense, however, in most other areas, and the precise control and details of the history would be more difficult to extract elsewhere. We can be reasonably confident that, by analogy, much of the eastern margin of Nash Draw develops by similar processes, although perhaps at differing rates and times. Sulfate was also removed from the Rustler in Nash Draw, although data on structure and well logs indicate this is not the dominant process along the Livingston Ridge at the Cabin Lake Field. Data on upper Salado halite have not been developed in comparable detail along the western margin of Nash Draw, and we cannot evaluate the relationship between upper Salado halite dissolution and that very distinctive margin. The fact that the western margin can be drawn along different escarpments suggests an even more complicated history. Nevertheless, based on additional data, we feel more confident than Vine (1963) about the relationship between Nash Draw topography and upper Salado halite dissolution.
>
> The data on upper Salado halite around Laguna Grande are consistent with a low along a north-south axis of the lake that may provide, or have provided, a pathway for brine movement southward out of the area under the lake before migrating further south and southwest toward the Pecos River. The elevation on the top of halite, as shown by a few wells in this area, indicates

more halite removal, and the rocks at the surface have developed internally-drained, elongate valleys as well as small, circular basins over this area in response. There are some indications that more localized topography, including some drainages east of Laguna Grande, have developed in response to local differences in halite dissolution. This inference will likely remain very tentative since it is unlikely that significantly closer spacing of drillhole data will be obtained.

The array of surface karst features that developed on gypsum beds and gypsite in the southeastern arm of Nash Draw show evidence of stratigraphic control and reveal some aspects of their evolution. Sharply defined, vertical-walled collapse sinks are more common on upper Rustler beds, but they also are more recently exposed by erosion. Similar beds, lower stratigraphically and exposed farther from the edge of the draw, show more collapse and fill. These features likely show some steps in the evolution of karst with time in this setting. Blind valleys are, at least now, associated with the Magenta Dolomite and upper Tamarisk gypsum. They do not resemble collapse sink development; rather it appears that the less-soluble carbonate over gypsum is an important factor in maintaining the cave system instead of collapsing. The features we call karst valleys, however, may be a later step in collapse sink development, where they coalesce into a longer feature. Because the karst valleys developed in lower stratigraphic units than do the more individual collapse sinks described here, it is not certain what role stratigraphy plays in the evolutionary timing of these features.

Springs near the mouth of the southeastern arm of Nash Draw are dominated by sulfate-rich water. Moderate specific gravity and gypsum formation from the evaporating water differentiate these springs from those with high specific gravity and brines that precipitate halite. The brines precipitating halite undoubtedly flow through very shallow gypsum karst, but the brine source is a lake maintained by potash refinery effluent. The sulfate-rich springs are part of the karst hydraulic system in the southeastern arm of Nash Draw, which is developed mainly on beds of sulfate and gypsite. Given the year-round flow in an area with strong seasonal differences in rainfall, the system has considerable storage. Because we cannot quantify what proportion of the fluid flow in this arm of Nash Draw goes to this spring, and have not quantified flow from the springs into Laguna Cinco, it is not practical to estimate how storage occurs there. Subsurface fluids are likely stored in the alluvium that fills some sinks and valleys. Thin (~3–5 m thick) mudstones between Rustler gypsum beds and Rustler dolomites may also provide storage. Hillesheim, Beauheim, and Richardson (2006) suggest recharge reaches the Culebra Dolomite (which is significantly deeper than the near-surface features described here). The Culebra is not storage for these springs, however, as the hydraulic heads for the Culebra are not sufficient to reach the surface here. The systems that discharge to the springs are quite likely feeding open porosity that is locally strata-bound. The degree to which the shallow system in the southeastern arm of Nash Draw is connected to deeper beds, such as the Culebra, is not yet established. Hillesheim et al. (2006) show that heavier precipitation across Nash Draw does affect water levels in the Culebra. Local gradients and flow toward the springs at Laguna Grande, as described here, is not evidence that the Culebra follows a similar local flow path.

The investigations of springs in the southeastern arm of Nash Draw discussed above are documented by Powers (2006a). Powers (2006b) also mapped numerous closed catchment basins in southeastern Nash Draw (Figure HYDRO-47). The basins drain to holes in Rustler gypsum units above the Culebra. Some of the water entering this gypsum karst discharges into brine ponds ("lagunas") in Nash Draw, such as Laguna Cinco (Powers 2006a). Some water must also reach a water table in the gypsum units with which the Culebra is in hydraulic communication, at least locally, because Culebra wells in Nash Draw show water-level responses to major rainfall events (e.g., Figure HYDRO-14).

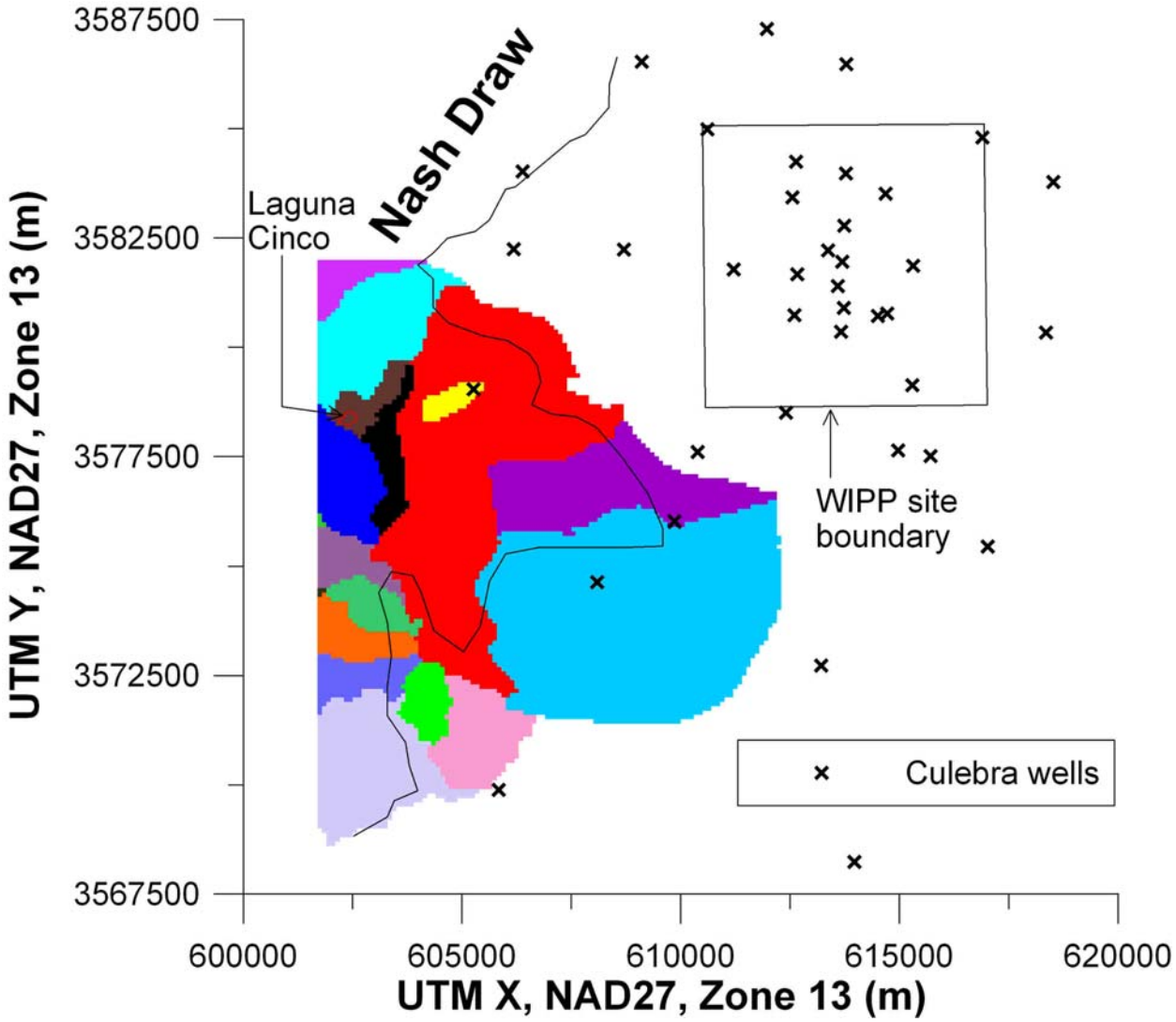

Figure HYDRO-47. Catchment Basins (color coded) Mapped in Southeastern Nash Draw

HYDRO-8.0 Water-Quality Sampling and Evaluation

Water-quality sampling has been performed under two programs at WIPP. Culebra wells WQSP-1 through WQSP-6 and Dewey Lake well WQSP-6A are sampled twice a year under the WIPP Water Quality Sampling Program (WQSP). Sample analysis results are published in the ASERs (U.S. Department of Energy 2004c, 2005, 2006, 2007, and 2008). Water-quality samples are collected in conjunction with pumping tests, as well as during dedicated sampling events under TP 03-01 (Chace and Beauheim 2006) or TP 00-03 (Chace 2003). Most Culebra samples were collected after repeated field measurements showed that pH, specific gravity, and electrical conductivity had stabilized while several wellbore volumes were pumped.

Two exceptions were the samples from SNL-6 and SNL-15. Because of the very low Culebra transmissivity at these two locations (Table HYDRO-4), these wells could not be pumped at any sustainable rate. The wells had been drilled using compressed air as the circulation medium (Powers [In progress]a, Powers and Richardson 2008c), and very little water had accumulated in the holes by the time the wells were completed. Thus, almost all of the water in the wells came from the Culebra. The SNL-6 sample was collected at the depth of the Culebra after ~140 m (460 ft) of water had accumulated in the well, and the SNL-15 sample was collected ~43 m (150 ft) below the water surface in the well.

A few samples from various formations were collected opportunistically during drilling of new wells. No purging or well cleanup was performed before collecting these samples—the waters were representative of what flowed into the borehole after drilling through the sampled interval using compressed air as the circulation medium. These samples cannot be considered as reliable as those collected during pumping tests or dedicated sampling events, but should provide qualitative indications of the waters in the sampled formations.

The non-WQSP samples are analyzed only for major ions and general chemical parameters (pH, specific gravity, and specific conductance). The non-WQSP wells sampled and the analytical results are listed in Table HYDRO-5. All these samples were analyzed by Hall Environmental Analysis Laboratory, Albuquerque, NM. Evaluation of the water-chemistry data is being performed under *AP-125, Analysis Plan for the Evaluation of Culebra Brine Compositions* (Domski and Beauheim 2005).

HYDRO-8.1 Culebra Groundwater Chemistry

Repeated sampling of the WQSP wells has demonstrated how stable the Culebra water chemistry is in these wells. Figure HYDRO-48 presents Piper plots (Piper 1944) for each well showing that the groundwater composition between 2003 and 2007 was consistent with that measured since the WQSP program began in 1995.

Table HYDRO-5. Analytical Results for Water Samples Collected by SNL

Well ID	Unit	Sample Date	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	Br^- (mg/L)	F^- (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	Na^+ (mg/L)	Sr^{2+} (mg/L)	Specific Conductance (µmhos/cm@ 25°C)	pH[a]	Specific Gravity[a]	Charge Balance Error (%)[j]
C-2737	C	3/4/2004	44000	6000	71	65	0.7	1600	770	320	28000	NA	140000	7.16	1.064	0.03
H-19b0	C	8/31/2006	47000	4800	46	50	ND	1600	1100	680	27000	23	170000	7.25	1.068	-2.33
IMC-461	C	8/4/2006	3900	2300	100	ND	2.3	1000	250	30	1800	15.4	14000	6.80	1.008	-3.45
SNL-1	C	5/29/2004	19000	3700	76	17	ND	1400	730	340	10000	NA	150000	7.04	1.027	-3.5
SNL-2	C	1/17/2004	4800	2400	90	3.1	2	930	230	46	2600	NA	19000	7.32	1.010	-2.2
SNL-3	C	4/16/2004	26000	4700	63	32	ND	1400	740	360	14000	NA	140000	7.36	1.036	-5.31
SNL-5	C	7/24/2004	7000	1700	64	17	1.5	1400	510	67	1900	NA	19000	7.02	1.011	-8.89
SNL-6[b]	C	1/16/2008	220000	1800	170	5100	ND	5500	22000	4800	97000	140	580000	6.17[d]	1.21[d]	1.24
SNL-8	C	8/2/2007	77000	6400	49	100	ND	2000	3100	1500	47000	33	280000	6.95	1.097	2.74
SNL-9	C	11/19/2004	14000	1600	140	16	2.5	3100	810	44	4700	NA	50000	6.73	1.021	-0.52
SNL-10	C	11/3/2006	1100	4400	46	2.3	2.7	500	170	72	1900	9.3	11000	8.11	1.008	-0.12
SNL-12	C	8/14/2004	740	1900	92	1.7	3.3	610	120	15	440	NA	5000	7.07	1.004	-2.15
SNL-13	C	7/17/2006	8500	3300	50	31	3.2	990	330	190	5200	16.9	40000	8.42	1.017	-0.39
SNL-14	C	8/21/2007	47000	6900	48	40	2.5	1500	1100	620	30000	22	130000	7.81	1.061	0.51
SNL-15[b]	C	3/30/2007	180000	1600	200	1100	6.2	4800	12000	6800	90000	130	610000	6.64[d]	1.205[d]	1.79
SNL-16	C	6/9/2006	8600	2500	97	ND	2.5	1400	430	290	4400	18.2	35000	7.01	1.014	1.22
SNL-17A	C	9/15/2006	250	1800	94	ND	1.3	620	150	5.3	130	7.8	3500	7.26	1.003	2.5
SNL-18	C	8/18/2006	8700	3700	75	5.6	1.7	1100	360	120	5200	15.9	38000	7.44	1.016	-1.62
SNL-19	C	7/28/2006	2700	2300	90	1.6	1.5	850	220	43	1600	11.4	12000	7.19	1.007	1.88
USGS-4	C	7/19/2006	1100	1800	35	ND	2.3	530	120	15	540	7.24	5900	6.80 [d]	NA	-7.05
WIPP-11	C	2/20/2005	26000	6300	78	37	ND	1600	810	360	15000	NA	160000	7.07	1.038	-3.49
WIPP-25	C	9/23/2004	14000	2600	100	ND	ND	1800	660	720	8000	NA	130000	6.92	1.023	6.12
WIPP-30	C	5/6/2005	18000	3900	44	12	3.3	1300	320	170	13000	NA	130000	8.58	1.030	5.66
SNL-1[c]	DL[e]	3/25/2004	190000	15000	290	440	ND	540	4500	21000	91000	NA	>199900	6.82[d]	1.210	-7.45
SNL-13[c]	DL[f]	4/12/2005	440	2200	58	1.3	1.6	680	150	5.7	270	NA	4300	8.02[d]	1.000	-1.42
SNL-14[c]	DL[g]	5/3/2005	54	160	180	ND	1.1	74	51	6.1	29	NA	860	7.98[d]	1.026	1.25
SNL-14[c]	DL[h]	5/5/2005	350	1300	140	0.86	1.4	430	150	4.9	240	NA	3100	7.68[d]	1.003	4.91
SNL-13[c]	LM[i]	4/26/2005	190000	5300	76	1400	ND	3700	10000	2300	95000	NA	NA	6.55[d]	1.190	-2.72
C-2737	M	1/30/2007	4100	2400	38	6	3.4	910	290	26	2200	17	14000	8.32	1.011	-0.3

C – Culebra
DL – Dewey Lake
LM – Los Medaños
M – Magenta
NA – Not analyzed
mg/L – milligrams per liter

ND – Not detected above detection limit

[a] Denotes measurement made in the field; pH values uncorrected for ionic strength

[b] Denotes sample collected by bailing/pumping with little purging

[c] Denotes opportunistic sample collected during drilling

[d] Denotes laboratory value instead of field measurement; pH values uncorrected for ionic strength

[e] open hole 11 m deep

[f] open hole 64 m deep

[g] open hole 63.4 m deep

[h] open hole 92.7 m deep

[i] open hole 146.3 m deep

[j] ([sum of cation milliequivalents-sum of anion milliequivalents]/[sum of cation milliequivalents+sum of anion milliequivalents])×100

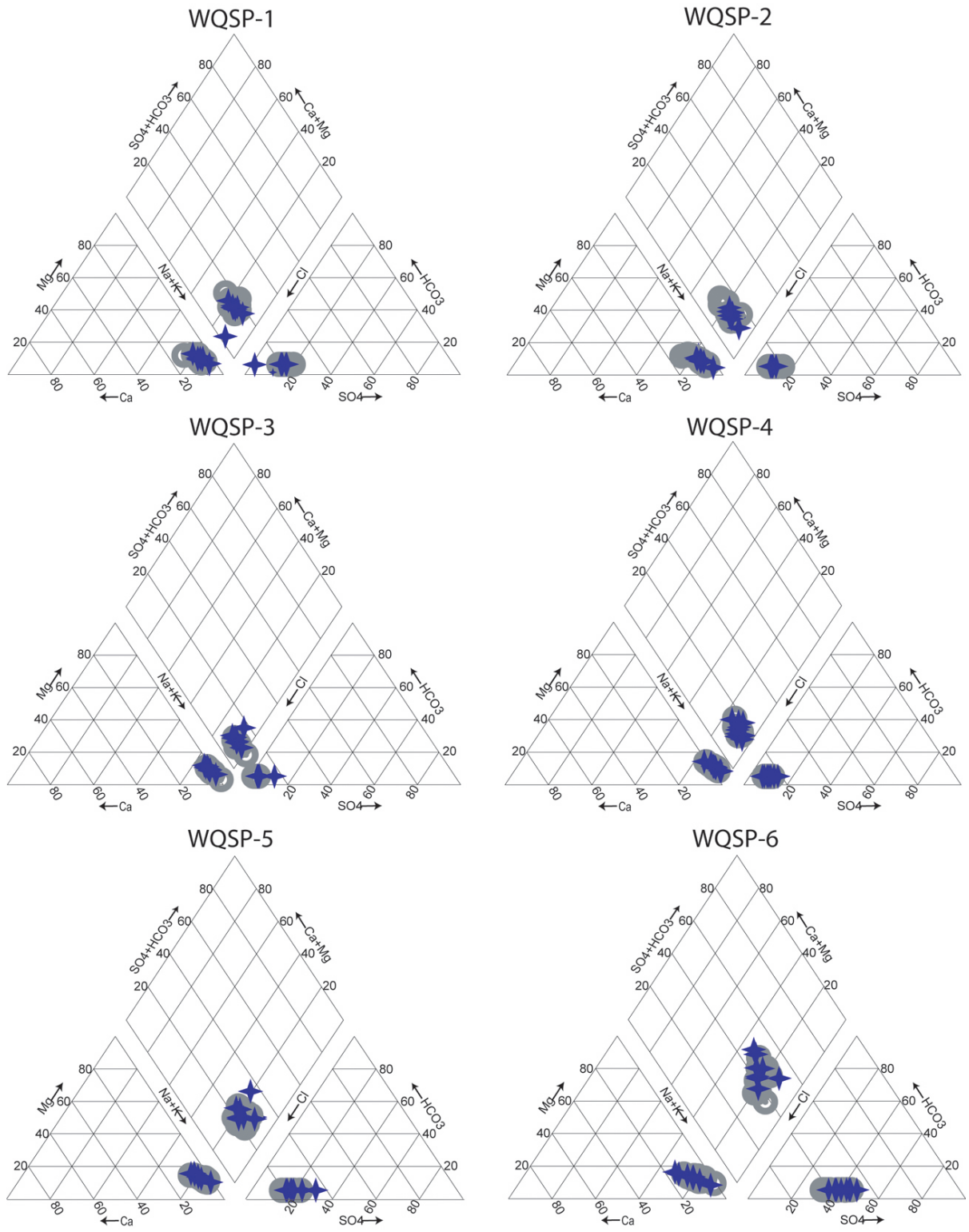

Figure HYDRO-48. Piper Plots for Water Samples from Culebra Wells WQSP-1 Through WQSP-6 Showing Both Historical Data from 1995 Through 2002 (Gray Areas) and Results from 2003 Through 2007 (Blue Stars)

Using data from only 22 wells, Siegel, Robinson, and Myers (1991) originally defined four hydrochemical facies (A, B, C, and D) for Culebra groundwater based primarily on ionic strength and major constituents (Table HYDRO-6). With the data now available from 59 wells, Domski and Beauheim (2008) defined transitional A/C and B/C facies, as well as a new facies E for high- moles per kilogram (molal) Na-Mg Cl brines. The spatial distribution of these wells and facies is shown in Figure HYDRO-49, along with the ionic strength of the Culebra water at each well. Note especially the position of facies E with respect to the Rustler halite margins. Figure HYDRO-50 presents a Piper plot showing how the facies differ in the relative percentages of major ions.

Table HYDRO-6. Culebra Hydrochemical Facies

	Facies	Siegel, Robinson, and Myers (1991)	Domski and Beauheim (2008)
Increasing Salinity ↓	B	Dilute (ionic strength ≤0.1 molal) $CaSO_4$-rich groundwater, from southern high-T area	Same as Siegel, Robinson, and Myers (1991), Mg/Ca molar ratio 0.32 to 0.52
	B/C	Not differentiated	Ionic strength 0.18 to 0.29 molal, Mg/Ca molar ratio 0.4 to 0.6
	C	Variable composition waters, Mg/Ca molar ratio 0.3 to 1.2 for waters with ionic strength <1.25 molal	Ionic strength 0.3 to 1.0 molal, Mg/Ca molar ratio 0.4 to 1.1
	A/C	Not differentiated	Ionic strength 1.1 to 1.6 molal, Mg/Ca molar ratio 0.5 to 1.2
	A	Ionic strength ~2 to 3 molal, Mg/Ca molar ratio 1.2 to 2	Ionic strength >1.66 molal, up to 5.3 molal, Mg/Ca molar ratio 1.2 to 2.4
	D	Defined based on inferred contamination related to potash refining operations. Ionic strength 3 molal, K/Na weight ratios of ~0.2	Same as Siegel, Robinson, and Myers (1991)
	E	Not sampled	Wells east of the mudstone-halite margins, ionic strength 6.4 to 8.6, Mg/Ca molar ratio 4.1 to 6.6

The low-ionic-strength (≤0.1 molal) facies B waters contain more sulfate than chloride, and are found southwest and south of the WIPP site within and down the Culebra hydraulic gradient from the southernmost closed catchment basins mapped by Powers (2006b) in the southwest arm of Nash Draw (Figure HYDRO-47). These waters reflect relatively recent recharge through gypsum karst overlying the Culebra. However, with total dissolved solids (TDS) concentrations in excess of 3000 mg/L, the facies B waters do not in any way represent modern-day precipitation rapidly reaching the Culebra. They must have residence times in the Rustler sulfate units of thousands of years before reaching the Culebra.

The higher-ionic-strength (0.3–1 molal) facies C brines have differing compositions, representing meteoric waters that have dissolved $CaSO_4$, overprinted with mixing and localized processes. Facies A brines (ionic strength 1.6–5.3 molal) are high in NaCl and are clustered along the M3-H3 halite margin (Figure HYDRO-49). Facies A represents old waters (long flow paths) that have dissolved halite and/or mixed with connate brine from facies E. The facies D

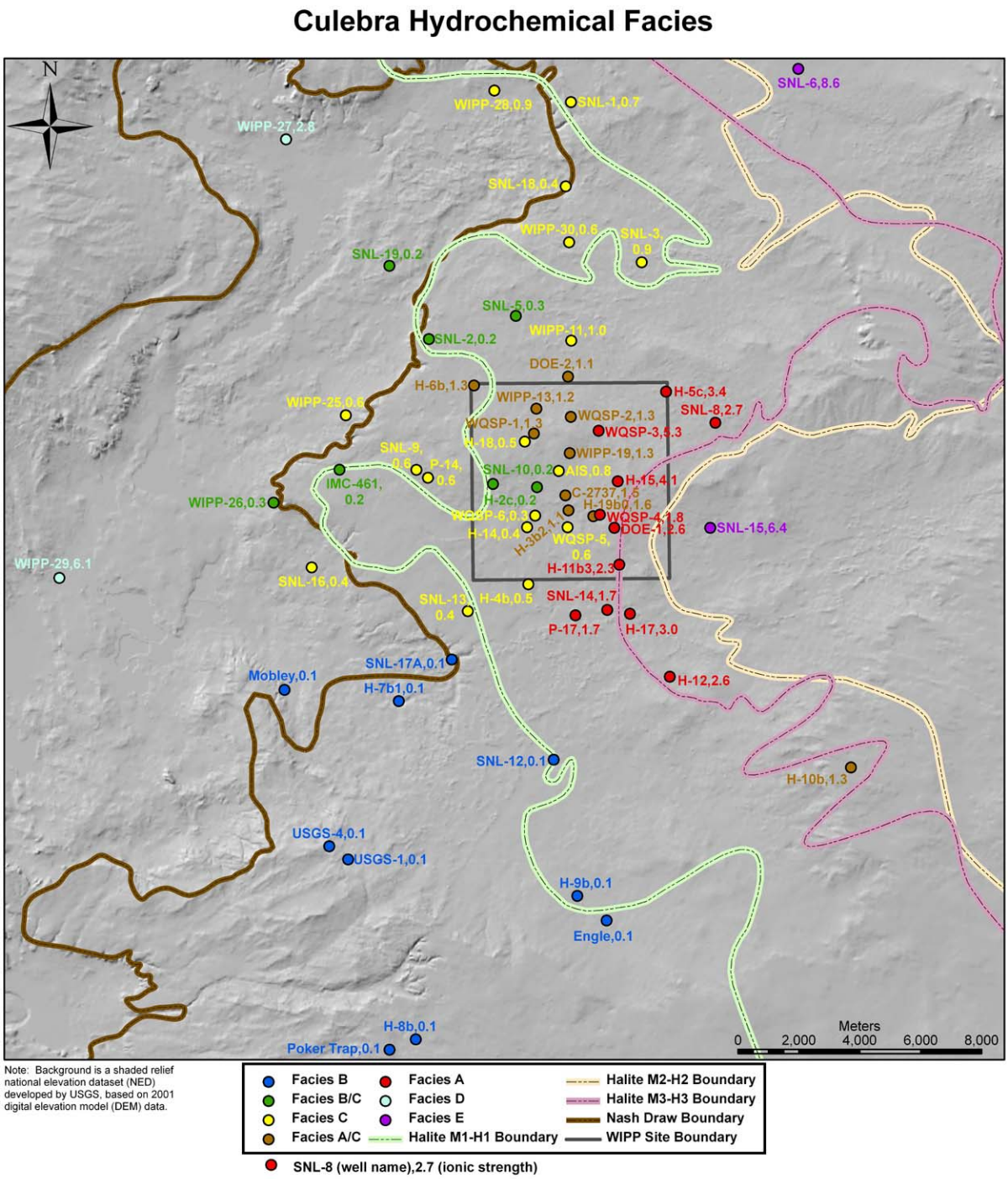

Figure HYDRO-49. Culebra Hydrochemical Facies

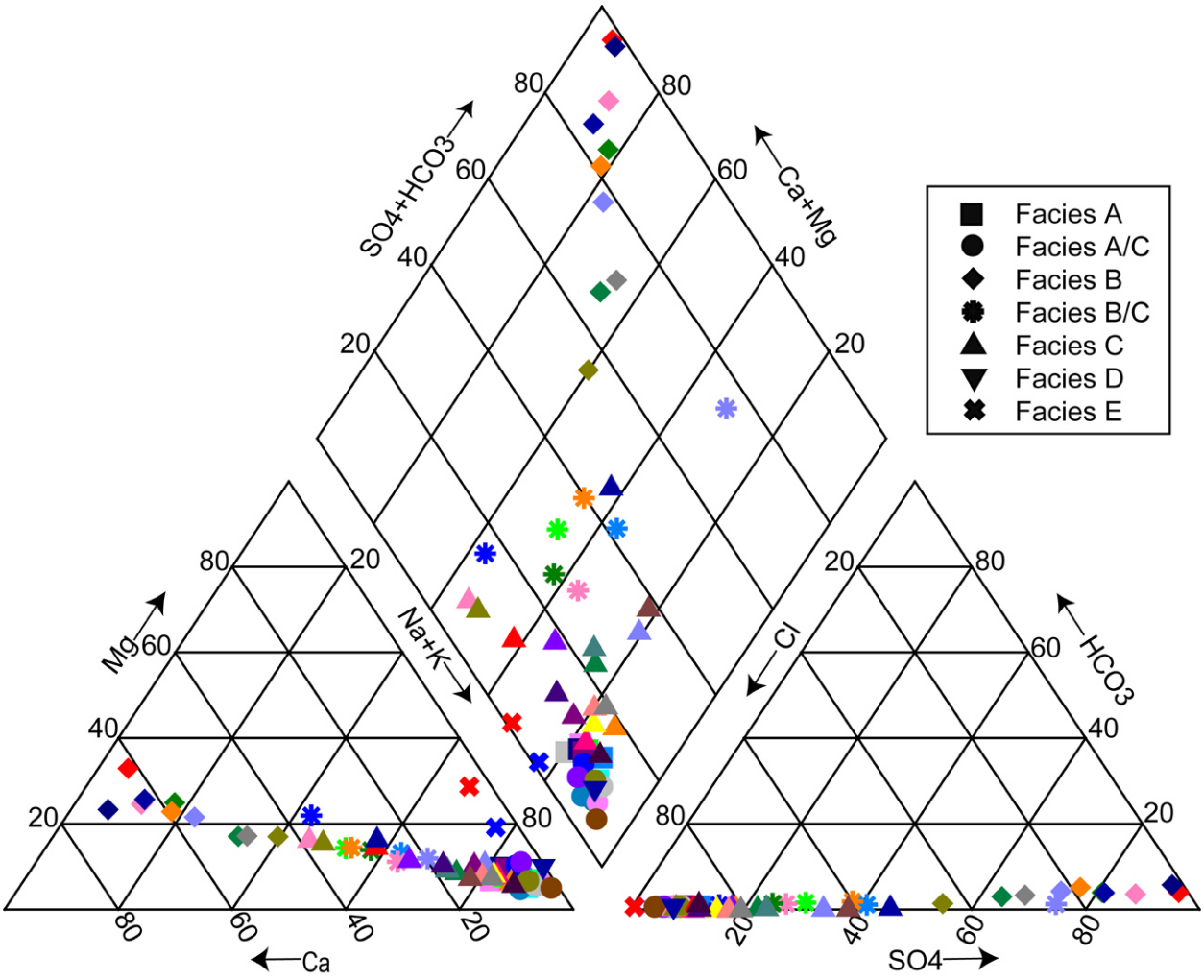

Figure HYDRO-50. Piper Plot for Culebra Water Samples Categorized by Hydrochemical Facies

brines, as identified by Siegel, Robinson, and Myers (1991), are high-ionic-strength solutions found in western Nash Draw with high K/Na ratios representing waters contaminated with effluent from potash refining operations. Similar water is found at shallow depth (<11 m [36 ft]) in the upper Dewey Lake at SNL-1, just south of the Intrepid East tailings pile (see below). The newly defined facies E waters are very high ionic strength (6.4–8.6 molal) NaCl brines with high Mg/Ca ratios. The facies E brines are found east of the WIPP site, where Rustler halite is present above and below the Culebra, and halite cements are present in the Culebra. They represent primitive brines present since deposition of the Culebra and immediately overlying strata.

HYDRO-8.2 Groundwater Chemistry of Other Units

Five "opportunistic" groundwater samples are listed in Table HYDRO-5. A sample was collected during the drilling of SNL-1 when the hole was at a depth of 11 m (36 ft) in the upper Dewey Lake (Powers and Richardson 2004c). The water level in the hole at the time of sampling was approximately 9.5 m (31 ft) below ground surface (bgs). Another sample was collected during drilling of SNL-13 when the hole was at a depth of 64 m (210 ft), 5.5 m (18 ft)

past the Dewey Lake-Rustler contact in the upper anhydrite of the Forty-niner (Powers and Richardson 2008a). The water level in the hole at the time of sampling was approximately 45.9 m (151 ft) bgs. Two samples were collected during drilling of SNL-14 when the hole was at different depths in the Dewey Lake: 63.4 m (208 ft) and 92.7 m (304 ft) bgs (Powers and Richardson 2008b). When the first sample was collected, the water level was at approximately 53.8 m (176.6 ft) bgs, and was at approximately 51.2 m (167.9 ft) bgs when the second sample was collected. The fifth sample was collected during drilling of SNL-13 when the hole was at a depth of 146.3 m (480 ft) in the Los Medaños Member of the Rustler (Powers and Richardson 2008a). The lower ~4 m (12 ft) of the hole produced 1.6 to 1.9 L/s (25 to 30 gpm) of brine, preventing continuation of the hole using compressed air as the circulation medium. The sample was collected from a container used to hold the brine blown from the hole. Considering how little water was produced to the hole from other zones (e.g., Culebra, Magenta, Dewey Lake), the sample should be largely representative of the Los Medaños brine.

Figure HYDRO-51 shows a Piper plot of the relative solute concentrations for the five opportunistic groundwater samples and also for Dewey Lake water from well WQSP-6A (Round 17; U.S. Department of Energy 2004c). The Dewey Lake samples from SNL-13, SNL-14, and WQSP-6A fall in approximately the same region as Culebra facies B samples (Figure HYDRO-50), except that the SNL-14 sample collected when the hole was only 63.4 m (208 ft) deep contained more magnesium and bicarbonate than the other samples. These are all low-TDS waters originating from meteoric recharge. The Dewey Lake sample from SNL-1, in contrast, is a high-TDS brine with a K/Na weight ratio of 0.23, similar to the Culebra facies D brines. This brine appeared to be perched in the upper Dewey Lake and probably comes from the Intrepid potash tailings pile, which is only a few hundred meters north of SNL-1 (see Figure HYDRO-6). The Los Medaños sample from SNL-13 is also a high-TDS brine, but it lacks a high K/Na ratio. It appears to be similar to the Culebra facies E brines, which occur where halite is present above, below, and within the Culebra (Figure HYDRO-49). While no halite was noted in the Los Medaños at SNL-13 during drilling (Powers and Richardson 2008a), the hole is adjacent to the margin of halite in the Los Medaños (M1-H1) identified by Powers 2007, Figure HYDRO-49. Halite may be dissolving, or have been dissolved, along this margin.

HYDRO-8.3 Summary

Biannual sampling of wells WQSP-1 through 6 has shown that Culebra water chemistry has remained stable for over 12 years at these wells, as expected. Groundwater sampling over the entire Culebra well network has greatly expanded on the database used by Siegel, Robinson, and Myers (1991) to delineate four Culebra groundwater facies. Five primary facies and two transitional facies are now recognized. The new facies (E) is a high ionic strength (6.4-8.6 molal) Na-Mg Cl brine found in new wells east of all the Rustler M-H boundaries where halite is present in the Culebra. It is thought to represent primitive brine present since deposition of the Culebra and immediately overlying strata. The definition of transitional A/C and B/C facies adds detail to the original conclusions of Siegel, Robinson, and Myers (1991).

A brine sample collected from the Los Medaños in SNL-13 near the M1-H1 boundary is very similar to the Culebra facies E brine, and may have a similar Permian origin. A sample collected at shallow depth in SNL-1 is a high-TDS brine similar to the Culebra facies D brines that have

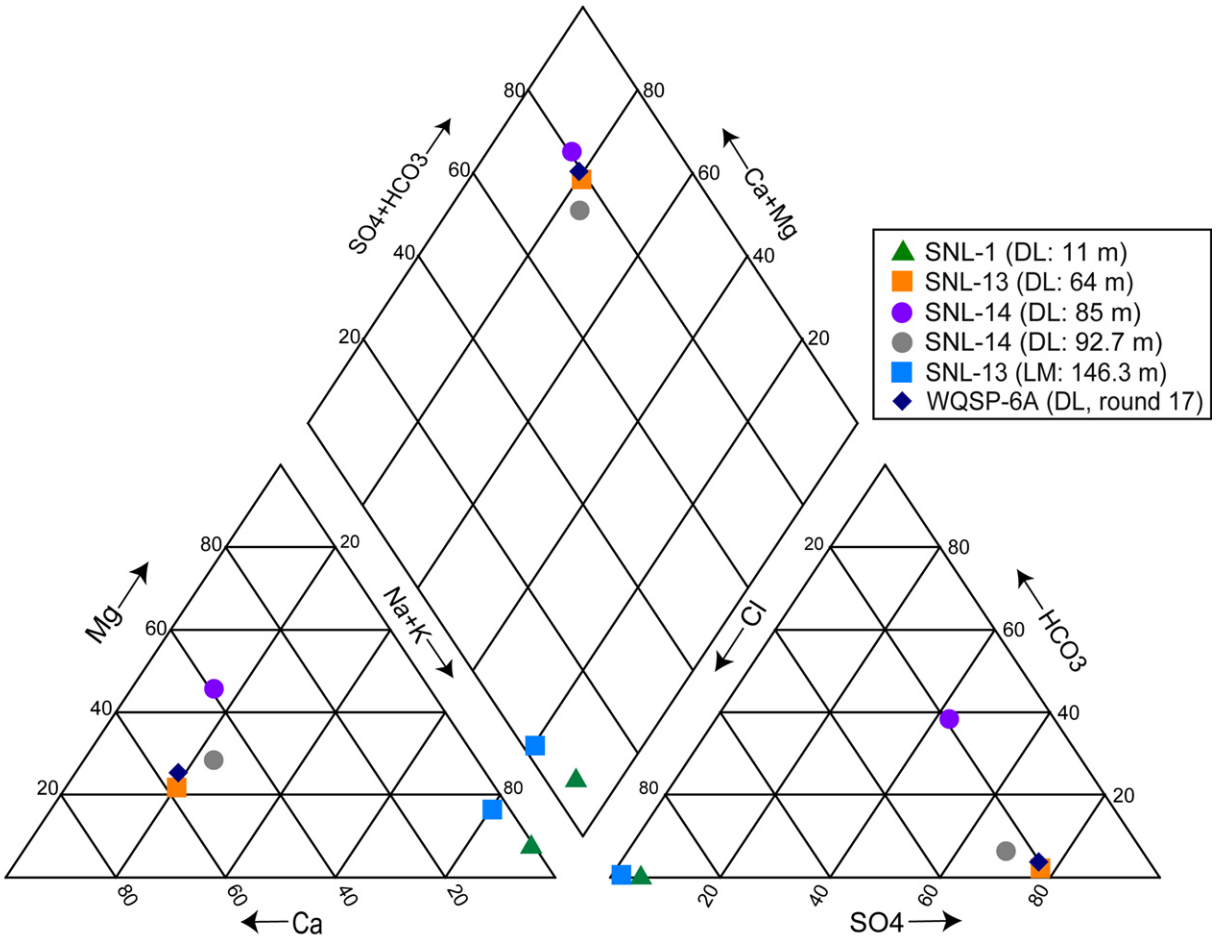

Figure HYDRO-51. Piper Plot of WQSP-6A and Opportunistic Samples

been contaminated by potash processing. The SNL-1 brine probably originates from the Intrepid East tailings pile a few hundred meters to the north. Dewey Lake samples from SNL-13, SNL-14, and WQSP-6A are low-TDS waters similar to, but fresher than, the Culebra facies B waters. The Dewey Lake water originates from meteoric recharge of undetermined age.

HYDRO-9.0 Modeling of Culebra Water-Level Rise

Since 1989, a general long-term rise in Culebra and Magenta water levels has been observed in WIPP wells. As the rise in water levels continued through the 1990s and early 2000s, observed heads exceeded the ranges of uncertainty established for the steady-state heads in most of the 32 wells used to calibrate the T fields for the CCA, necessitating an investigation into the cause(s) and consequences of the rise. In *AP-110, Analysis Plan for Evaluation of Culebra Water-Level-Rise Scenarios*, Beauheim (2003) postulated three scenarios that could account for the long-term water-level rise. The scenarios were (1) leakage into the Culebra of refining process water discharged onto potash tailings piles or into ponds, probably through subsidence-induced fractures and/or leaky boreholes; (2) leakage into the Culebra of water from units above the Culebra (Magenta and/or Dewey Lake) or below the Culebra (e.g., Salado, Bell Canyon) through poorly plugged and abandoned boreholes; and (3) leakage into the Culebra of water being injected at depth (e.g., into the Bell Canyon Formation) through leaky boreholes. Note that this analysis plan and the strategy it defined to evaluate the three scenarios were developed before the wells and new data showing Culebra water-level responses to rainfall discussed in Section HYDRO-5.0 were available.

Three tasks defined in AP-110 have been completed to date:

Task 1—Data assembly and screening

Task 2—Simulate leakage from tailings pile

Task 3—Simulate leakage through poorly plugged and abandoned potash boreholes

The Intrepid East tailings pile located 10 to 12 km (6 to 7.5 mi) due north of the WIPP site (Figure HYDRO-6) is the tailings pile most likely to affect water levels north of and on the WIPP site. Disposal of mine tailings and refining-process effluent at that location began in 1965. Records obtained from the New Mexico Office of the State Engineer show how much water has been pumped from local aquifers (Ogallala or Capitan) each year from 1973 through 1999 for use in the potash-refining process at the Intrepid East facility (Figure HYDRO-52). Over that period, an average of 2400 acre-ft (3.0×10^6 m^3) of water per year was pumped. Geohydrology Associates (1978) estimated that approximately 90% of this water is discharged onto the tailings pile, and that approximately half of the brine discharged seeps into the ground annually, while the remainder evaporates. Therefore, on average, approximately 1100 acre-ft (1.4×10^6 m^3) of brine may infiltrate each year. Brine from this tailings pile may enter the Rustler through leaky boreholes and/or by first moving laterally into Nash Draw and then downward through subsidence fractures that have opened over potash mine workings.

For Task 1 of AP-110 (data assembly and screening), Powers (2004a) examined the P&A records filed with the BLM for 576 potash exploration holes within (or very near to) the Culebra modeling domain, and divided the holes among the categories given in Table HYDRO-7. The spatial distribution of these holes is shown in Figure HYDRO-53. Twenty-six holes within the active portion of the Culebra modeling domain were found to belong to Categories 4 or 5, indicating the potential for communication between the Culebra and other units.

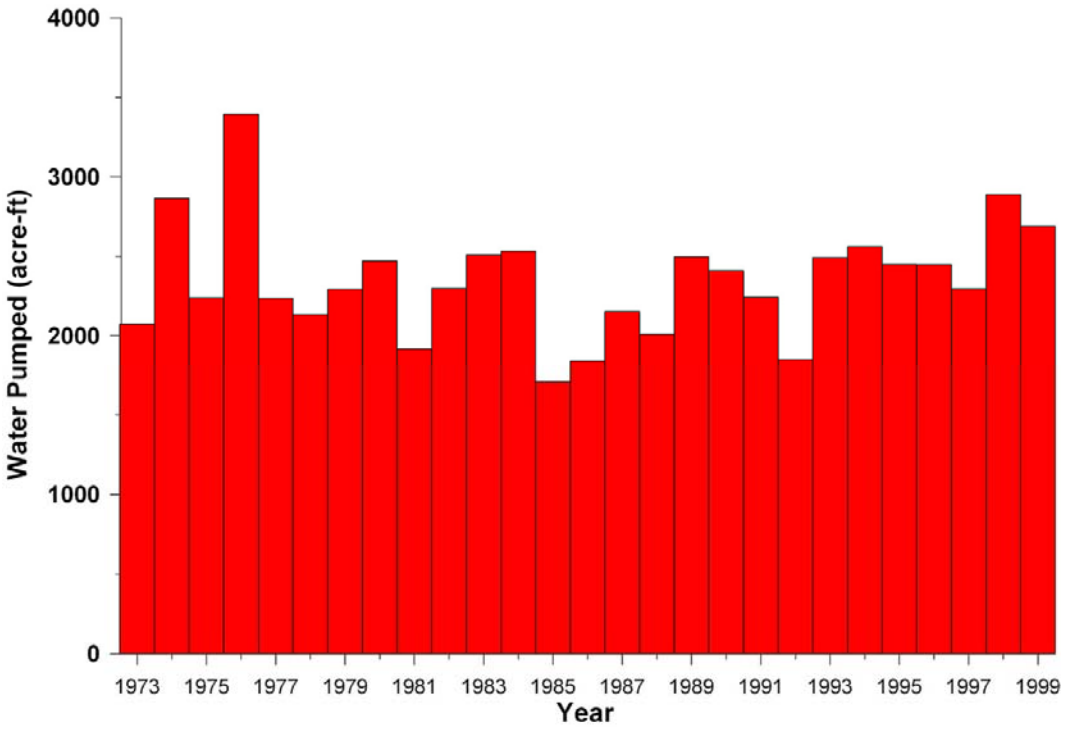

Figure HYDRO-52. Annual Water Pumped for Intrepid East Potash Mill Location

Table HYDRO-7. Cementing Categories for Potash and Other Drillholes in the Modeling Domain

Cementing Category	Characteristics
1	Data indicate drillhole was cemented from total depth to surface
2	Data indicate Culebra interval is completely cemented, with a high degree of certainty
3	Culebra intercepted by drillhole; cement intervals in drillhole; data not clear regarding cementing across Culebra interval
4	Culebra intercepted by drillhole; cement interval in drillhole does not match Culebra interval
5	Apparent open hole
6	Plugging information not available for drillhole
7	Drillhole is too shallow to intercept Culebra; plugging not considered
10	Drillhole is completed to Culebra for monitoring or water well; plugging not considered

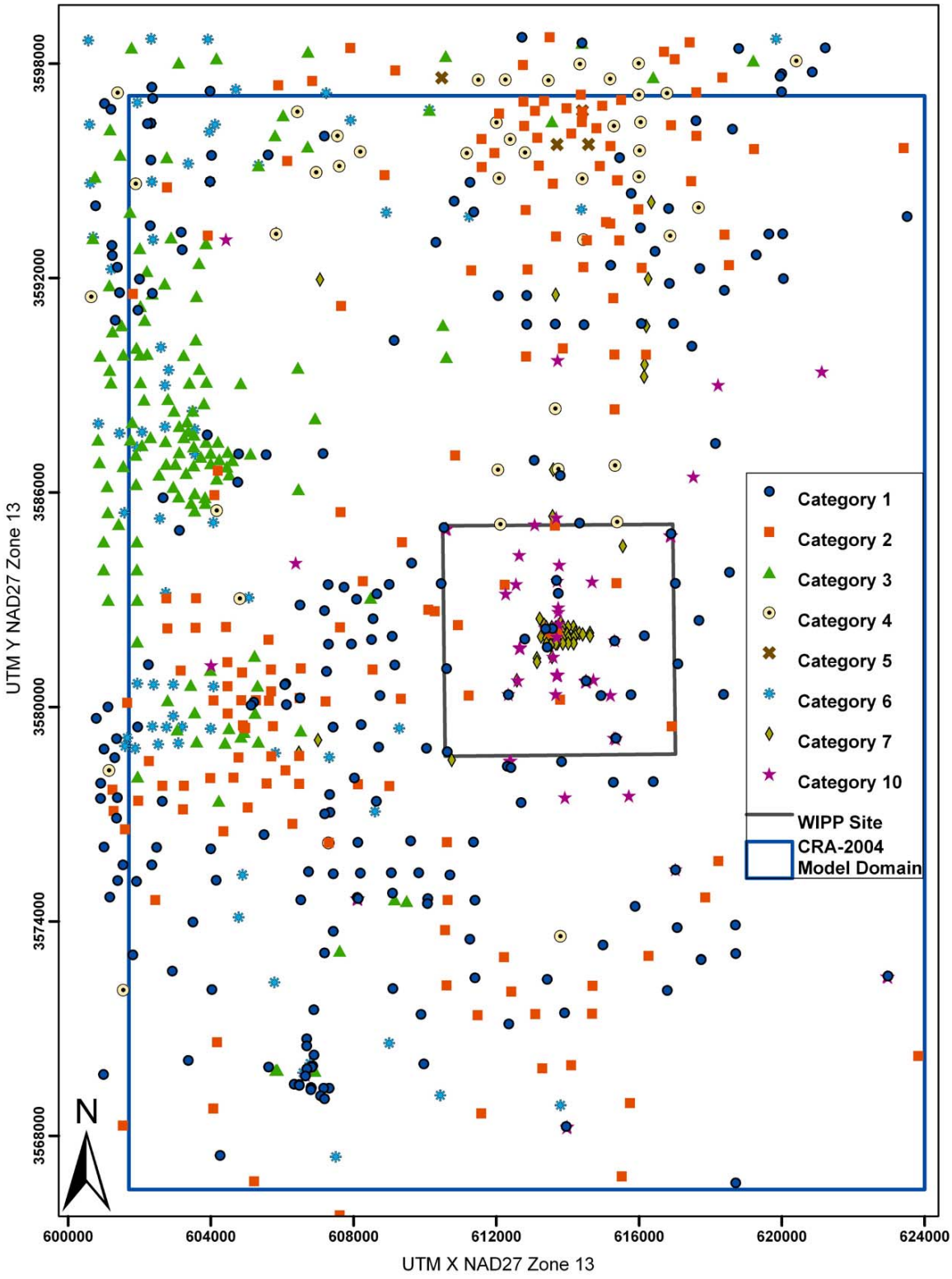

Figure HYDRO-53. Cementing Categorization for Potash Exploration Holes Within and Near the Culebra Modeling Domain. (See Table HYDRO-7 for Key to Categories.)

Powers (2004b) also evaluated cementing and casing records for all plugged and abandoned oil and gas wells within or near the Culebra modeling domain. He found records for 92 plugged and abandoned wells, of which 57 were clearly plugged through the Culebra, 24 were clearly not plugged through the Culebra, 8 lacked information to evaluate plugging through the Culebra, and 3 were possibly open to at least part of the Culebra (Figure HYDRO-54).

For Task 2 of AP-110 (simulate leakage from tailings pile), Lowry and Beauheim (2004) used MODFLOW (Harbaugh et al. 2000) and PEST (Doherty 2002) to model the amount of water that would have to infiltrate into the Culebra at the Intrepid East tailings pile north of the WIPP site to cause water levels to rise as much as has been observed. The modeling was performed using the 100 calibrated T fields from McKenna and Hart (2003) found in CRA-2004. Each T field was recalibrated using PEST to match the average rates of water-level rise in 13 monitoring wells (AEC-7, D-268, DOE-2, H-4b, H-5b, H-6b, H-7b1, P-14, P-15, WIPP-13, WIPP-25, WIPP-26, and WIPP-30) close to the tailings pile or Nash Draw over the last 10 to 25 years of record. The recalibration was performed using three calibration parameters: specific storage (S_s) in the Nash Draw area, S_s outside the Nash Draw area, and a constant leakage or recharge rate from the Intrepid East tailings pile to the Culebra. The calibration was transient using a simulation time of 27 years, 1977 through 2003, which goes back to the beginning of water-level monitoring for the WIPP. The simulations did not attempt to match transient aspects of the water-level rise in a well, but only the average rise over the period showing a consistent rise. Simple linear regression was used to calculate the average slopes of both the observed and simulated water-level changes.

Inverse modeling using PEST only guarantees that an objective function reaches a minimum value. It does not guarantee that the calibrated values will reflect reality, or other observations not included in the calibration process. Thus, the recalibrated T fields were filtered using the following criteria:

1. If the calibrated value of any parameter reached its allowable maximum or minimum, or if the total recharge was greater than the amount applied to the tailings pile, the T field was not included

2. If the value for S_s in the Nash Draw area was lower than that elsewhere in the model domain, the T field was not included

Filtering the 100 original T fields resulted in 53 left for analysis.

The calibrated recharge through the Intrepid East tailings pile to the Culebra ranged from 2.17×10^{-4} to 1.47×10^{-2} cubic meters per second (m^3/s) (5.5 to 376 acre-ft/yr), with a mean value of 2.88×10^{-3} m^3/s (73.5 acre-ft/yr). Thus, only 0.5 to 34% of the 1100 acre-ft/yr estimated to be infiltrating from the tailings pile, with a mean of 6.7%, would have to reach the Culebra to cause water levels to rise as much as has been observed in the various wells. This may indicate that the majority of the infiltrating water may be reaching only shallower strata, such as the Dewey Lake and/or Magenta.

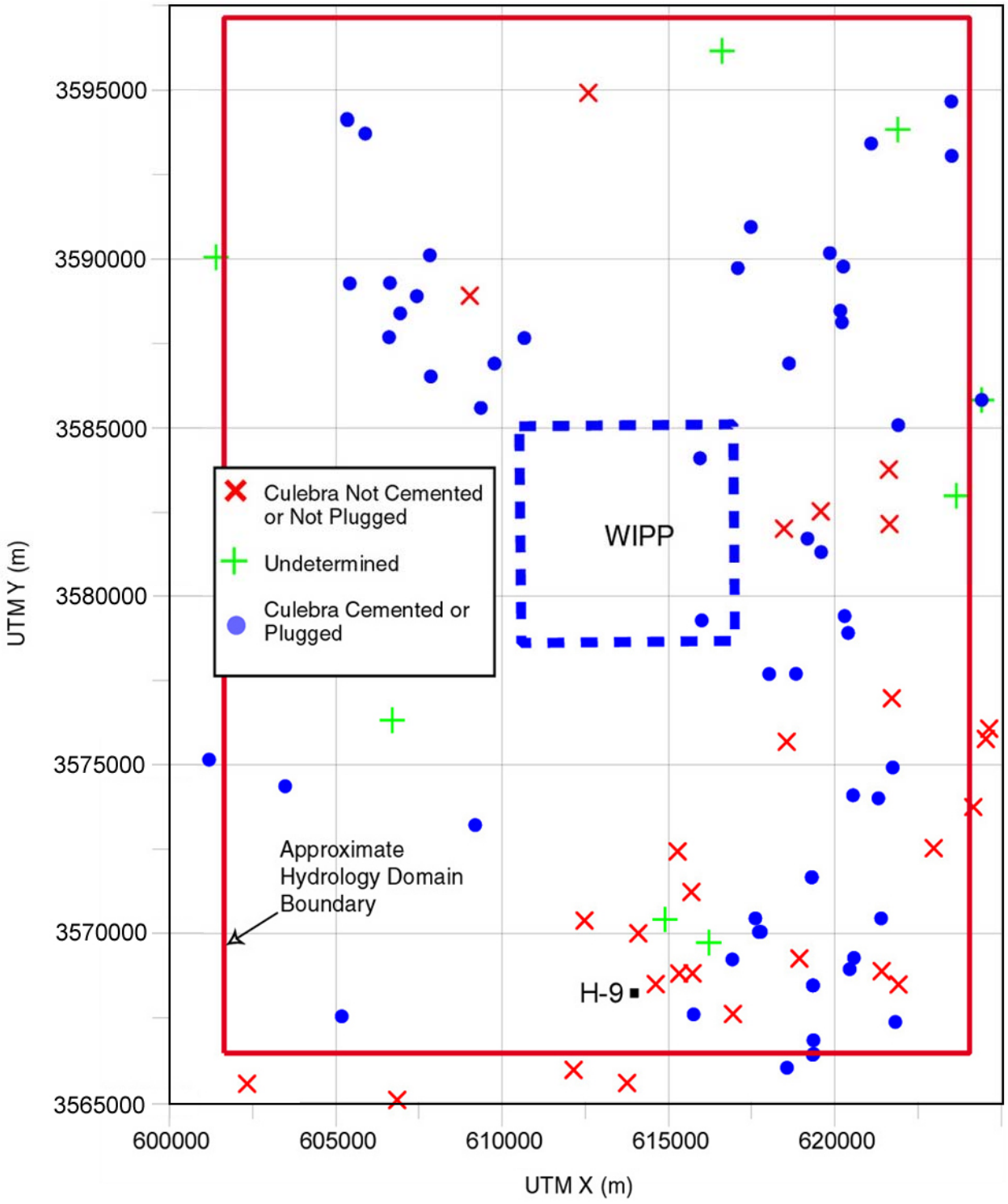

Figure HYDRO-54. Plugged and Abandoned Oil and Gas Wells Within and Near the Culebra Modeling Domain

For Task 3 of AP-110 (simulate leakage through poorly plugged and abandoned potash boreholes), Lowry and Beauheim (2005) used the information compiled by Powers (2004a) on plugged and abandoned potash boreholes to model the effects that leakage into the Culebra through these holes might have on Culebra water levels. Specifically, using each of the 100 T fields developed for CRA-2004, they attempted to calibrate the T fields to the observed rates of water-level rise at 12 wells (those used for Task 2, excluding DOE-2) by adjusting the leakage rates in the 26 holes identified by Powers (2004a) as being in Categories 4 and 5. To simplify the calibration, the 26 potentially leaky holes were divided into 4 groups based on their locations, as shown in Figure HYDRO-55, and the same leakage rate was applied to all holes within a group.

Lowry and Beauheim (2005) tried three ways of matching the observed water-level rises. All three methods involved linearizing the observation-well hydrographs over the last 10 to 25 years of record to calculate an average rate of water-level rise. Information about the three options is summarized in Table HYDRO-8. The calibration attempted to adjust the calibration variables to minimize the difference between the linearized observed and simulated water-level change at each of the 12 wells. The values of variables kept fixed during the calibrations are shown in parentheses in Table HYDRO-8.

HYDRO-9.1 Option A

In the first method (Option A), the leakage (injection) rates in the four groups of boreholes were varied in an attempt to match the amount (not rate) of water-level rise that would be produced by injecting water into the Culebra at the leaky borehole locations for 15 years to the amount of rise given by the linearized observed rate over the same period. Of the 100 T fields, 66 completed the calibration process. The calibrated leakage rates for the groups of boreholes are shown in Table HYDRO-8.

On average, a total of 4.41×10^{-4} m^3/s (11.3 acre-ft/yr or 7 gpm) of leakage was required to match the observed water-level rises, with 66.5% leaking through the Upper group of holes, 0.1% from the Mid group, 16.1% from the Nash Draw group, and 17.3% from the Lower group. However, the Option A method tended to produce higher rates of water-level rise at the start of the 15-year simulation and lower rates at the end than the linearized observed rates. On average, the Option A fits tended to be worst at wells P-14, WIPP-25, H-4b, and P-15, and best at wells H-5b and AEC-7.

HYDRO-9.2 Option B

For Option B, rather than attempting to match the amount of water-level rise over 15 years, only the rise over the last 6 years of the 15-year simulation period was compared to the rise produced by the linearized observed rate. In addition, the Mid and Nash Draw groups of boreholes were combined into a single group for this option. T fields were disqualified if the calibration produced a total water-level rise in any well over the 15-year simulation period exceeding 50 m, because that would put the head above that of the potential sources of leakage in the Magenta and Dewey Lake. With this exclusion criterion, 77 of the 100 T fields produced acceptable results. The calibrated leakage rates for Option B for the groups of boreholes are shown in Table HYDRO-10.

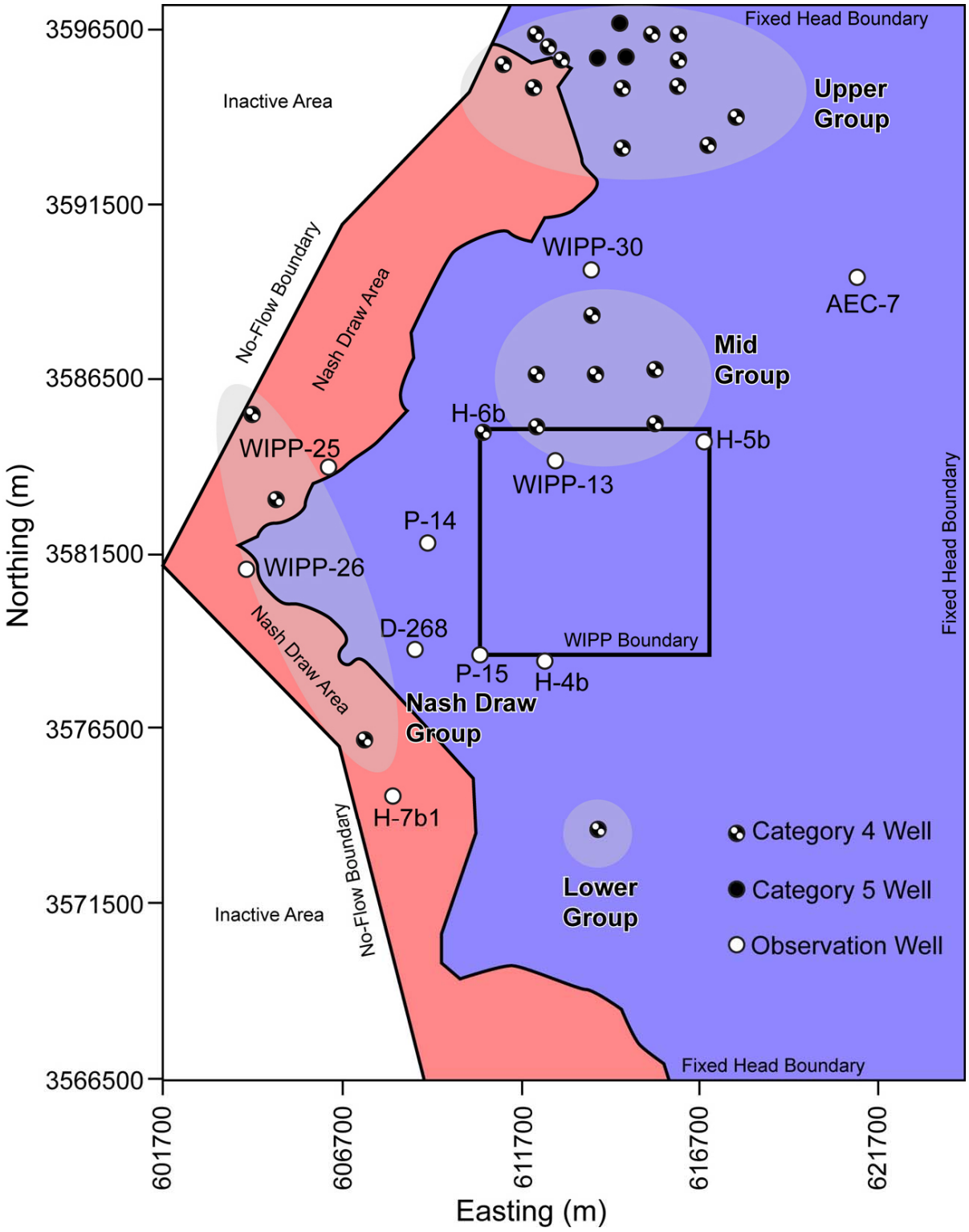

Figure HYDRO-55. Modeling Domain Showing Boundary Features, Monitoring Well Locations, Nash Draw Area, WIPP Boundary, and the Grouping of the Leaky Boreholes for Use in the Calibration Process. Well Categories are Defined in Table HYDRO-7.

Table HYDRO-8. Options Used to Recalibrate T Fields to Leaking Boreholes

Option	A	B	C
Calibration Parameter			
—	**Total head rise over length of simulation**	**Head rise over last six years of simulation**	**Head rise over last six years of simulation**
Calibration Variables			
Leakage in Upper Group	Yes	Yes	Yes
Leakage in Mid Group	Yes	Yes (Mid and ND groups combined)	Yes
Leakage in Nash Draw Group	Yes		Fixed (2.36×10^{-5} m^3/s per borehole)
Leakage in Lower Group	Yes	Yes	Yes
S_s within Nash Draw	Fixed (1.29×10^{-6} m^{-1})	Fixed (1.29×10^{-6} m^{-1})	Yes
S_s outside of Nash Draw	Fixed (1.29×10^{-6} m^{-1})	Fixed (1.29×10^{-6} m^{-1})	Yes

Table HYDRO-9. Option A Total Leakage Rates for Each Group of Leaky Boreholes

Statistic	Leakage by Group (m^3/s)				
	Upper	**Mid**	**Nash Draw**	**Lower**	**Total**
Average	2.93×10^{-4}	6.39×10^{-7}	7.09×10^{-5}	7.63×10^{-5}	4.41×10^{-4}
Median	2.31×10^{-4}	3.00×10^{-9}	5.95×10^{-5}	6.47×10^{-5}	3.55×10^{-4}
Maximum	3.17×10^{-3}	4.94×10^{-6}	2.56×10^{-4}	3.10×10^{-4}	3.28×10^{-3}
Minimum	1.33×10^{-5}	6.00×10^{-10}	5.19×10^{-9}	7.60×10^{-6}	8.10×10^{-5}
Std. Dev.	4.01×10^{-4}	1.34×10^{-6}	6.56×10^{-5}	5.64×10^{-5}	4.05×10^{-4}

Table HYDRO-10. Option B Total Leakage Rates for Each Group of Leaky Boreholes

Statistic	Leakage by Group (m^3/s)				
	Upper	**Mid**	**Nash Draw**	**Lower**	**Total**
Average	8.00×10^{-4}	7.24×10^{-8}	3.62×10^{-8}	2.32×10^{-3}	3.12×10^{-3}
Median	8.85×10^{-5}	5.78×10^{-8}	2.89×10^{-8}	1.63×10^{-3}	2.26×10^{-3}
Maximum	1.22×10^{-2}	5.65×10^{-7}	2.82×10^{-7}	1.02×10^{-2}	1.22×10^{-2}
Minimum	7.54×10^{-8}	6.33×10^{-10}	3.17×10^{-10}	2.50×10^{-6}	2.46×10^{-4}
Std. Dev.	1.80×10^{-3}	9.18×10^{-8}	4.59×10^{-8}	2.33×10^{-3}	2.60×10^{-3}

As expected, more leakage was required under Option B than under Option A. On average, a total of 3.12×10^{-3} m^3/s (80 acre-ft/yr or 49 gpm) of leakage was required to match the observed water-level rises, with 25.6% leaking through the Upper group of holes and 74.4% through the Lower group. The leakages through the Mid and Nash Draw groups of holes were comparatively negligible. On average, the Option B fits tended to be worst at wells P-14, WIPP-25, H-4b, and P-15, the same as for Option A, but best at wells H-7b1 and WIPP-13, different from Option A.

HYDRO-9.3 Option C

For Option C, modeling attempted to match only the rise over the last 6 years of the 15-year calibration period, as was done for Option B, but the leakage rate for the Nash Draw group of boreholes was fixed at 7.09×10^{-5} m^3/s (1.8 acre-ft/yr or 1.12 gpm) (the average rate from Option A), and S_s was allowed to vary between Nash Draw and the area outside of Nash Draw. T-fields were disqualified if the water-level rise at any well exceeded 50 m (164 ft), if the calculated S_s reached either the upper or lower calibration limit (1×10^{-4} and 1×10^{-8} m^{-1}, respectively), or if the S_s calculated for Nash Draw was lower than that calculated for the region outside of Nash Draw. As a result, only 65 of the 100 T fields produced results considered acceptable. The calibrated leakage rates and S_s values for Option C are shown in Table HYDRO-11.

Less total leakage was required under Option C than under Option B, but more than under Option A. On average, a total of 1.28×10^{-3} m^3/s (33 acre-ft/yr or 20 gpm) of leakage was required to match the observed water-level rises, with 28.5% leaking through the Upper group of holes, 1.9% through the Mid group, 5.5% (fixed) through the Nash Draw group, and 64.1% through the Lower group. The average S_s in Nash Draw was 4.9×10^{-5} m^{-1}, while that outside of Nash Draw was 6.4×10^{-6} m^{-1}. On average, the Option C fits tended to be worst at wells H-7b1, WIPP-13, WIPP-25, and P-14, and best at wells AEC-7 and WIPP-26, and generally better than the fits from either Option A or Option B. Overall, the Option C fits were better than those from the other options.

Table HYDRO-11. Option C Total Leakage Rates for Each Group of Leaky Boreholes and S_s values. S_s^{ND} is the Specific Storage in Nash Draw, S_s is the Specific Storage Elsewhere.

Statistic	Leakage by Group (m^3/s)				Specific Storage (m^{-1})	
	Upper	Mid	Lower	Total[a]	S_s^{ND}	S_s
Average	3.64×10^{-4}	2.42×10^{-5}	8.18×10^{-4}	1.28×10^{-3}	4.91×10^{-5}	6.40×10^{-6}
Median	2.30×10^{-4}	9.10×10^{-6}	6.57×10^{-4}	1.18×10^{-3}	4.72×10^{-5}	3.02×10^{-6}
Maximum	1.59×10^{-3}	3.07×10^{-4}	2.98×10^{-3}	3.85×10^{-3}	9.99×10^{-5}	5.55×10^{-5}
Minimum	8.23×10^{-7}	6.65×10^{-8}	7.19×10^{-5}	2.73×10^{-4}	3.28×10^{-6}	1.02×10^{-8}
Std. Dev.	4.07×10^{-4}	4.55×10^{-5}	6.04×10^{-4}	7.08×10^{-4}	2.51×10^{-5}	8.91×10^{-6}

The calibrated Option C T fields were then used to evaluate the continuing effects of leakage. Simulations were run for an additional 100-yr period holding the leakage rates constant at their calibrated values to see how much water levels might continue to rise. For most wells and T fields, the additional rise is less than 8 m (26 ft). Figure HYDRO-56 shows a histogram of the results.

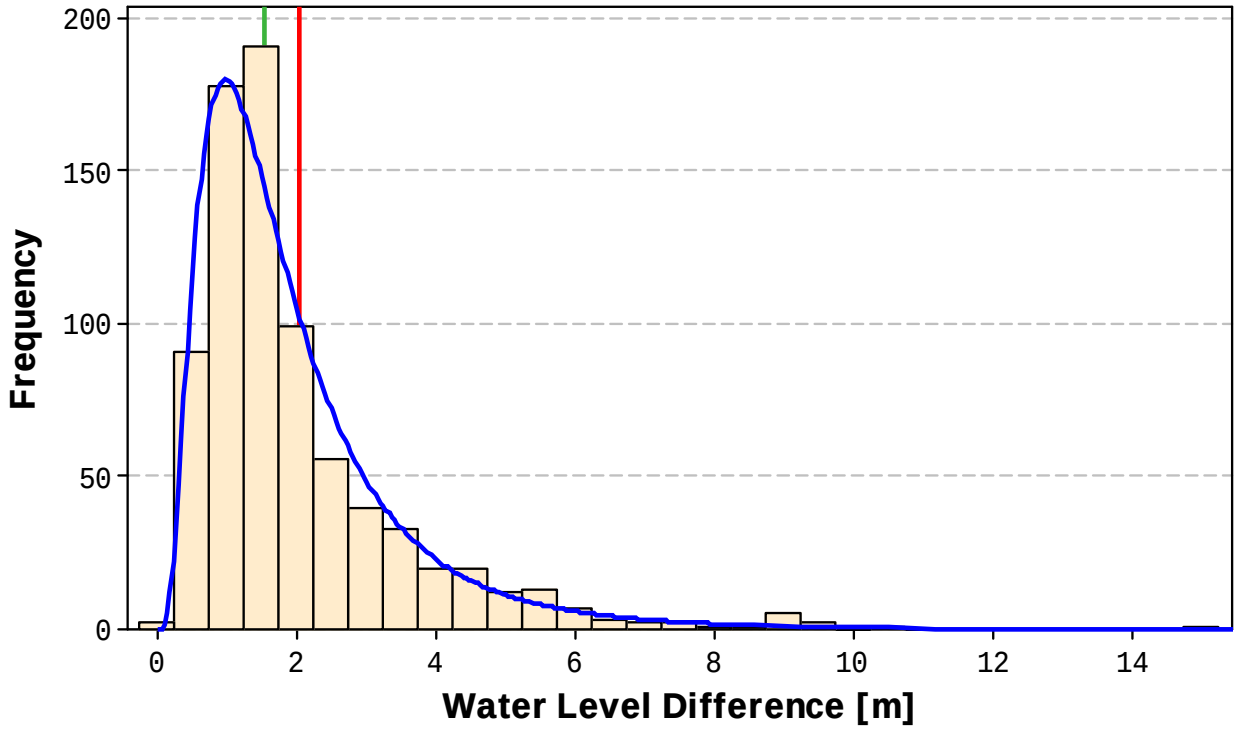

Figure HYDRO-56. Histogram of the Maximum Additional Water-Level Rise for the Last 100 Years of the Long-Term Option C Simulations. The Vertical Green and Red Lines Represent the Median (1.53 m [5.01 ft]) and Mean (2.02 m [6.62 ft]) Values, Respectively.

HYDRO-9.4 Conclusions

Comparisons of the leakage rate in each group of boreholes for each option are shown in Table HYDRO-12. For all three options, the leakage rate for the Upper group of boreholes was the most consistent, ranging from 2.93×10^{-4} to 8.00×10^{-4} m^3/s (7.5 to 20.5 acre-ft/yr or 4.64 to 12.7 gpm). Leakage rates for the other three groups show a variability of two to three orders of magnitude among the different options. The total leakage rate was about one order of magnitude higher for Options B and C than for Option A, primarily because the early transient period, in which most of the head rise occurred, was excluded from the calibration process for Options B and C. With this early period excluded, more leakage was required to match the late-time head rise.

The contribution to the total leakage from the Upper group of boreholes for Option A was much higher than for Options B or C (66.5% for Option A versus 25.6% and 28.5 % for Options B and

Table HYDRO-12. Comparison of Mean Calibration Parameters for All Three Options. Percentages Show Percent of Leakage from That Group to the Total Leakage

Parameter	Option		
	A	B	C
Leakage in Upper Group (m^3/s)	2.93×10^{-4} (66.5%)	8.00×10^{-4} (25.6%)	3.64×10^{-4} (28.5%)
Leakage in Mid Group (m^3/s)	6.39×10^{-7} (0.1%)	7.24×10^{-8} (0.0%)	2.42×10^{-5} (1.9%)
Leakage in Nash Draw Group (m^3/s)	7.09×10^{-5} (16.1%)	3.62×10^{-8} (0.0%)	7.09×10^{-5}[a] (5.5%)
Leakage in Lower Group (m^3/s)	7.63×10^{-5} (17.3%)	2.32×10^{-3} (74.4%)	8.18×10^{-4} (64.1%)
Total Leakage (m^3/s)	4.41×10^{-4}	3.12×10^{-3}	1.28×10^{-3}

[a] Fixed as the average from Option A

C, respectively). Conversely, the contribution by the Lower group was 17.3%, 74.4%, and 64.1% for Options A, B, and C, respectively. This highlights the difference between the two conceptual models (full-time calibration and late-time calibration) and means that if the water-level rise is in quasi-steady-state, a significant amount of leakage must be entering the Culebra from a source south of the WIPP site.

The amounts of leakage listed in Table HYDRO-12 are not large, and are not unreasonable when compared to the capacities of the potential sources. Taking the Option C results as an example, the average total leakage through the Upper group of boreholes is only 3.64×10^{-4} m^3/s (5.8 gpm or 9.3 acre-ft/yr), distributed among 16 boreholes. The 1100 acre-ft/yr of water that may be infiltrating from the Intrepid East tailings pile into the upper groundwater system in the vicinity of the Upper group is over 100 times the amount calculated to be leaking through the Upper group boreholes. The average total leakage through the Mid group of boreholes is only 2.42×10^{-5} m^3/s (0.6 acre-ft/yr or 0.38 gpm), distributed among 6 boreholes. This is within the capacity of the Magenta in this area (but see the discussion in the next paragraph). The fixed leakage through the 3 boreholes in the Nash Draw group totaled 7.09×10^{-5} m^3/s (1.8 acre-ft/yr or 1.12 gpm). Considering the fractured nature of most of the geologic section in Nash Draw due to subsidence and collapse, the Magenta (or Dewey Lake where saturated) could easily be the source of the leakage through the Nash Draw group of boreholes. The average total leakage through the single borehole in the Lower group is 8.18×10^{-4} m^3/s (20.9 acre-ft/yr or 13.0 gpm). A Dewey Lake water table is present in this area (Powers and Richardson 2004a). Beauheim and Ruskauff (1998) report that the Dewey Lake could be pumped at a rate of 7.57×10^{-4} m^3/s (19.4 acre-ft/yr or 12 gpm) in well WQSP-6A with only 2 m of drawdown. Hence, the Dewey Lake could plausibly be providing 8.18×10^{-4} m^3/s to a leaky borehole.

With respect to the Mid group of boreholes, monitoring points on the nearby NW and NE corners of the WIPP site (wells H-6 and H-5, respectively) show Magenta heads rising in a manner similar to those in the Culebra, the opposite of what would be expected if Magenta water were leaking into the Culebra. The Dewey Lake does not appear to be saturated in any zone with significant permeability in this region, so no driving force seems to be present above the Magenta. Given these observations and the low leakage rates calculated by the model, the boreholes in the Mid group may not, in fact, be leaking. The observed rises in both Culebra and

Magenta heads in the vicinity of the Mid group of boreholes may be explained by pressure propagation from the Upper group of boreholes, or by pressure propagation from recharge reaching the Magenta and Culebra in Nash Draw.

The modeling results show that a balance must be achieved between leakage in the Upper group of boreholes and in the Lower and (to a much lesser extent) Nash Draw groups of boreholes in order to produce the observed head rise in the 12 monitoring wells. If no water is leaking through the Lower borehole, then heads to the south of the WIPP site are too low and the observed water-level rise cannot be reproduced in the middle part of the modeling domain. As discussed above, the required amount of leakage could plausibly be coming from the Dewey Lake to the Culebra through the Lower group borehole. As a conceptual model alternative to the potentially leaking Lower group borehole, however, the Culebra could instead (or also) be receiving natural recharge southwest of the WIPP site, where it is believed to be unconfined. This hypothesis is consistent with the recent observations of Culebra wells responding to rainfall in Nash Draw discussed in Section HYDRO-5.0.

Lowry and Beauheim (2005) expected the leaky-borehole scenario to require less water to match the observed water-level rise than the tailings-pile scenario investigated by Lowry and Beauheim (2004) because it distributes the source, allowing head rises to occur in the south without the water having to come from the north. The tailings-pile scenario, on the other hand, relied only on inflow from the northern portion of the model domain. The mean leakage rate from the tailings-pile recharge scenario from Lowry and Beauheim (2004) is 2.88×10^{-3} m^3/s (73.6 acre-ft/yr or 45.6 gpm). This value is similar to the total leakage rates from Options B and C for the leaky-borehole scenario. However, the tailings-pile-scenario modeling used the Option A method of trying to match the head rise over the entire simulation period to the linearized hydrographs. Had that modeling used the Option B or Option C method of fitting to only the last six years' data, an order of magnitude more leakage may well have been required. Note that the tailings-pile scenario introduces water into the Culebra at essentially the same location as the Upper group of boreholes in the leaky-borehole scenario. Even using the Option A method of calibration, the tailings-pile scenario required an order of magnitude more leakage at the north end of the model domain than the leaky-borehole scenario.

Given the uncertainties and limitations in the model and available data, Lowry and Beauheim (2005) concluded that leakage from units above the Culebra through poorly plugged and abandoned boreholes is a plausible explanation for the long-term rise in water levels observed on and around the WIPP site. The Intrepid East tailings pile may well be the source of the water leaking through a northern group of boreholes, so a combination of the tailings-pile and leaky-borehole scenarios is probably the best explanation for the water-level rises. Natural recharge south of the WIPP where the Culebra is unconfined (or leakage through poorly plugged oil and gas wells) could provide the water ascribed to the southern borehole in the Task 3 calculations. The objective of the water-level rise investigation is considered to have been met by the completion of Tasks 2 and 3. Consequently, modeling the effects of leakage through poorly plugged oil and gas wells and simulation of leakage from injection wells (Task 4 of AP-110) are no longer considered necessary—they would only provide further confirmation that some physically reasonable amount of leakage through unconfirmed, but realistic, pathways is consistent with the observed rising water levels.

HYDRO-10.0 Summary and Conclusions

Hydrological investigations conducted from 2003 through 2007 provided a wealth of new information, some of it confirming long-held assumptions and some offering new insight into the hydrological system around the WIPP site. A Culebra monitoring-network optimization study was completed by McKenna (2004) to identify the locations where new Culebra monitoring wells would be of most value, and to identify wells that could be removed from the network with little loss of information. Eighteen new wells have been completed, guided by the optimization study, geologic motivations, and/or unique opportunities. Seventeen unneeded wells have been plugged and abandoned, and two others have been transferred to the BLM.

The WIPP groundwater monitoring program has augmented monthly water-level measurements in wells with continuous (~hourly) fluid-pressure measurements using downhole programmable pressure gauges (TROLL®). The most significant new finding arising from the high-frequency measurements has been the observation of Culebra water-level responses to rainfall in Nash Draw. The Culebra has long been suspected of being unconfined in at least portions of Nash Draw because of dissolution of the upper Salado, subsidence and collapse of the overlying Rustler, and karst in Rustler gypsum units (e.g., Beauheim and Holt 1990). Continuous monitoring with TROLL® gauges, however, has provided the first direct evidence of Culebra water levels responding to rainfall. Furthermore, the rainfall-induced head changes originating in Nash Draw are now observed to propagate under Livingston Ridge and across the WIPP site over periods of days to months (Hillesheim, Hillesheim, and Toll 2007), explaining some of the changes in Culebra water levels that have occurred from one month to the next. Other water-level changes that appear to occur quite suddenly can now be conclusively related to drilling of nearby oil and gas wells.

Extensive hydraulic testing has been performed in the new wells. This testing has involved both single-well tests, which provide information on local transmissivity and heterogeneity, and long-term (19 to 32 days) pumping tests that have created observable responses in wells up to 9.5 km (5.9 mi) away. The transmissivity values inferred from the single-well tests support the correlation between geologic conditions and Culebra transmissivity developed by Holt and Yarbrough (2002) and elucidated by Holt, Beauheim, and Powers (2005). The types of heterogeneities indicated by the diagnostic plots of the pumping-test data are consistent with the known spatial distribution of transmissivity in the Culebra. Mapping of diffusivity values obtained from analysis of observation-well responses to pumping tests shows areas north, west, and south of the WIPP site connected by fractures, and also a wide area that includes a NE-to-SW swath across the WIPP site where hydraulically significant fractures are largely absent (Beauheim 2007). This mapping, combined with the responses observed to the long-term SNL-14 pumping test, has confirmed the presence of a high-T area extending from the SE quadrant of the WIPP site to at least 10 km to the south.

Geologic studies between 2003 and 2007 focused on Rustler halite margins and karst. The map of Rustler halite margins delineated by Powers (2002) for CRA-2004 was revised by Powers (2007) to incorporate data from recent drilling around the WIPP site. Lorenz (2006a and 2006b) reviewed all historical data and arguments on karst at WIPP, concluding that most of the geological evidence offered for the presence of karst in the subsurface at the WIPP site "has been used uncritically and out of context, and does not form a mutually supporting, scientifically

defensible framework. The remaining evidence is more readily interpreted as primary sedimentary features" (Lorenz 2006b, p. 243). Powers et al. (2006b) provided new details on the gypsum karst present in the Rustler in Nash Draw. Powers (2006a) studied some of the natural brine lakes in Nash Draw, finding some of them to be fed by a shallow gypsum karst system with enough storage to sustain year-round flow, while others were fed by the potash processing effluent discharged by Mosaic Potash Carlsbad into Laguna Uno. Powers (2006a) also mapped closed catchment basins in the southwestern arm of Nash Draw that drain internally to karst features.

Extensive groundwater sampling has been performed in the new wells and selected older wells. The last major geochemical evaluation of Culebra groundwater was performed by Siegel, Robinson, and Myers (1991) based on samples from 22 wells. Samples are now available from 59 wells, allowing refinement and deepening of the conceptual understanding provided by Siegel et al. (1991). Whereas Siegel, Robinson, and Myers (1991) identified only four hydrochemical facies based primarily on ionic strength and major constituents, two transitional facies and one entirely new facies can now be delineated (Domski and Beauheim 2008). The spatial distribution of these facies is consistent with the locations of the Rustler halite margins, the distribution of transmissivity in the Culebra, and the areas of known or suspected recharge to the Culebra.

Combining the Culebra monitoring data with the mapping of catchment basins in southwestern Nash Draw and with groundwater geochemistry data provides insight into Culebra recharge. While some of the water entering gypsum karst in Nash Draw discharges into brine ponds such as Laguna Cinco, some portion of it must come into hydraulic communication with the Culebra, at least locally, because Culebra wells in Nash Draw show water-level responses to major rainfall events (e.g., Figure HYDRO-14). However, these responses do not mean that the precipitation reached the Culebra. Rather, they indicate that the Culebra cannot be completely confined, but must be in hydraulic communication with a water table in a higher unit that does receive direct recharge from precipitation. Some of this water must eventually reach the Culebra, where it is recognized as hydrochemical facies B, but it must first have spent a considerable period in the Rustler gypsum beds to have as high a TDS as it does. As a further indication of the indirect nature of recharge, the water from SNL-16 (located within the small catchment basin shown in yellow in Figure HYDRO-47) does not even fall in the domain of facies B, but is instead facies C water, even though SNL-16 shows a clear pressure response to major rainfall events (Figure HYDRO-14). This shows conclusively that rainfall is not flushing the Culebra rapidly in this area.

Lowry and Beauheim (2004 and 2005) concluded from two modeling studies that leakage from units above the Culebra through poorly plugged and abandoned boreholes is a plausible explanation for the long-term rise in water levels observed on and around the WIPP site. The Intrepid East tailings pile may well be the primary source of leaking water north of the WIPP site, while natural recharge where the Culebra is unconfined southwest of the site could provide the leaking water ascribed to a southern borehole in one of the modeling studies. The studies showed that a physically reasonable amount of leakage through unconfirmed but realistic pathways is consistent with the observed rising water levels.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix IGP-2009
Individual and Groundwater
Protection Requirements

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix IGP-2009
Individual and Groundwater Protection Requirements

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Acronyms and Abbreviations

%	percent
An	actinide
CARD	Compliance Application Review Document
CCA	Compliance Certification Application
CH-TRU	contact-handled transuranic
Ci	curies
Ci/L	curies per liter
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEPs	features, events, and processes
gpd	gallons per day
gpm	gallons per minute
IMC	International Minerals and Chemical
kg/m^3	kilogram per cubic meter
km	kilometer
LWB	Land Withdrawal Boundary
MB	Marker Bed
mg/L	milligrams per liter
mi	mile
mrem	millirem
PA	performance assessment
PAVT	Performance Assessment Verification Test
pCi/L	picocuries per liter
ppm	parts per million
RH-TRU	remote-handled transuranic
SNL	Sandia National Laboratories
TDS	total dissolved solids
TRU	transuranic
UP	undisturbed performance
USDW	underground source of drinking water

WIPP	Waste Isolation Pilot Plant
WQSP	water quality sampling program

Elements and Chemical Compounds

Am	americium
Pu	plutonium
Ra	radium
Th	thorium
U	uranium

IGP-1.0 Introduction

The quantitative release limits set forth in the Containment Requirements provisions of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993) are one of three long-term numerical performance requirements contained in 40 CFR Part 191 Subparts B and C. The Waste Isolation Pilot Plant (WIPP) must also comply with two other quantitative performance standards contained in the individual protection requirements (40 CFR § 191.15, U.S. Environmental Protection Agency 1993) and groundwater protection requirements (Part 191 Subpart C). This appendix describes the U.S. Department of Energy's (DOE's) demonstration of compliance for the WIPP with both the individual and groundwater protection requirements.

In performing the compliance assessment for the Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the CCA Performance Assessment Verification Test (PAVT) (Dials 1997a), the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), and the CRA-2009, the DOE applied a bounding-analysis approach using conservative assumptions that overestimate potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of an underground source of drinking water (USDW) in close proximity to the WIPP Land Withdrawal Boundary (LWB), even though available data indicate that none exists near the boundary. Using this very conservative approach, the maximum potential dose to an individual is 0.032 millirems (mrem) in the CCA PAVT and 0.93 mrem for the CCA evaluation (as revised, consistent with EPA direction). Both values are well below the individual protection standard [40 CFR § 191.15(a)] of 15 mrem as an annual committed effective dose. In addition, the estimated potential maximum combined radium-226 (^{226}Ra) and ^{228}Ra concentration in groundwater is 0.49 picocuries per liter (pCi/L) in the CCA PAVT and 0.14 pCi/L in the CCA Performance Assessment, both well below the acceptable standard of 5 pCi/L required by 40 CFR § 191.24(a)(1) (Dials 1997a).

This conservative approach also assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds potential impacts of underground interconnections among bodies of surface water, groundwater, and any USDW.

In support of its initial recertification effort (the CRA-2004), the DOE reexamined concentrations of radionuclides that could potentially reach the accessible environment under undisturbed conditions. The CRA-2004 evaluation shows that the maximum concentration of radionuclides reaching the boundary is projected to be six orders of magnitude less than the maximum concentration projected in the CCA, as discussed in Section IGP-2.1. Based on this and additional, updated information presented in the CRA-2004, Chapter 8.0, the DOE concluded that the project continued to comply with the individual and groundwater protection provisions of Part 191 Subparts B and C.

In support of the CRA-2009, the DOE has reexamined concentrations of radionuclides that could potentially reach the accessible environment under undisturbed conditions. The CRA-2009 analysis shows that the maximum concentration of radionuclides reaching the boundary is projected to be an order of magnitude less than the maximum concentration projected in the CCA. Based on this and additional information updated for the CRA-2009 evaluation, the DOE concludes that the WIPP continues to comply with the individual and groundwater protection provisions of Part 191 Subparts B and C.

IGP-2.0 Individual Protection Requirements

The individual protection requirements are contained in section 191.15 of the long-term disposal regulations. Section 191.15(a) requires

> Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system to any member of the public in the accessible environment, to exceed 15 mrems (150 microsieverts).

Undisturbed performance (UP) is defined in Part 191 Subpart B to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events" (40 CFR § 191.12, U.S. Environmental Protection Agency 1993). The CCA and CRA-2004 Chapter 6.0, Section 6.3.1 provide a description of UP, the conceptual models associated with UP, and the screening of features, events, and processes (FEPs) that are important to UP.

The method used to evaluate compliance with the individual protection requirements is related to that developed for assessing compliance with the containment requirements. If the evaluation of the UP scenario considered for the containment requirements shows contaminants will reach the accessible environment, the resulting dose to exposed individuals must be calculated and compared to the 15-mrem annual committed effective dose specified in section 191.15.

Further guidance on the implementation of the individual protection requirements is found in 40 CFR Part 194. 40 CFR § 194.51 (U.S. Environmental Protection Agency 1996) states,

> Compliance assessments that analyze compliance with § 191.15 of this chapter shall assume that an individual resides at the single geographic point on the surface of the accessible environment where that individual would be expected to receive the highest dose from radionuclide releases from the disposal system.

40 CFR § 194.52 (U.S. Environmental Protection Agency 1996) states,

> In compliance assessment that analyze compliance with § 191.15 of this chapter, all potential exposure pathways from the disposal system to individuals shall be considered. Compliance assessments with part 191, subpart C and § 191.15 of this chapter shall assume that individuals consume 2 liters per day of drinking water from any underground sources of drinking water in the accessible environment.

In addition, 40 CFR § 194.25(a) (U.S. Environmental Protection Agency 1996) provides criteria related to the assumptions that should be made when undertaking dose calculations:

> Unless otherwise specified in this part or in the disposal regulations, performance assessments and compliance assessments conducted pursuant to the provisions of this part to demonstrate compliance with § 191.13, § 191.15 and part 191, subpart C shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions.

IGP-2.1 Compliance Assessment of Undisturbed Performance

Section 194.52 specifies that compliance assessments shall consider "all potential pathways from the disposal system to individuals." The DOE has considered the following potential pathways for groundwater flow and radionuclide transport:

- Existing boreholes, as required by 40 CFR § 194.55(b)(1) (U.S. Environmental Protection Agency 1996)

- Potential boreholes, including those that may be used for fluid injection, as required by 40 CFR § 194.32(c) (U.S. Environmental Protection Agency 1996) and 40 CFR § 194.54(b)(2) (U.S. Environmental Protection Agency 1996)

After considering all of these pathways, the DOE found that contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial degradation. Two credible pathways by which radionuclides could reach the accessible environment have been identified.

1. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado Formation.

2. Transport may occur through access drifts or anhydrite interbeds (primarily Marker Bed [MB] 139) to the base of the shafts. If the pressure in the panels is greater than the lithostatic pressure of the overlying strata, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface or laterally away from the shafts, through permeable strata, such as the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra), toward the subsurface boundary of the accessible environment.

These conceptual release pathways for UP are illustrated in Appendix PA-2009, Figure PA-8. The modeling system described in the CCA; the CRA-2004, Chapter 6.0, Section 6.4; and Appendix PA-2009, Section PA-2.3.1 does not preclude potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

Although both pathways are possible, the PA modeling indicates that under undisturbed conditions, only the first is a potential pathway during the 10,000-year period of interest specified in the regulation (see Appendix PA-2009, Section PA-7.2).

The DOE has used the modeling system applied to the PA to make this determination. Scenario screening for the UP is described in Appendix SCR-2009. As specified by section 194.54(b)(2), Appendix SCR-2009 identifies activities that may occur in the vicinity of the disposal system prior to or soon after disposal, and documents which of these are included in the compliance assessment calculations. The CRA-2004, Chapter 6.0, Section 6.2, Table 6-8 identifies FEPs included in the UP modeling; these FEPs remain unchanged for the CRA-2009. The CRA-2004, Appendix PA, Attachment SCR also identifies FEPs that were considered, but are not included,

in the modeling evaluation and the reasons for their elimination; this information is also unchanged for the CRA-2009.

As specified by 40 CFR § 194.55(a), uncertainty in the performance of the compliance assessment is documented in the CRA-2004, Chapter 6.0, Section 6.1.2. Probability distributions for uncertain disposal system parameter values used in the compliance assessment were developed and are documented in Fox (2008), which identifies sampled parameters used in the compliance assessment for the CRA-2009.

For the CCA compliance assessment, the CRA-2004 compliance assessment, and the CRA-2009 compliance assessment, 300 realizations of the modeling system were generated to evaluate UP. These 300 realizations are composed of three sets of 100 realizations, each generated using the Latin hypercube sampling method. In all three of the evaluations, none of the 300 realizations show any radionuclides reaching the top of the Salado through the sealed shafts.

In the CCA evaluation, 9 of the 300 realizations show concentrations of radionuclides greater than 0 reaching the accessible environment through the anhydrite interbeds. None of the remaining 291 realizations show radionuclides reaching the accessible environment through the anhydrite interbeds during the 10,000-year period (a realization is considered to have a 0 release if it is less than 1×10^{-18} curies per liter [Ci/L]). The maximum concentrations of radionuclides calculated by the modeling evaluation as reaching the accessible environment in the nine nonzero CCA realizations are shown in Table IGP-1. The full range of estimated values for radionuclide concentrations in the CCA evaluation is from zero to the values shown in Table IGP-1. The maximum concentration values shown in Table IGP-1 occur 10,000 years after the time of decommissioning.

The maximum concentrations of radionuclides calculated by the CRA-2004 evaluation to reach the accessible environment are shown in Table IGP-2. In the CRA-2004 evaluation, only 1 of the 300 realizations shows concentrations of radionuclides greater than 0 reaching the accessible environment through the anhydrite interbeds (see the CRA-2004, Appendix PA, Section PA-7.2). The remaining 299 realizations show no radionuclides reaching the accessible environment during the 10,000-year period. The reduction in the number of realizations showing radionuclides reaching the accessible environment is due to changes in the BRAGFLO grid and enhancements to the PA modeling system that increased model accuracy and decreased numerical dispersion.

In this single CRA-2004 realization, only one radionuclide has a nonzero concentration reaching the accessible environment. The radionuclide plutonium-239 (^{239}Pu) has a concentration of 2.53×10^{-18} Ci/L (Garner 2003). This compares with the maximum concentration of ^{239}Pu calculated for the CCA evaluation of 5.85×10^{-12} Ci/L. The concentration of ^{239}Pu in the CRA-2004 evaluation is six orders of magnitude lower than that shown for the CCA evaluation. In the CRA-2004 evaluation, no other radionuclides are calculated in concentrations greater than the 10^{-18} cutoff, whereas americium-241 (^{241}Am), uranium-234 (^{234}U), and thorium-230 (^{230}Th) all had concentrations exceeding the cutoff in the CCA. Because the CRA-2004 evaluation shows only one radionuclide contributing to a potential dose, and the concentration is six orders of magnitude lower than that shown for the CCA evaluation, the CCA dose estimates are bounding. No new dose calculations were necessary.

Table IGP-1. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CCA Analysis

CCA Realization No.	Maximum Concentrations (Ci/L)					
	Vector No.[a]	^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 46	1.36×10^{-17}	4.33×10^{-12}	Negligible[b]	5.82×10^{-13}	2.10×10^{-14}
2	Replicate 2 Vector 16	Negligible	5.13×10^{-14}	Negligible	6.77×10^{-15}	1.89×10^{-17}
3	Replicate 2 Vector 25	Negligible	1.35×10^{-15}	Negligible	1.65×10^{-16}	7.00×10^{-18}
4	Replicate 2 Vector 33	1.32×10^{-17}	7.18×10^{-14}	Negligible	9.76×10^{-15}	9.36×10^{-16}
5	Replicate 2 Vector 81	Negligible	6.23×10^{-18}	Negligible	Negligible	Negligible
6	Replicate 2 Vector 90	Negligible	5.20×10^{-16}	Negligible	7.40×10^{-17}	Negligible
7	Replicate 3 Vector 3	3.50×10^{-18}	3.08×10^{-13}	Negligible	4.32×10^{-14}	1.07×10^{-16}
8	Replicate 3 Vector 60	5.98×10^{-17}	7.41×10^{-14}	Negligible	9.09×10^{-15}	2.30×10^{-15}
9	Replicate 3 Vector 64	5.42×10^{-17}	5.85×10^{-12}	Negligible	7.61×10^{-13}	4.68×10^{-15}
10-300	—	Negligible	Negligible	Negligible	Negligible	Negligible

[a] Parameter values applied to each vector may be found in the CCA, Appendix IRES, Table IRES-2, Table IRES-3, and Table IRES-4.
[b] Values less than 10^{-18} Ci/L are considered negligible relative to the other values and are not reported.

Table IGP-2. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CRA-2004 Analysis

CRA-2004 Realization No.	Vector No.[a]	Maximum Concentrations (Ci/L)				
		^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 82	Negligible[b]	2.53×10^{-18}	Negligible	Negligible	Negligible
2-300	—	Negligible	Negligible	Negligible	Negligible	Negligible

[a] Parameter values applied to each vector may be found in the CRA-2004, Appendix PA, Attachment PAR.
[b] Values less than 10^{-18} Ci/L are considered negligible relative to the other values and are not reported.

As with the CRA-2004 evaluation, the CRA-2009 evaluation shows that 1 of the 300 realizations results in concentrations of radionuclides greater than 0 reaching the accessible environment through the anhydrite interbeds (Ismail 2008a). All of the remaining 299 realizations show no radionuclides reaching the accessible environment during the 10,000-year period. The maximum concentrations of radionuclides calculated by the CRA-2009 evaluation to reach the accessible environment are shown in Table IGP-3.

Table IGP-3. Maximum Concentrations of Radionuclides Within the Salado Interbeds at the Disposal System Boundary for the CRA-2009 Analysis[a,b]

CRA-2009 Realization No.	Vector No.[c]	Maximum Concentrations (Ci/L)				
		^{241}Am	^{239}Pu	^{238}Pu	^{234}U	^{230}Th
1	Replicate 1 Vector 53	1.71×10^{-18}	3.83×10^{-13}	Negligible	1.14×10^{-15}	1.83×10^{-16}
2-300	—	Negligible	Negligible	Negligible	Negligible	Negligible

[a] Ismail and Garner 2008.
[b] Values less than 10^{-18} Ci/L are considered negligible relative to the other values and are not reported.
[c] Parameter values applied to each vector may be found in Fox 2008.

The increase in the maximum concentration of radionuclides reaching the accessible boundary in the CRA-2009 PA compared with the CRA-2004 PA is due to an error correction in the halite porosity parameter (Ismail 2007). In undisturbed conditions, pressure strongly influences the extent to which contaminated brine might migrate from the repository to the accessible environment. In general, pressure increased in the CRA-2009 PA compared with the CRA-2004 PA (see Nemer and Clayton, Table 6-10 [2008]). The increase was attributed to the correction in the halite porosity. The upper bound of the halite porosity distribution was increased from 0.03 to 0.05, while the lower bound and the mean remained the same. Halite porosity is positively correlated with pressure, so the increase in porosity resulted in an increase in pressure (Nemer and Clayton 2008).

As with the CRA-2004, the CCA dose calculations are bounding for the CRA-2009 evaluation. All of the radionuclide concentrations resulting from the CRA-2009 analysis are at least one order of magnitude smaller than the concentrations derived from the CCA analysis; no new dose calculations are necessary.

It is important to understand that the magnitude of the computed releases reported in Table IGP-1 through Table IGP-3 is smaller than the effective numerical precision of the transport calculations. As explained in Lowry (2005), the values for the single vector showing nonzero concentrations are believed to be the result of numerical dispersion inherent in the NUTS finite-difference solution method. The magnitude of the nonzero releases is indicative of numerical dispersion resulting from the coarse grid spacing between the repository and the LWB, rather than containment transport.

IGP-2.2 Dose Calculation

As quoted earlier, section 194.51 states that doses must be estimated for an individual who resides at the location in the accessible environment where that individual would be expected to receive the highest exposure to radionuclide releases from the disposal system. All potential pathways for exposure associated with the UP of the repository must be assessed (section 194.52).

IGP-2.2.1 Transport Pathway

To perform the required dose calculation for the CCA, it was necessary to select possible pathways for the transport of the contaminants from the anhydrite interbeds to a receptor. The chosen pathway is an abandoned, deep borehole that intersects the contaminant plume in the accessible environment. Consistent with assumptions described in the CRA-2004, Chapter 6.0, Section 6.4.7.2 and the information provided in the CCA, Appendix DEL, the hole is assumed to have the permeability of an uncased hole filled with silty sand after the degradation of a borehole plug in the Rustler Formation. A pressure gradient is assumed to exist because of the pressures in the anhydrite resulting from gas generation in the repository. The pressures are assumed to be greater than hydrostatic to force contaminants up the abandoned hole to the Culebra or the Dewey Lake Formation. The contaminants would then be available to a receptor through a well used to supply drinking water. This conceptual transport pathway is shown in Figure IGP-1. This is the only credible pathway that the DOE has been able to identify.

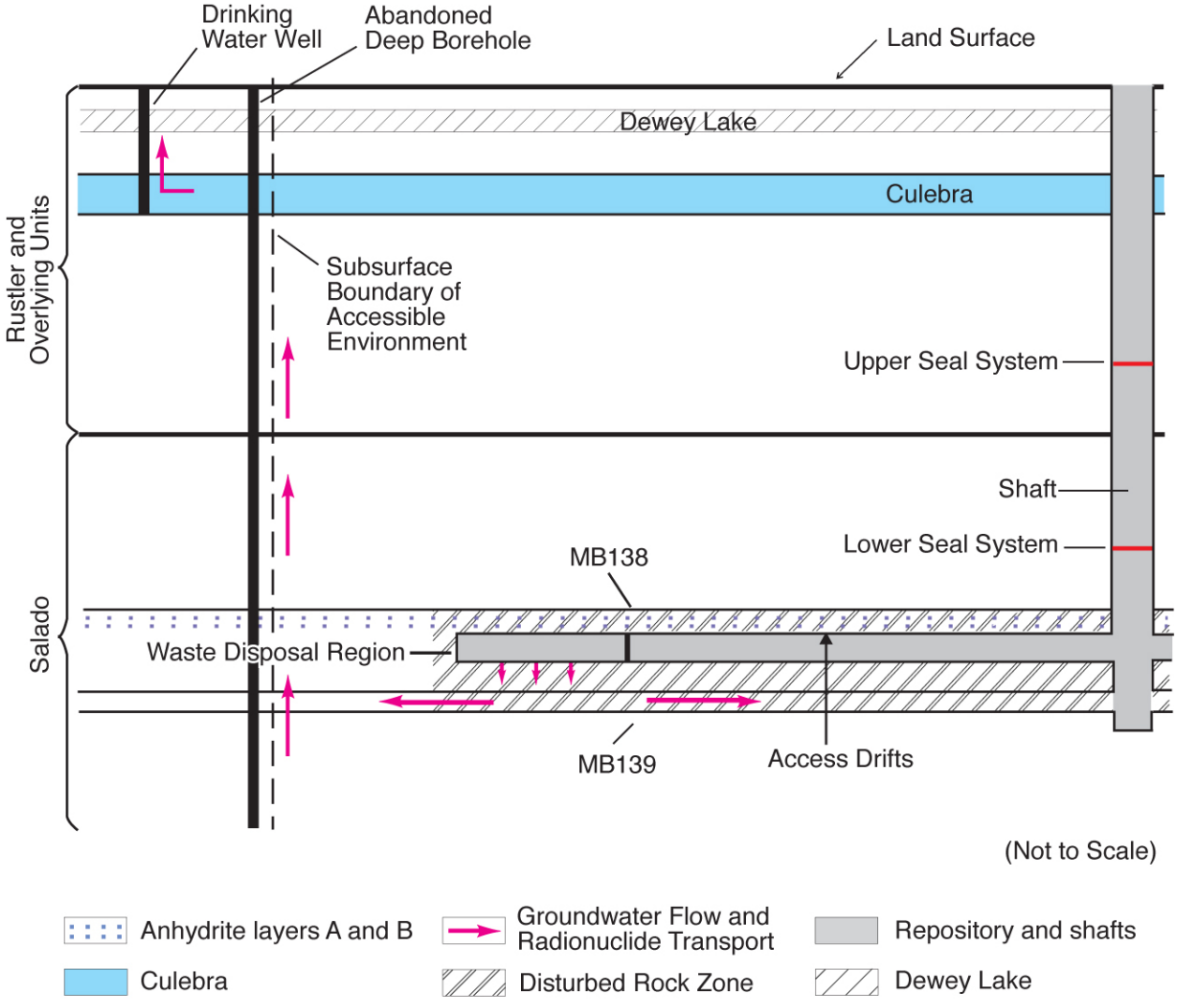

Figure IGP-1. Conceptual Transport Pathway

As specified in 40 CFR § 194.54(b), this pathway considers the presence of an existing borehole. As discussed in the CRA-2004, Chapter 6.0, Section 6.2.5, the influence of other existing boreholes has been evaluated in the FEPs screening for UP.

IGP-2.2.2 Bounding Analysis

Uncertainty in calculating radionuclide concentrations in the anhydrite interbeds is described in the CRA-2004, Chapter 6.0, Section 6.1.2 and updated for the CRA-2009 by Ismail and Garner (2008). Additional uncertainty is involved in the calculation of doses resulting from the specified exposure pathway. Given this uncertainty, the DOE elected for the CCA evaluation to perform a bounding analysis using assumptions that do not represent reality, but that would result in a bounding estimate much greater than any reasonably expected dose to a receptor. If this bounding analysis results in calculated doses to the receptor that are below the regulatory limit, compliance with the standard is demonstrated. If subsequent analyses, such as those performed to support this application, have lower initial concentrations than the bounding CCA analysis, recalculating the doses is unnecessary because the results of the original bounding analysis are below regulatory limits.

The bounding analysis used for the CCA assessment was based on the following factors and assumptions:

1. No specific transport mechanism was postulated. Instead, it was assumed that all contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases (that is, year 10,000) were available to a receptor.

2. Brine derived from the anhydrite interbeds had total dissolved solids (TDS) concentrations of about 324,000 parts per million (ppm); this represents a concentration that could not be consumed by humans. For the bounding analysis, the calculation includes the dilution of this brine by a factor of 32.4 to a TDS concentration of 10,000 ppm, which is the upper limit for potable water.

3. The resulting annual committed effective dose was calculated based on a 50-year dose commitment. A 50-year dose commitment was selected because this period is specified in Part 191, Appendix B and because it is the duration for which published external dose-rate conversion factors are readily available in the literature (U.S. Department of Energy 1988).

4. The individual receptor was assumed to drink two liters of water each day (as specified in section 194.52) for one year (in accordance with the specification of an annual committed effective dose in Part 191, Appendix B).

Section 194.51 states that DOE shall assume an individual resides at the single geographic point where that individual would receive the highest dose. With the bounding analysis, the DOE complies with the intent of this criterion, but the specific location of the receptor is not identified because all contaminants reaching the accessible environment within the anhydrite interbeds during the year of maximum releases are assumed to be directly available to the receptor, regardless of the receptor's location. The well from which the receptor drinks is assumed to be

located where the contaminants reaching the anhydrite interbeds are delivered directly to the well.

The bounding analysis dose calculation was performed using the GENII-A code. The CCA, Appendix GENII describes the modeling method. GENII-A incorporates dose-calculation guidance provided in Part 191, Appendix B.

IGP-2.3 Dose Calculation Results

The maximum doses calculated from the releases listed in Table IGP-1, after applying the factors and assumptions listed above, are shown in Table IGP-4. These doses are greater than any realistic doses that could be delivered to a receptor. The calculated doses are well below the regulatory standard, which is an annual committed effective dose of 15 mrem.

Table IGP-4. Calculated Maximum Annual Committed Effective Doses for the CCA Evaluation

Realization No.	Vector No.[a]	Maximum Annual Committed Effective Dose (mrem)
1	Replicate 1 Vector 46	3.4×10^{-1}
2	Replicate 2 Vector 16	4.3×10^{-3}
3	Replicate 2 Vector 25	1.1×10^{-4}
4	Replicate 2 Vector 33	5.8×10^{-3}
5	Replicate 2 Vector 81	5.1×10^{-7}
6	Replicate 2 Vector 90	4.3×10^{-5}
7	Replicate 3 Vector 3	2.5×10^{-2}
8	Replicate 3 Vector 60	6.2×10^{-3}
9	Replicate 3 Vector 64	4.7×10^{-1}
10-300	—	Negligible[b]

[a] Parameter values applied to each vector may be found in the CCA, Appendix IRES, Table IRES-2, Table IRES-3, and Table IRES-4.
[b] Doses derived from Table IGP-1 concentration values of less than 10^{-18} Ci/L are considered negligible and are not reported.

On February 26, 1997, the DOE submitted supplementary information to the EPA in response to an EPA request for additional information (Dials 1997b, Enclosure 2h). The supplementary information describes how the DOE extended its initial bounding analysis to account for exposure pathways other than direct ingestion of contaminated water by humans. Specifically, the analysis was expanded to include consumption of contaminated water by cattle (leading to

the receptor's consumption of contaminated milk and beef), consumption of crops irrigated with contaminated water, and inhalation of airborne dust from soil contaminated by irrigation. The DOE found that the contribution of these pathways added 0.46 mrem per year to the calculated groundwater dose associated with the realization showing the highest concentration of radionuclides reaching the boundary of the accessible environment under undisturbed conditions of 0.47 mrem per year. Thus, the maximum total dose calculated from all pathways was 0.93 mrem per year, well below the 15-mrem-per-year standard.

Given that the maximum concentration of radionuclides shown to reach the accessible environment for the CRA-2004 analysis is six orders of magnitude less than the maximum value calculated for the CCA evaluation, resulting potential doses to the receptor would also be well below the 15-mrem standard. As such, the CCA dose calculation bounded any possible dose to a receptor for the CRA-2004 evaluation, and new dose calculations were not needed to demonstrate compliance.

The CRA-2009 calculations show that radionuclides reach the accessible environment at a maximum concentration one order of magnitude smaller than the maximum concentration shown for the CCA analysis. As such, the CCA results continue to be bounding for the CRA-2009; continued compliance with the individual protection standard is demonstrated.

IGP-2.4 Statistical Assessment

40 CFR § 194.55(d) specifies that the "number of estimates generated pursuant to paragraph (c) of this section shall be large enough such that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates with at least a 0.95 probability." The probability that an individual estimate is below the 99th percentile is, by definition, 0.99. This means that only 1 in 100 estimates would have a value exceeding the 99th percentile, or conversely, 99 times out of 100 the estimate would have a value below the 99th percentile. It follows that for 2 independent estimates, the probability of both estimates having a value below the 99th percentile is equal to the product (0.99)(0.99), or $(0.99)^2$, and that for n estimates, the probability that all estimates have a value below the 99th percentile is equal to $(0.99)^n$. To ensure a value exceeds the 99th percentile with a specified probability, the complement $(1 - 0.99^n)$ is used to calculate the number of estimates required.

The probability specified by section 194.55(d) is 0.95, or 95% confidence, that the maximum estimates of doses and concentrations generated exceed the 99th percentile of the population of estimates. Therefore, the following equation can be solved for n, and the number of estimates required is

$$1 - 0.99^n = 0.95 \text{ or } (n)\log(0.99) = \log(0.05) \qquad \text{(IGP.1)}$$

which implies $n > 298$.

The solution requires n to be greater than 298 and was used to determine that 300 realizations of the modeling system is a sufficient number to meet the confidence level specified in section 194.55(d).

The 300 realizations of the modeling system (as described in Section IGP-2.1) report concentrations of radionuclides reaching the accessible environment within the Salado anhydrite interbeds and not doses to a receptor, as specified by section 194.55(d). Nevertheless, the maximum possible resulting annual dose to an individual for the CCA analysis is 0.93 mrem, the sum of 0.47 mrem (as reported in Table IGP-4) plus the additional value of 0.46 mrem determined to be contributed through additional dose pathways. All other calculated doses resulting from the 300 realizations of the modeling system for the CCA, CRA-2004, and CRA-2009 evaluations are below this value.

40 CFR § 194.55(f) specifies that the DOE shall

> document that there is at least a 95 % level of statistical confidence that the mean and the median of the range of estimated radiation doses and the range of estimated radionuclide concentrations meet the requirements of § 191.15 and part 191, subpart C of this chapter, respectively.

The DOE has developed a bounding analysis that exceeds the mean and median doses, providing greater than 95% confidence that all potential doses will be below the 0.93 mrem value.

IGP-2.5 Parameter Values

Parameter values applied to the CCA modeling assessment for UP are described in the CCA, Appendix PAR and Chapter 8.0, Section 8.1.5. Parameters used in the PA and compliance assessment modeling program for the CRA-2004 are described in the CRA-2004, Appendix PA, Attachment PAR. As provided by 40 CFR § 194.55(b), the CRA-2004, Appendix PA, Attachment PAR also identifies the probability distributions for these parameters, their units, the models and codes in which the parameters are used, the functional form of the probability distributions used for the sampled parameters, and associated input data. This same information is provided in support of the CRA-2009 in Fox (2008).

IGP-2.6 Summary of Compliance with the Individual Protection Standard

In performing the compliance assessment, the DOE applied a bounding-analysis approach using conservative assumptions that overestimate potential doses and contaminant concentrations. This conservative approach assumes that all contaminants reaching the accessible environment are directly available to a receptor. Using this very conservative approach, the calculated maximum potential dose to an individual from the CCA evaluation would be about one-sixteenth of the individual protection standard. Given that modeled maximum radionuclide concentrations in the accessible environment for the CRA-2004 and the CRA-2009 evaluations are well below those of the CCA evaluation, the CCA results are bounding and continued compliance with the individual protection standard is demonstrated.

IGP-3.0 Groundwater Protection Requirements

The groundwater protection requirements are contained in Part 191 Subpart C. In particular, 40 CFR § 191.24(a)(1) requires the following:

> *General.* Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment, to exceed the limits specified in 40 CFR Part 141 as they exist on January 19, 1994.

40 CFR Part 141 specifies the National Primary Drinking Water Standards. The levels of radioactivity (and dose equivalent, in the case of 40 CFR § 141.16(a)) specified as of January 19, 1994 were

1. Combined ^{226}Ra and ^{228}Ra (40 CFR § 141.15(a)): 5 pCi/L

2. Gross alpha particle activity, including ^{226}Ra but excluding radon and uranium (40 CFR § 141.15(b)): 15 pCi/L

3. Annual dose equivalent to the total body or any internal organ from the average annual concentration of beta particle and photon radioactivity from man-made radionuclides (section 141.16(a)): 4 mrem per year

In addition, 40 CFR § 194.53 (U.S. Environmental Protection Agency 1996) applies to DOE's consideration of USDWs. The criterion specifies

> In compliance assessments that analyze compliance with part 191, subpart C of this chapter, all underground sources of drinking water in the accessible environment that are expected to be affected by the disposal system over the regulatory time frame shall be considered. In determining whether underground sources of drinking water are expected to be affected by the disposal system, underground interconnections among bodies of surface water, groundwater, and underground sources of drinking water shall be considered.

To assess compliance with these provisions of the regulations, it is first necessary to identify any USDW that may be located near the WIPP. The DOE's evaluation of whether any USDW is located near the WIPP is provided in the CCA, Appendix USDW and is summarized in the CCA, Chapter 8.0, Section 8.2.2. In developing the CRA-2004, the DOE reevaluated the presence of USDWs near the WIPP and supplemented the information presented in the CCA, Appendix USDW. The supplemental information is provided in the CRA-2004, Chapter 8.0, Section 8.2.2. Based on the CRA-2004 review, the DOE concluded that no deviation from the findings and conclusions of the 1996 evaluation was warranted.

For the CRA-2009, the DOE has again reevaluated the presence of USDWs near the WIPP. Supplemental information is provided in Section IGP-3.2. Based on this reevaluation, the DOE again concludes that no deviation from the CCA findings and conclusions is warranted.

IGP-3.1 Criteria for USDW Determination

In evaluating the presence of any USDW, it is necessary to establish criteria for water quality and quantity data from wells in the vicinity of the WIPP. The criteria must be based on the regulatory definition of a USDW, as provided in 40 CFR § 191.22 (U.S. Environmental Protection Agency 1993). A USDW is defined in section 191.22 to mean an aquifer or its portion that

> (1) Supplies any public water system; or
> (2) Contains a sufficient quantity of groundwater to supply a public water system; and
> (i) Currently supplies drinking water for human consumption; or
> (ii) Contains fewer than 10,000 milligrams of total dissolved solids per liter.
> "Public water system" means a system for the provision to the public of piped water for human consumption, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals. Such term includes:
> (1) Any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with such system; and
> (2) Any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system.
> "Total dissolved solids" means the total dissolved (filterable) solids in water as determined by use of the method specified in 40 CFR Part 136.

Criteria based on these definitions were developed by the DOE and are used to assess the presence of any USDW near the WIPP. These criteria are defined in the sections that follow.

IGP-3.1.1 Groundwater Quantity

Two subcriteria have been identified by the DOE and applied to the groundwater quantity definition.

1. An aquifer or its portion must be capable of producing water at an adequate rate.

2. An aquifer or its portion must be capable of producing water for a sufficient duration.

Water-consumption information was evaluated by the DOE to define the first subcriterion (the ability to produce at an adequate rate). The value to be applied is determined by obtaining the following information:

1. The rate, over a 24-hour period, at which water is consumed by 15 service connections

2. The rate, over a 24-hour period, at which water is consumed by 25 individuals

To define a USDW, the lower of these two values is assigned by the DOE to the first subcriterion. Based on calculations presented in the CCA, Appendix USDW and updated in support of the CRA-2004, a quantity of 5 gallons per minute (gpm) is assigned as the first subcriterion. Details on the derivation of the five-gpm value is provided below.

For the CCA evaluation, the rate of consumption by 15 service connections was calculated using the data provided in Table IGP-5. These are 1990 U.S. Bureau of the Census data for the number of persons per household in southeastern New Mexico communities, and water-

consumption data for the same communities. The water-consumption data were obtained from the New Mexico State Engineer's Office (Wilson and Lucero 1997).

Table IGP-5. Persons Per Household and Water Consumption Values Used in the CCA

Community	Persons Per Household, 1990[a]	Gallons Per Capita Per Day[b]
Artesia	2.69	285
Carlsbad	2.63	307
Hobbs	2.81	267
Lovington	2.96	264
Roswell	2.66	285
Average	2.75	282

Sources: a. U.S. Bureau of the Census (1990, pp. 15–16); b. Wilson and Lucero (1997).

As reported in Wilson and Lucero (1997), the average water usage in these communities was 282 gallons per person per day. The 1990 census statistics for these communities show an average of 2.75 people per household. One household equals one service connection.

Therefore,

- 2.75 people × 282 gallons per person, per day = 775.5 gallons per service connection, per day
- 775.5 gallons per day (gpd), per service connection × 15 connections = 11,633 gpd
- 11,633 gpd/1,440 minutes per day = 8.08 gpm

The rate of consumption by 15 service connections, based on the 1990 and 1992 statistics, is calculated to be 8.08 gpm.

The rate at which water would be consumed by 25 individuals over a 24-hour period may be calculated using these same data. The average water usage was 282 gallons per person, per day in area communities. The consumption of water by 25 people equals

- 282 gallons per person, per day × 25 people = 7,050 gpd
- 7,050 gpd/1,440 minutes per day = 4.89 gpm

Based on these two calculations, the quantity consumed by 25 individuals (4.89 gpm; nominally 5 gpm) is smaller than the quantity consumed by 15 service connections (8.08 gpm). Therefore, the 5-gpm value was applied to the CCA evaluations.

In updating this calculation for the CRA-2004, more current census data and water consumption data were obtained (Wilson et al. 2003). These more current data are provided in Table IGP-6.

The average water usage in these communities is 305 gallons per person per day, and the 2000 census statistics for these communities show an average of 2.64 people per household (Table IGP-6). One household equals one service connection.

Table IGP-6. Persons Per Household and Water Consumption Values Used in the CRA-2004

Community	Persons Per Household, 2001[a]	Gallons Per Capita Per Day, 2000[b]
Artesia	2.61	390
Carlsbad	2.51	277
Hobbs	2.72	284
Lovington	2.80	289
Roswell	2.58	283
Average	2.64	305

Sources: a. U.S. Bureau of the Census (2001); b. Wilson et al. (2003).

Therefore,

- 2.64 people × 305 gallons per person, per day = 805.2 gallons per service connection, per day
- 805.2 gpd, per service connection × 15 connections = 12,078 gpd
- 12,078 gpd/1,440 minutes per day = 8.39 gpm

Using updated data, the rate of consumption by 15 service connections is calculated to be 8.39 gpm.

The rate at which water would be consumed by 25 individuals over a 24-hour period may be calculated using these same data. The current average water usage is 305 gallons per person, per day in area communities. The consumption of water by 25 people equals

- 305 gallons per person, per day × 25 people = 7,625 gpd
- 7,625 gpd/1,440 minutes per day = 5.30 gpm

Based on these two calculations, the quantity consumed by 25 individuals (5.30 gpm; nominally 5 gpm) is smaller than the quantity consumed by 15 service connections (8.39 gpm). To conservatively determine the quantity derived from a well that meets the quantity subcriterion, the 5-gpm value is applied. No change in this subcriterion is warranted as a result of applying current census and water consumption data to the calculation.

In updating this information for the CRA-2009, more recent water consumption data were obtained from the New Mexico Office of the State Engineer (Longworth et al. 2008). More recent persons-per-household data were not available. The water consumption data show that the average per capita consumption decreased to 273 gpd (Table IGP-7). When the calculation above is repeated with the updated average consumption value, the rate of consumption for 15

service connections is 7.51 gpm. For 25 people, the value is 4.74 gpm. Based on this rate, it is concluded that applying the 5-gpm subcriterion is still valid for a bounding analysis. No change in this subcriterion is warranted as a result of applying more current water-consumption data to the calculation.

Table IGP-7. Persons Per Household and Water Consumption Values Used in the CRA-2009

Community	Persons Per Household, 2001[a]	Gallons Per Capita Per Day, 2005[b]
Artesia	2.61	344
Carlsbad	2.51	271
Hobbs	2.72	257
Lovington	2.80	235
Roswell	2.58	256
Average	2.64	273

Sources: a. U.S. Bureau of the Census (2001); b. Longworth et al. (2008).

The definition of the second quantity subcriterion (the acceptable production duration of a well) is more subjective. Because the creation of a public water supply system involves considerable capital expense, it is reasonable to assume that such a water system would not be constructed unless the water source would continue to be available for some time, at least long enough to recover the capital expense. The Rural Utility Service of the U.S. Department of Agriculture provides loans to fund new rural water supply systems. The loan periods are generally 40 years in duration. Based on this, a duration of 40 years is applied by the DOE to the second quantity subcriterion.

IGP-3.1.2 Groundwater Quality

A criterion of 10,000 milligrams per liter (mg/L) of TDS is specified in section 191.22. Any aquifer or its water-producing portion with TDS concentrations below this level is determined to produce water that meets the quality criterion for a USDW. Any aquifer or its water-producing portion with TDS concentrations at or above this level is determined to produce water that does not meet the quality criterion and the regulatory definition of a USDW.

IGP-3.2 Comparison with USDW Determination Criteria

For the CCA evaluation, current conditions and available hydrogeologic data were reviewed by the DOE to assess the presence of USDWs near the WIPP. This assessment compares current conditions and available data to the groundwater quantity and quality criteria described above. The results of this comparison are summarized below and provided in detail in the CCA, Appendix USDW.

Five geologic units within the vicinity of the WIPP could potentially meet the definition of a USDW under Part 191, Subpart C:

1. The Capitan Aquifer of the Guadalupian reef complex
2. The Culebra
3. The Magenta
4. The Dewey Lake
5. The Santa Rosa

Investigations conducted in the vicinity of the WIPP to characterize the hydrology of these formations are described in the CCA, Appendix USDW. Important sources of relevant information are identified and findings or conclusions related to the presence of USDWs are provided. Based on this work and the updates performed to support the CRA-2004 and the CRA-2009, the DOE has concluded that USDWs are present in the Culebra, and, because of inconclusive groundwater production data, possible USDWs are present in the Dewey Lake and the Santa Rosa. USDWs in the Culebra are located at WIPP water quality sampling program (WQSP) wells H-07b1, H-08b, and H-09b about 4.8, 14.5, and 10.5 kilometers (km) (3, 9, and 6.5 miles (mi)) to the south/southwest of the controlled area boundary, respectively. Possible USDWs may occur in the Dewey Lake, about 1.6 km (1 mi) south of the controlled area boundary, and the Santa Rosa, 12.4 to 14.5 km (7.7 to 9 mi) to the east of the controlled area boundary, where private wells (used predominantly for supplying water to livestock) have not generated sufficient available groundwater production data to assess their potential to meet section 191.22 requirements. In the absence of such data, these wells are designated as being located in possible USDWs.

In reevaluating the conclusions presented in the CCA, Appendix USDW for the CRA-2004, the DOE reviewed available groundwater quality and quantity data for the wells identified in the appendix to determine if any data collected since 1996 were available. In addition, a review was performed to determine if any wells not reported in the CCA, Appendix USDW were drilled that could provide groundwater quality (i.e., TDS concentrations) and groundwater quantity data. The CRA-2004 reports that one new well, identified as well C-2737, was developed at the WIPP site. This well was drilled during February and March of 2001 to replace well H-1, which was plugged and abandoned. In February of 2001, a water sample from the upper Dewey Lake Formation was obtained from this well. Laboratory analysis of this sample showed a TDS concentration of 2,590 ppm (Powers 2002).

The CRA-2004 also reports that additional wells were installed across the WIPP site to investigate the extent of anthropogenic groundwater at the contact of the Santa Rosa and Dewey Lake. Four monitoring wells and 12 piezometer wells were emplaced. The results of multiple rounds of sampling and analyses from these wells are reported in Duke Engineering Services (1997). Samples from several of these wells show TDS concentrations both below and above 10,000 ppm, although it was not possible to pump water from any of these wells at rates of 5 gpm or more.

In addition, State of New Mexico records indicate that several new wells were drilled in the southwestern portion of the study area evaluated in the CCA, Appendix USDW. These records, however, include no TDS or production data.

In developing the CRA-2009, available groundwater data were reviewed again to determine if any data from new or existing wells might influence USDW determinations. Since the submittal of the CRA-2004, 18 new wells have been completed in the Culebra. The locations of these wells are shown in Figure IGP-2. TDS concentrations and pumping rates observed from these

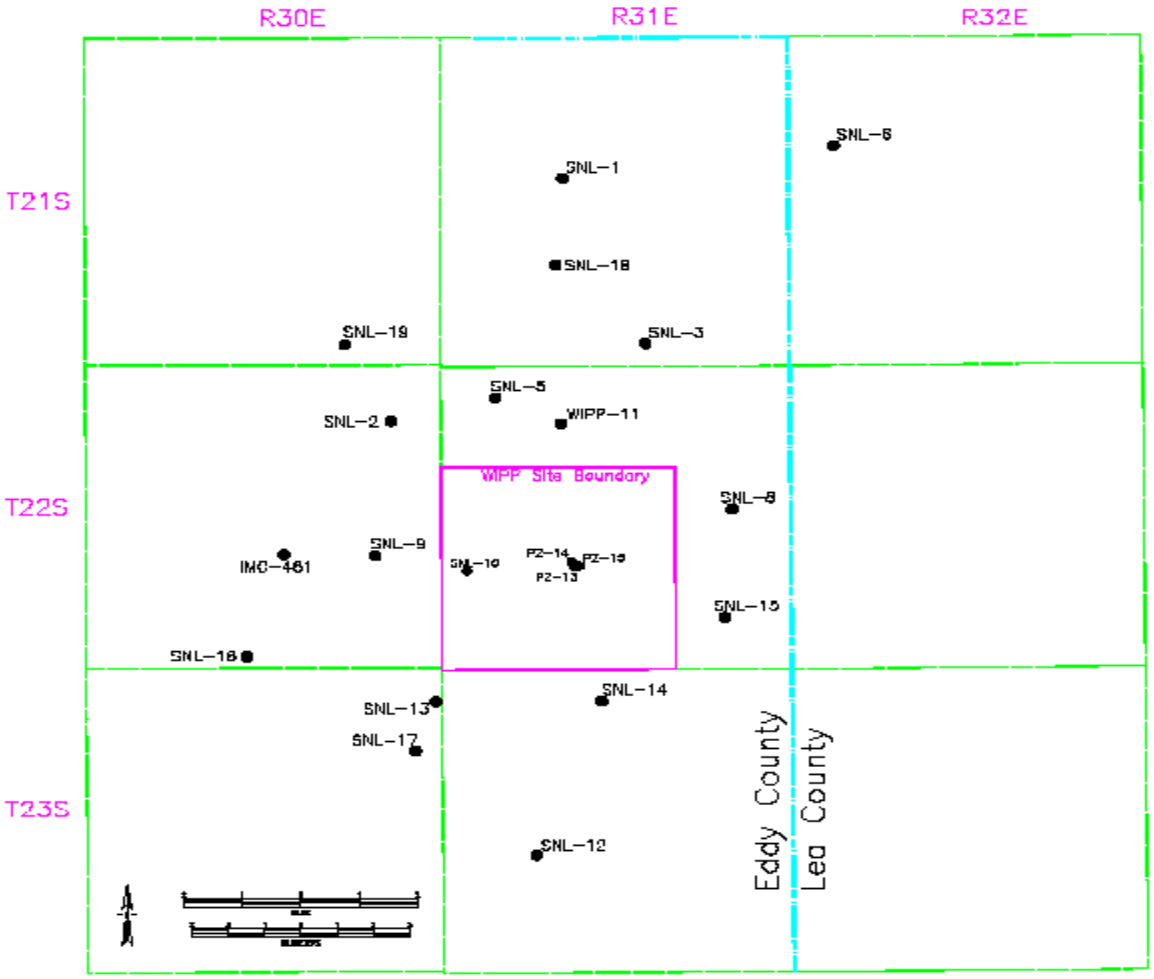

Figure IGP-2. Locations of Recent Culebra Wells and Shallow Piezometers

wells are provided in Table IGP-8. The table also shows USDW determinations based on the determination criteria. These data support the earlier conclusion that a USDW occurs in parts of the Culebra in the vicinity of the WIPP.

In 2007, three shallow (77 feet deep) piezometer wells were drilled on the WIPP site in the vicinity of the Site and Preliminary Design Validation salt pile to determine if shallow subsurface water exists in this area (U.S. Department of Energy 2008). Water samples from PZ-13 and PZ-14 showed TDS concentrations significantly in excess of 10,000 mg/L; PZ-15 showed levels below that concentration. Results from the first two samples are believed to indicate that this shallow water is associated with the salt pile, whereas the source of PZ-15 perched water is believed to be shallow infiltration from a topographic depression east of the salt pile. Despite the fact that the PZ-15 well showed a low TDS concentration, none of these wells

meet the pumping rate subcriterion; all wells pumped dry within the sampling period. Therefore, none of these wells indicates the presence of a USDW.

Recent TDS data are also available through the WIPP WQSP, which is a detection monitoring program operated under the provisions of the WIPP Hazardous Waste Facility Permit. One WQSP well, WQSP-6A, shows TDS concentrations below 10,000 mg/L. This well is completed

Table IGP-8. Data Obtained from Recent Culebra Wells

Well	Date Sample Collected	TDS (mg/L)	Pumping Test Dates	Pumping Rate (gpm)	Meets USDW Criteria? (Y, N)
SNL-1[a]	5/29/2004	36,000	5/24-5/29/2004	12.00	N
—	3/10/2005	34,000	—	—	N
SNL-2	1/17/2004	11,000	1/19-1/24/2005	12.00	N
—	1/24/2005	9,500	—	—	Y
SNL-3	4/16/2004	47,000	4/13-4/16/2004	10.00	N
SNL-5	7/24/2004	130,000	7/19-7/24/2004	3.50	N
SNL-6	NA	NA	NA	NA	NA
SNL-8	8/2/2007	140,000	7/31-8/3/2007	0.50	N
SNL-9	11/19/2004	25,000	10/22-11/23/2004	16.00	N
SNL-10	11/3/2006	8,500	10/30-11/3/2006	0.25	N
SNL-12	8/14/2004	4,200	8/9-8/14/2004	20.00	Y
SNL-13	7/17/2006	21,000	NA	NA	N
SNL-14	8/26/2005	83,000	8/4-8/26/2005	30.00	N
—	7/30/2007	86,000	—	—	N
WIPP-15	3/30/2007	280,000	NA	NA	N
WIPP-16	6/9/2006	18,000	6/5-6/9/2006	25.00	N
WIPP-17	9/15/2006	3,200	9/11-9/15/2006	32.00	Y
WIPP-18	8/18/2006	19,000	8/14-8/18/2006	30.00	N
WIPP-19	7/28/2006	8,100	7/24-7/28/2006	30.00	Y
WIPP-11	12/15/2004	50,000	2/1-2/20/2005	35.00	N
—	2/20/2005	49,000	—	—	N
IMC-461[b]	8/4/2006	9,900	NA	NA	Possible

Source: CRA-2009, Appendix HYDRO-2009

[a] SNL = Sandia National Laboratories

[b] IMC = International Minerals and Chemical

in the Dewey Lake. All of the other WQSP wells, Wells 1 through 6, are completed in the Culebra. All of the recent data for the Culebra wells show TDS concentrations above 10,000 mg/L. All of the recent data from the WQSP wells are consistent with earlier data in the context of USDW determinations. No changes to the earlier USDW determinations are warranted based on the recent data.

As with the CRA-2004, it was found that State of New Mexico records indicate that several new wells were drilled in the study area evaluated in the CCA, Appendix USDW. These records, however, include no TDS or production data.

Based on this review, no modification of the USDW determinations reported in the CCA, Appendix USDW is warranted. The DOE concludes that in the vicinity of the WIPP, USDWs are present in the Culebra, and potential USDWs are present in the Dewey Lake and the Santa Rosa.

During its review of the CCA, the EPA requested that the DOE provide a map or maps showing the location of USDWs. The DOE responded to this request with supplementary information dated February 26, 1997 (Dials 1997b, Enclosure 1j). The supplementary information includes a map showing the boundaries of known USDWs nearest the WIPP in the Culebra and potential USDWs in the Santa Rosa and Dewey Lake. The EPA found the map sufficient for purposes of compliance assessment because it identifies potential USDWs near the WIPP (see Compliance Application Review Document [CARD] 53, U.S. Environmental Protection Agency 1998).

IGP-3.3 Comparison with the National Primary Drinking Water Standards

To provide additional assurance of the safety of the WIPP, the DOE prepared a bounding assessment of the concentrations of contaminants that could occur in a nearby USDW. Bounding doses that could be received by drinking from the USDW are also calculated. As with the individual protection standard, the analysis is bounding; the results illustrate the maximum, yet unrealistic, concentrations of contaminants in a hypothetical USDW and the maximum, yet unrealistic, resulting doses. As with the dose calculations, maximum concentrations were summed to develop concentrations for comparison with the National Primary Drinking Water Standards. The conclusions of this work, provided below, illustrate that the consequences of the undisturbed repository are negligible, even when conservative assumptions are applied to the performance evaluation. Because a hypothetical USDW is assumed to exist at the site boundary in these analyses, the results of the bounding analysis support the position that additional characterization of groundwater near the WIPP to make a more definitive USDW determination is not warranted.

IGP-3.3.1 Transport Pathway

Section IGP-2.2.1 describes the transport pathway assumed for the bounding analysis performed to evaluate compliance with the individual protection standard. This same transport pathway is assessed to evaluate compliance with the groundwater protection standard.

This pathway assumes that a hypothetical USDW is located where the maximum possible concentration of radionuclides could be realized in the USDW and the maximum possible dose to an individual who drinks from the USDW could be delivered to the individual. As such, the analysis bounds the section 194.53 criterion specifying that the DOE must consider underground interconnections among bodies of surface water, groundwater, and USDWs.

IGP-3.3.2 Combined ^{226}Ra and ^{228}Ra

The modeling system employed to simulate the performance of the undisturbed repository tracks the transport of the most important radionuclides to releases in the accessible environment (see the CCA, Appendix WCA and the CRA-2004, Appendix TRU WASTE). These radionuclides, listed in Table IGP-1, are ^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. They do not include ^{226}Ra or

^{228}Ra because these radionuclides are not a prevalent component of the projected inventory (Fox 2003a). However, an analysis of ^{226}Ra and ^{228}Ra is required to evaluate compliance with the groundwater protection standard.

To perform the bounding analysis for the CRA-2004, the results of a NUTS code tracer exercise were used to scale the anticipated releases of ^{226}Ra and ^{228}Ra. The tracer exercise shows that an initial 1 kilogram/cubic meter (kg/m^3) concentration of radionuclides in the repository results in a concentration at the accessible environment boundary of 1.025×10^{-7} kg/m^3. By applying this scaling factor to the quantity of ^{226}Ra and ^{228}Ra projected to be emplaced in the repository, it was determined and reported in the CRA-2004 that the maximum concentration of these radionuclides in the accessible environment is 0.07 pCi/L (Wagner 2003), which is below the section 141.15(a) standard of 5 pCi/L.

This concentration was calculated by transporting the passive tracer in the flow field generated using the BRAGFLO code for Realization 1 (Replicate 1, Vector 82), shown in Table IGP-2. The calculation uses the mass and activity loads for ^{226}Ra and ^{228}Ra in the radionuclide inventory at closure and at 10,000 years. These values are provided in Table IGP-9. The ORIGEN 2.2 code was used to calculate the activity loads at 10,000 years; these loads are 51.43 curies (Ci) of ^{226}Ra in contact-handled (CH-) and remote-handled- (RH-) transuranic (TRU) waste and 7.95 Ci of ^{228}Ra in CH- and RH-TRU waste. The calculated concentration is based on the volume of brine, 5,577 cubic meters (m^3) (169,924 ft^3), in the repository at time zero in the BRAGFLO calculation.

Table IGP-9. Total Inventory and Mass Loading of ^{226}Ra and ^{228}Ra Reported in the CRA-2004

Radionuclide	Waste Type	Total Inventory at Closure (Ci)	Total Inventory at 10,000 Years (Ci)	Mass Loading (kilograms)
^{226}Ra	CH	6.28×10^{0}	4.98×10^{1}	6.35×10^{-3}
^{226}Ra	RH	4.99×10^{-5}	1.63×10^{0}	5.05×10^{-8}
^{228}Ra	CH	7.63×10^{0}	7.70×10^{0}	2.81×10^{-5}
^{228}Ra	RH	2.51×10^{-1}	2.54×10^{-1}	9.23×10^{-7}

Source: Fox (2003b)

The total concentration (CH- and RH-TRU**)** of either ^{226}Ra or ^{228}Ra at 10,000 years at the accessible environment boundary was calculated using the following steps:

1. Calculate the total mass load at 10,000 years by multiplying the total mass load at decommissioning by the ratio of activity loadings at 10,000 years and decommissioning, respectively.

2. Calculate the total mass concentration at the accessible environment boundary by dividing by the value of brine from the BRAGFLO simulation and multiplying by the scaling factor.

3. Convert to total concentration of activity at the accessible environment boundary by multiplying by the ratio of activity loading to mass loading at decommissioning.

4. Divide the concentration by the dilution factor 32.4 (see Section IGP-2.2.2).

The 0.07 pCi/L maximum concentration calculated for the CRA-2004 occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

In the CCA, this value is reported as 2 pCi/L. During the PAVT (U.S. Department of Energy 1997), it was determined that the CCA calculation used an inappropriate brine volume value and failed to account for the dilution factor. Accordingly, the PAVT analysis shows that the correct value that should have been reported in the CCA is 0.14 pCi/L (Dials 1997).

For the CRA-2009, a new derivation concept is applied to demonstrate that the combined ^{226}Ra and ^{228}Ra concentrations are below the regulatory limit of 5 pCi/L over the 10,000-year performance period (Ismail and Nemer 2008). The new method better represents the actinide (An) concentration at the LWB because it does not use the cumulative tracer scaling factor. Current PA calculations do not explicitly track Ra concentrations in the groundwater, so an alternate method was first used in the CCA to derive conservative estimates of potential Ra concentrations at the LWB. This method was also used in the CRA-2004. The original method overestimated the potential Ra concentration because the estimates used a cumulative scaling factor. An alternate method was chosen that is more consistent with the methods used to calculate An concentrations in PA.

As described in Section IGP-2.1, Ismail (2008) identifies only one vector in the CRA-2009 PA that has nonzero releases at the LWB. Replicate 1, Vector 53 showed a tracer concentration in the MB at the LWB of 1.24×10^{-4} kg/m^3 (Ismail 2008). The maximum concentrations of radionuclides at the LWB during the 10,000-year regulatory period are shown in Table IGP-3.

As stated above, the Ra concentration was not previously calculated in PA. However, a new analysis was performed using the current PA methods and including Ra. The analysis shows a maximum ^{226}Ra concentration of 1.7×10^{-5} pCi/L for the CRA-2009 PA and 6.5×10^{-7} for the CRA-2004 PABC. These concentrations of ^{226}Ra are more than five orders of magnitude below the regulatory limit of 5 pCi/L (Ismail 2008b).

Based on this updated analysis, continued compliance with the combined ^{226}Ra and ^{228}Ra standard is demonstrated.

IGP-3.3.3 Gross Alpha Particle Activity Including ^{226}Ra But Excluding Radon and U

For the CCA evaluation, compliance with the section 141.15(b) standard was assessed by summing the maximum concentration values provided in Table IGP-1 for ^{241}Am, ^{239}Pu, ^{238}Pu, and ^{230}Th and adding the CCA value for ^{226}Ra obtained to perform the section 141.15(a) assessment. The value obtained by this method is 7.81 pCi/L, which is below the section

141.15(b) standard of 15 pCi/L. This concentration occurs in the anhydrite interbeds within the Salado and not in a zone that could realistically be a source of drinking water.

For the CRA-2004 evaluation, the only contributing radionuclide is ^{239}Pu, with a concentration of 2.53×10^{-6} pCi/L (Table IGP-2). This value, summed with the 0.07-pCi/L value derived for the section 141.15(a) assessment, is essentially 0.07 pCi/L, well below the 15-pCi/L standard.

For the CRA-2009 evaluation, there are four contributing radionuclides with a total concentration of 3.84×10^{-1} pCi/L (Table IGP-3). As with the CRA-2004 analysis, this value, when summed with the 1.7×10^{-5} pCi/L value derived for the section 141.15(a) assessment, remains essentially 3.84×10^{-1} pCi/L, well below the 15-pCi/L standard.

As described above, no contribution from ^{226}Ra is expected. The gross alpha particle activity including ^{226}Ra and excluding radon and U is expected to be zero. Continued compliance with the section 141.15(b) standard is demonstrated.

IGP-3.3.4 Annual Dose Equivalent to the Total Body or Any Internal Organ from the Average Annual Concentration of Beta Particle and Photon Radioactivity from Man-Made Radionuclides

To assess compliance with the section 141.16(a) standard, an annual dose equivalent of 4 mrem per year, the transport of the following radionuclides was evaluated: ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th. The maximum annual committed effective dose calculated for the CCA evaluation from any of these radionuclides is 0.93 mrem, which is the value reported for transport through MB 139 and is well below the regulatory standard. The 0.93 mrem value includes alpha particle radioactivity, as well as beta particle and photon radioactivity. Thus, the value is very conservative, as the 4-mrem annual dose equivalent limit is only for beta particle and photon radioactivity.

By comparison, the maximum radionuclide concentration in the accessible environment calculated for the CRA-2004 evaluation is six orders of magnitude less than the maximum bounding value calculated for the CCA. Resulting doses for the CRA-2004 case would be correspondingly lower, as well.

For the CRA-2009 evaluation, the maximum radionuclide concentration in the accessible environment is one order of magnitude less than the maximum bounding CCA value. As such, resulting doses for the CRA-2009 case would be correspondingly lower, and continued compliance with the section 141.16(a) standard is demonstrated.

IGP-4.0 Compliance Summary

In performing the compliance assessment, the DOE applied a bounding-analysis approach using assumptions that overestimate potential doses and contaminant concentrations. To provide added assurance, the DOE assumed the presence of a USDW in close proximity to the WIPP LWB, even though available data indicate that none currently exists near the boundary. Using this conservative approach, the calculated maximum potential dose to an individual determined for the CCA evaluation would be about one-sixteenth of the individual protection standard.

For the CRA-2004 evaluation, this concentration is well below the CCA value. In addition, the maximum concentrations of contamination in the hypothetical USDW would be much less than half of the EPA groundwater protection limits, and the maximum potential dose to a receptor who drinks from the hypothetical USDW would be well below one-quarter of the standard.

For the CRA-2009 evaluation, the maximum potential dose remains below the CCA value and continued compliance with the individual protection standard is maintained. The potential concentrations of contaminants in the hypothetical USDW and the maximum potential dose to a receptor who drinks from the hypothetical USDW continue to be bounded by the CCA analysis.

This approach also conservatively assumes that all contaminants reaching the accessible environment are directly available to a receptor. The analysis bounds any potential impacts of underground interconnections among bodies of surface water, groundwater, and USDWs.

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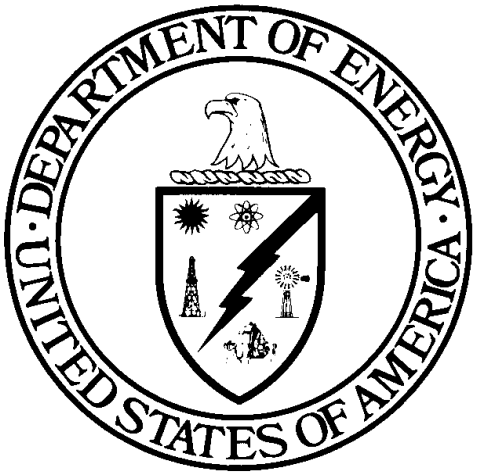
Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix MASS-2009
Performance Assessment
Modeling Assumptions



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix MASS-2009
Performance Assessment
Modeling Assumptions

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Acronyms and Abbreviations

An	actinide
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CH-TRU	contact-handled transuranic
cm	centimeters
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
DBR	direct brine release
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
EPA	U.S. Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FEP	feature, event, and process
ft	foot
gal	gallon
in.	inch
INL	Idaho National Laboratory
km	kilometer
LHS	Latin hypercube sample
m	meter
MB	marker bed
MPa	megapascals
NIST	National Institute of Standards and Technology
OS	operating system
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
PR	productivity ratio
QA	quality assurance
RH-TRU	remote-handled transuranic
RoR	rest of repository

SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
T field	transmissivity field
TRU	transuranic
WIPP	Waste Isolation Pilot Plant

Elements and Chemical Compounds

$CaCO_3$	calcite
CH_4	methane
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
$Mg(OH)_2$	brucite, magnesium hydroxide
$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	hydromagnesite
MgO	magnesium oxide

MASS-1.0 Introduction

This appendix presents supplementary information to Appendix PA-2009 regarding the assumptions, simplifications, and approximations used in the models of the second recertification performance assessment (PA) of the Waste Isolation Pilot Plant (WIPP) called the 2009 Compliance Recertification Application (CRA-2009) PA. Within this appendix, relevant issues in the formulation or development of the various types of models (for example, conceptual, mathematical, numerical, or computer code) used for the topic under consideration in each section are discussed, and references to relevant historical information are included where appropriate. The CRA-2009 PA is similar to the CRA-2004 PA used in the first recertification of the WIPP. The technical baseline for the first recertification includes the modifications required by the U.S. Environmental Protection Agency (EPA) during their review of the CRA-2004 PA (Cotsworth 2005). These required modifications resulted in a PA called the Performance Assessment Baseline Calculation (PABC), or the CRA-2004 PABC. The CRA-2009 PA is not significantly different than the CRA-2004 PABC. The differences include error corrections, updated parameters, and new software code versions. This appendix references the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) and the CRA-2004 (U.S. Department of Energy 2004) when the information discussed has not changed from past demonstrations of compliance with the EPA's disposal standards. Some of the information important to PA methodology has been repeated from the CRA-2004, Appendix PA, Attachment MASS for completeness.

Section MASS-2.0 contains a summary of changes in PA since the CRA-2004. Section MASS-3.0 includes a discussion of general modeling assumptions applicable to the disposal system as a whole, including a table of assumptions made in PA models, with cross-references. The remainder of this appendix discusses assumptions specific to the conceptual models used in the CRA-2009 PA. Historical development of the WIPP conceptual models that led to the PA used in the CCA is documented in the CCA, Appendix MASS, Section MASS-2.0. Historical development of the modeling assumptions for the CRA-2004 PA is documented in the CRA-2004, Appendix PA, Attachment MASS.

MASS-2.0 Summary of Changes in Performance Assessment

Since the CCA, there have been changes to a number of the conceptual models and processes important in assessing the performance of the WIPP. Changes for the first recertification were discussed in the CRA-2004, Chapter 9.0, Section 9.3.1.3, and Appendix PA, Attachment MASS. Other recertification-related, EPA-mandated changes were documented in the CRA-2004 PABC (Leigh et al. 2005). The technical baseline used to demonstrate continued compliance with the EPA's disposal standards was documented in these two documents. Since this time, ongoing confirmatory experiments, monitoring results, and operational practices have generated information relevant to the features, events, and processes (FEPs), modeling assumptions, and conceptual models for PA, and provided additional support to the conceptual basis of PA. The results of these investigations are included in a new PA for this recertification. Appendix MASS-2009 has been updated to include the impacts of these ongoing investigations and results. Included in the CRA-2009 PA are changes that have occurred since the CRA-2004 PA and new information that is important to PA. These changes are

1. Reassessment of FEPs
2. Compliance monitoring
3. Experimental activities
4. Assessment of model and systems changes and updates
5. Incorporation of CRA-2004 PABC changes, including
    A. Parameter changes: solubility parameters; solubility uncertainty ranges; probability of microbial cellulosic, plastic, and rubber (CPR) degradation
    B. Error corrections
    C. Inventory updates
    D. Changes to CPR degradation implementation
    E. New Culebra transmissivity fields (T fields)
6. Incorporation of CRA-2009 changes, including
    A. The parameter representing the maximum flow duration for direct brine releases (DBRs)
    B. The sampling method applied to the humid and inundated CPR degradation rates
    C. Additional chemistry parameters
    D. Capillary pressure and relative permeability models
    E. Updated drilling rate

F. Parameter corrections – emplacement material parameters, halite/disturbed rock zone (DRZ) porosity, and fraction of the repository occupied by waste

G. Input file corrections

7. Operational considerations

A summary of each change is presented in this section. References to appropriate sections of this appendix are provided for those changes that impact modeling assumptions. In addition, references are provided to other sections of the CRA-2009 where implementation of the changes is discussed.

MASS-2.1 FEPs Assessment

In the WIPP PA methodology (see Appendix PA-2009, Section PA-2.3), FEPs are elements used to develop the conceptual models and modeling assumptions represented in PA. The process used to develop and screen FEPs is outlined in Appendix SCR-2009, Section SCR-2.0. The results of the CRA-2004 FEPs screening are documented in the CRA-2004, Appendix PA, Attachment SCR. For the CRA-2009, a reassessment of the CRA-2004 baseline FEPs was conducted to determine whether changes in WIPP activities and conditions affected the original FEPs descriptions, bases, or screening decisions. This assessment also determined whether additional FEPs should be included in the CRA baseline. The reassessment results are documented in Appendix SCR-2009, Section SCR-3.0 and Section 32 of this application, Scope of Performance Assessment. Changes to the baseline FEPs include updating screening arguments with new information that has become available and separating general FEPs into more descriptive FEPs. No changes to PA implementation or modeling assumptions were made as a result of the FEPs reassessment because no FEPs that were previously screened out of PA calculations have been screened in and no FEPs that were screened in have been screened out.

MASS-2.2 Monitoring

Monitoring activities have continued since the certification of the WIPP. These activities are used to validate assumptions and PA parameters, and to detect substantial and detrimental deviation from expected repository performance. Monitoring, as discussed here, applies to the assurance requirement of 40 CFR § 191.14(b) (U.S. Environmental Protection Agency 1993) and the monitoring criteria at 40 CFR § 194.42 (U.S. Environmental Protection Agency 1996). Appendix MON-2009 details the monitoring program that meets these requirements. The monitoring program was assessed to determine if the results indicate that changes should be made to the monitoring program. The results did not indicate that changes were required (Wagner 2008). The monitoring program did, however, lead to a change in one monitored parameter used in PA: because of increased drilling in the Delaware Basin, the drilling rate parameter value used in the CRA-2009 PA has increased (see Appendix DATA-2009, Section DATA-2.0 for information on this parameter change).

In the CRA-2009 PA, the drilling rate has been changed to meet the requirements for 40 CFR § 194.33 (U.S. Environmental Protection Agency 1996). The drilling rate for boreholes is

discussed in Section 33 of this application. No changes to modeling assumptions are necessary to account for this parameter change.

MASS-2.3 Experimental Activities

The EPA requires the recertification documentation to include an update of "additional analyses and results of laboratory experiments conducted by the Department or its contractors as part of the WIPP program" (40 CFR § 194.15(a)(3); see also 40 CFR § 194.15, U.S. Environmental Protection Agency 1996). The following sections discuss analyses and experiments conducted to support compliance determinations. Only analyses with conclusions relevant to this recertification are discussed here.

MASS-2.3.1 Magnesium Oxide Investigations

The EPA has approved a U.S. Department of Energy (DOE) change request to reduce the magnesium oxide (MgO) excess factor from 1.67 to 1.2 times the quantity of MgO required to consume all of the carbon dioxide (CO_2) that would be produced if microbes consumed all the CPR materials in the emplaced waste at the WIPP (Reyes 2008 and Appendix MgO-2009, Section MgO-6.2.4.6). Since PA assumes there is always enough MgO to maintain a favorable chemical environment for actinide (An) solubilities, a reduction in the excess factor does not change the modeling assumptions used to represent MgO in PA.

Experiments have been performed to support the implementation of MgO as an engineered barrier. These experiments have characterized MgO and investigated the hydration and carbonization of MgO to confirm its ability to sequester CO_2, buffer brine pH, and subsequently help establish low An solubilities in the repository. These activities are described in detail in Appendix MgO-2009. The results of these MgO investigations have not impacted the modeling assumptions associated with MgO in PA (Appendix MgO-2009 and Appendix PA-2009, Section PA-2.1.4.4).

MASS-2.3.2 Actinide Investigations

The DOE has continued to investigate An speciation and solubilities since the certification of the WIPP. The current An experimental activities are described in Appendix SOTERM-2009, Section SOTERM-3.0. The CRA-2009 PA uses the same An assumptions as the CRA-2004 PABC.

MASS-2.4 Performance Assessment Models and Systems

Changes have been made to the systems used to perform PAs. The PA hardware, operating systems (OSs), and parameter database have been updated since the CRA-2004 and CRA-2004 PABC. These changes were necessary to replace obsolete hardware and OSs and to increase PA capabilities.

Sandia National Laboratories (SNL) maintains the computational platforms used to execute the WIPP PA modeling codes. A small number of modeling tasks that feed into compliance calculations are performed on desktop PC workstations running the Microsoft® Windows® XP

OS, as well as PC-based workstations and clusters running the Red Hat® Linux® OS. The WIPP PA parameter database is hosted on a PC-based server running Windows® 2000. However, the vast majority of the WIPP PA modeling codes used directly in compliance calculations are run on the WIPP PA Alpha Cluster composed of Hewlett Packard® (formerly Compaq®) AlphaServer™ systems. AlphaServers™ are built around the Alpha processor and run the OpenVMS™ OS.

The computer systems and OSs have been upgraded since the CRA-2004 because of increasing obsolescence of the OS and hardware. The current hardware and software versions used in the CRA-2009 PA calculations are shown in Table MASS-1 and Table MASS-2. Significant changes include those made to the WIPP PA Alpha cluster, where older AlphaServers™ were replaced with newer machines and the OS for all servers was upgraded. The WIPP PA Alpha cluster now consists of four ES47 AlphaServers™ and four ES45 AlphaServers™. The OS on these systems has been upgraded from OpenVMS™ 7.3-1 to OpenVMS™ 8.2. Regression testing of all codes used in compliance calculations has been performed to verify that the codes continue to perform correctly after the hardware and OS changes (Long 2006).

The PC-based Linux® clusters have also been upgraded since the CRA-2004, but the new configurations have not been used in compliance calculations included in the CRA-2009.

All changes to these systems are performed under the quality assurance (QA) program per the Carlsbad Field Office Quality Assurance Program Document, and include testing, validation, and verification to ensure that there is no impact on PA implementation. A synopsis of the changes and references to the QA documentation are found in Long (2006). It should be noted that the codes identified in Table 2-1 of Long (2006) are those that have changed since the CRA-2004 PABC. Some code outputs from previous certification PAs continue to be used in this CRA-2009 PA because these codes and their input parameters have not changed; therefore, the codes do not need to be rerun. These outputs are identified in Long (2008) and include the outputs of DRSPALL, MODFLOW, and SECOTP2D.

MASS-2.5 PABC

The EPA requested changes to the CRA-2004 PA during their review of the first recertification (Cotsworth 2005). These changes were incorporated in the CRA-2004 PABC and Leigh et al. (2005), and in the subsequent CRA-2009 PA. The changes were assessed by the EPA and approved as the certified WIPP baseline in their recertification decision (U.S. Environmental Protection Agency 2006). The CRA-2004 PABC changes are described in Table MASS-3.

MASS-2.5.1 Conceptual Model Changes

The CRA-2009 PA uses the same conceptual models used in the CRA-2004 PABC. No changes were made to the conceptual models used in the CRA-2004 PABC. For the CRA-2004 PABC, incorporation of the changes required by the EPA in Cotsworth (2005) led to several changes in the conceptual models used in the CRA-2004 PABC. Specifically, the requirement to assume that (1) microbial gas generation occurs for all vectors, and (2) the sequential consumption of CPR via the nitrate-to-sulfate-to-methanogenesis reaction sequence is constrained to limit the

Table MASS-1. CRA-2009 PA Codes

Code	Version	Build Date
ALGEBRACDB	2.35	31-JAN-1996
BRAGFLO	6.0	12-FEB-2007
CCDFGF	5.02	13-DEC-2004
CUTTINGS_S	6.02	9-JUN-2005
DRSPALL	1.10	14-JAN-2004
EPAUNI	1.15A	3-JUL-2003
GENMESH	6.08	31-JAN-1996
GROPECDB	2.12	27-JUN-1996
ICSET	2.22	1-FEB-1996
LHS	2.42	18-JAN-2005
MATSET	9.10	29-NOV-2001
MODFLOW-2000	1.6	20-SEP-2002
NUTS	2.05C	24-MAY-2006
PANEL	4.03	25-APR-2005
POSTBRAG	4.00A	28-MAR-2007
POSTSECOTP2D	1.04	5-JUN-1997
POSTLHS	4.07A	25-APR-2005
PREBRAG	8.0	8-MAR-2007
PRECCDFGF	1.01	7-JUL-2005
PRELHS	2.30	27-NOV-2001
PRESECOTP2D	1.22	12-JUN-1997
RELATE	1.43	6-MAR-1996
SECOTP2D	1.41A	9-JUL-2003
STEPWISE	2.21	2-DEC-1996
SUMMARIZE	3.01	21-DEC-2005

Table MASS-2. CRA-2009 PA Hardware

Node	Hardware Type	CPU
CCR	HP AlphaServer™ ES45	Alpha EV68
TDN	HP AlphaServer™ ES45	Alpha EV68
BTO	HP AlphaServer™ ES45	Alpha EV68
CSN	HP AlphaServer™ ES45	Alpha EV68
GNR	HP AlphaServer™ ES47	Alpha EV7
MC5	HP AlphaServer™ ES47	Alpha EV7
TRS	HP AlphaServer™ ES47	Alpha EV7
TBB	HP AlphaServer™ ES47	Alpha EV7

consumption reaction to only nitrate and sulfate reduction, changed the chemical conditions and gas generation conceptual models for the CRA-2004 PABC. These changes are also incorporated in the CRA-2009 PA and are discussed further in the CRA-2004 PABC summary report sections listed in Table MASS-3.

Table MASS-3. Changes Incorporated in the CRA-2004 PABC

Changes Included in the Performance Assessment Baseline Calculation		
EPA-Mandated Change	**Description of Change**	**Reference**
Solubility Parameters	Organic ligand concentrations recalculated, brine composition changes, U(VI) solubility changes, and change to account for no nonmicrobial vectors	PABC Summary (Leigh et al. 2005, Section 2.5) PANEL Analysis Package (Garner and Leigh 2005)
Solubility Uncertainty Ranges	Updated uncertainty ranges used	PABC Summary (Leigh et al. 2005, Section 2.6)
Probability of Microbial Activity	Microbial activity in all vectors versus 50% previously	PABC Summary (Leigh et al. 2005, Section 2.2)
CPR Degradation	Parameters for humid and inundated rate-changed Removal of methanogenesis	PABC Summary (Leigh et al. 2005, Section 2.3) PABC Summary (Leigh et al. 2005, Section 2.4)
Inventory	Inclusion of waste emplacement CPR Correct inventory errors	PABC Summary (Leigh et al. 2005, Section 2.1) PABC Inventory Report (Leigh, Trone, and Fox 2005)
Error Corrections	Additional DRSPALL vectors sampled; LHS, CCDFGF, CUTTING_S, SUMMARIZE and PRECCDFGF code corrections	PABC Summary (Leigh et al. 2005, Section 2.8) PABC Summary (Leigh et al. 2005, Section 2.9)
Culebra T Fields	Mining modifications incorporated in new flow fields	PABC Summary (Leigh et al. 2005, Section 2.7) The CRA-2004, Appendix PA, Attachment TFIELD

MASS-2.5.2 Recalculation of Culebra T Fields

The CRA-2009 PA uses the CRA-2004 PABC T fields. No changes were made to the T field modeling assumptions for the CRA-2009 PA. Water level rises in the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra) have continued over recent years, and the observed heads have exceeded the ranges of uncertainty established for the steady-state heads in many of the WIPP observation wells used in the calibration of the T fields described in the CCA (Sandia National Laboratories 2002). The DOE recalculated T fields for the CRA-2004 using new Culebra data and geologic information (see Appendix TFIELD-2009). Additionally, the treatment of potential potash mining was recalculated during the CRA-2004 PABC. The areas affected by mining were modified, and new flow fields were generated in response to the EPA's request for a PABC (Cotsworth 2005). (See also Leigh et al 2005, Section

2.7, and the CRA-2004, Appendix PA, Attachment TFIELD.) The DOE is continuing its field observation program to investigate other potential causes for the water-level rises (Sandia National Laboratories 2003). This program is discussed in Appendix HYDRO-2009.

MASS-2.5.3 Waste Inventory Update

The waste inventory used in the CCA was based on information contained in the Transuranic Waste Baseline Inventory Database (see the CCA, Appendix BIR). No waste had been emplaced in the repository at that time. Since 1996, waste has been emplaced in the repository and better estimates have been made of the existing and projected waste streams at the generator sites. Waste information in the CRA-2004 PA was updated to include the emplaced, currently stored, and projected waste streams. This information was collected in the Transuranic Waste Baseline Inventory Database, Rev 2.1, with the WIPP-specific information detailed in the CRA-2004, Appendix DATA, Attachment F.

During the CRA-2004 PABC, the inventory information used in PA was again updated. Leigh, Trone, and Fox (2005) summarizes these changes to the inventory. Changes include a correction to the waste volumes reported by the Hanford Office of Richland Operations, the inclusion of pre-1970 waste at Idaho National Laboratory (INL) as possible WIPP waste and a correction to the volume and concentration of waste from Los Alamos National Laboratory.

The waste information used in the CRA-2009 PA is the same as in the CRA-2004 PABC calculations, with the addition of cellulosic and plastic materials used for waste emplacement to the inventory. Waste information in the CRA-2009 PA is discussed further in Leigh, Trone, and Fox (2005).

MASS-2.6 CRA-2009 Changes

The CRA-2009 PA was updated based on new information since the CRA-2004 PABC. Information on the implementation of these changes is contained in Clayton (2008, Section 2.1) and is summarized in Table MASS-4.

MASS-2.7 Operational Considerations

No operational changes that would impact modeling assumptions have been made at the WIPP since the 2006 recertification decision. As a result, no changes were made to modeling assumptions for the CRA-2009 PA.

Shortly after submission of the CRA-2004 to the EPA, the DOE began using a new MgO supplier, Martin Marrietta Magnesia Specialties, for the engineered barrier because the existing vendor, Premier Chemicals, was no longer able to meet the stipulated MgO specifications. The MgO specification did not change, and no associated change was made to modeling assumptions as a result of the new vendor. Additional discussion of this operational change is found in Appendix MgO-2009, Section MgO-2.2.

Table MASS-4. Changes Incorporated in the CRA-2009

WIPP Project Change	Summary of Change and Cross-Reference
DBR Parameters	The maximum DBR duration was decreased from 11 days to 4.5 days (Kirkes 2007).
CPR Degradation Rates	A conditional relationship was introduced between the inundated and humid gas generation rate to ensure that the inundated rate is the maximum rate (Kirchner 2008).
BRAGFLO Chemistry Capillary Pressure and Relative Permeability Model	New capillary pressure and relative permeability model for open cavities was added. Cut-off saturation is used, below which no chemical reactions occur (H_2O-required reactions) (Nemer and Clayton 2008).
Drilling Rate	Rate changed from 52.5 to 58.5 boreholes per square kilometer (km^2) over 10,000 years (Clayton 2008).
Parameter Error Corrections	Emplaced CPR Error Correction Halite/DRZ Porosity Error Correction Fraction of Repository Occupied by Waste Correction NUTS and DBR Calculation Input Files (Nemer 2007, Dunagan 2007, Ismail 2007a, Ismail 2007b, Clayton 2007).

MASS-3.0 General Assumptions in PA Models

A number of assumptions are applied generally to the disposal system through the conceptual and mathematical models implemented in the CRA-2009 PA.

Table MASS-5, which lists modeling assumptions used in the PA, is a guide to general modeling assumptions and provides guidance for integrating the assumptions with (1) the CRA-2004 chapters or CRA-2009 appendices in which they are discussed, and (2) the code(s) that implement these assumptions.

The FEPs discussed in Appendix SCR-2009 that are relevant to these assumptions are also indicated. The final column in the table indicates whether the DOE considers each assumption to be reasonable or conservative. As discussed in the CRA-2004, Chapter 6.0, Section 6.5, the DOE has not attempted to bias the overall results of PA toward a conservative outcome. However, where data or models are impractical to obtain, or where effects on performance are not expected to be significant enough to justify development of a more complicated model, the DOE has chosen to use conservative assumptions. In all other cases, best unbiased conceptual models and parameter values have been selected. The designator R (reasonable) in the final column indicates that the DOE considers the assumption to be reasonable based on WIPP-specific data or information, data or information considered analogous to the WIPP disposal system, expert judgment, or other reasoning. The designator C (conservative) indicates the DOE considers the assumption may overestimate a process or effect that may contribute to releases to the accessible environment. The regulatory designator (Reg) indicates that the assumption is based on regulations in 40 CFR Part 191, criteria in 40 CFR Part 194, or other regulatory guidance.

MASS-3.1 Darcy's Law Applied to Fluid Flow Calculated by BRAGFLO, MODFLOW-2000, and DRSPALL

A mathematical relationship expressing fluid flux as a function of hydraulic head gradients in a porous medium, commonly known as Darcy's Law, is applied to geologic media for all fluid-flow calculations. For details about the specific formulation of Darcy's Law used in these calculations, refer to Appendix PA-2009, Section PA-4.2 for the disposal system and Section PA-4.8 for the Culebra. Darcy's Law is not applied for flow up a borehole being drilled (see Section MASS-16.2; the CRA-2004, Chapter 6.0, Section 6.4.7.1.1; and Appendix PA-2009, Section PA-4.6 for more discussion of this topic).

Darcy's Law generally applies for flow models if certain conditions are satisfied: (1) the flow occurs in a porous medium with interconnected porosity, (2) flow velocities are low enough that viscous forces dominate inertial forces, and (3) a threshold hydraulic gradient is exceeded. In the CCA, Appendix MASS, these conditions were shown to be valid for the WIPP PA.

Darcy's Law assumes laminar flow; that is, there is no motion of the fluid at the fluid/solid interface and velocity increases with distance from the fluid/solid interface. For liquids, it is reasonable to assume laminar flow under most conditions, including those found in and surrounding the WIPP repository. For gases at low pressure, however, gas molecules near the solid interface may not have intimate contact with the solid and may have finite velocity, not

Table MASS-5. General Modeling Assumptions

Chapter or Section	Assumption Number	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
MASS-3.0 Some General Assumptions in PA Models MASS-3.1 Darcy's Law Applied for Fluid Flow calculated by BRAGFLO, MODFLOW-2000, and SECOTP2D	1	BRAGFLO MODFLOW-2000	Flow is governed by mass conservation and Darcy's Law in porous media. Flow is laminar and fluids are Newtonian.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24) Brine Inflow (W40)	R
	2	BRAGFLO	Two-phase flow in the porous media is by simultaneous immiscible displacement.	Fluid Flow Due to Gas Production (W42)	R
	3	BRAGFLO	The Brooks-Corey or Van Genuchten/Parker equations represent interactions between brine and gas.	Fluid Flow Due to Gas Production (W42)	R
	4	BRAGFLO	The Klinkenberg effect is included for flow of gases at low pressures.	Fluid Flow Due to Gas Production (W42)	R
	5	BRAGFLO	Threshold displacement pressure for flow of gas into brine is constant.	Fluid Flow Due to Gas Production (W42)	R
	6	BRAGFLO MODFLOW-2000 SECOTP2D	Fluid composition and compressibility are constant.	Saturated Groundwater Flow (N23) Fluid Flow Due to Gas Production (W42)	R
MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO	7	BRAGFLO DRSPALL	The gas phase is assigned the density and viscosity properties of hydrogen.	Fluid Flow Due to Gas Production (W42)	R
MASS-3.3 Salado Brine as Surrogate for Liquid Phase Physical Properties in BRAGFLO	8	BRAGFLO	All liquid physical properties are assigned the properties of Salado brine.	Saturated Groundwater Flow (N23)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance

See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.2 Model Geometries MASS-4.0 Model Geometries CRA-2004, Chapter 6.0, Section 6.4.2.1 Disposal System Geometry MASS-4.1 Disposal System Geometry as Modeled in BRAGFLO	BRAGFLO	The disposal system is represented by a two-dimensional, north-south, vertical cross section.	Stratigraphy (N1) Physiography (N39)	R
	BRAGFLO	Flow in the disposal system is radially convergent or divergent centered on the repository, shaft, and borehole for disturbed performance.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24)	R
	BRAGFLO	Variable dip in the Salado is approximated by a 1 degree dip to the south.	Stratigraphy (N1)	R
	BRAGFLO	Stratigraphic layers are parallel.	Stratigraphy (N1)	R
	BRAGFLO	The stratigraphy consists of units above the Dewey Lake, the Forty-niner, the Magenta, the Tamarisk, the Culebra, the Los Medaños, and the Salado Formations (comprising impure halite, MB 138, anhydrites A and B [lumped together], and MB 139). The dimensions of these units are constant. A Castile brine reservoir is included in the BRAGFLO grid in all scenarios.	Stratigraphy (N1)	R
CRA-2004, Chapter 6.0, Section 6.4.2.2 Culebra Geometry MASS-4.3 Historical Context of Culebra Geometries as Modeled in MODFLOW-2000 and SECOTP2D	MODFLOW-2000 SECOTP2D	The Culebra is represented by a two-dimensional, horizontal geometry for groundwater flow and radionuclide transport simulation.	Stratigraphy (N1)	R
	MODFLOW 2000 PEST	Transmissivity varies spatially. There is no vertical flow to or from the Culebra.	Groundwater Recharge (N54) Groundwater Discharge (N53)	R
	SECOTP2D	The regional flow field provides boundary conditions for local transport calculations (see CRA-2004, Chapter 6.0, Section 6.4.10.2).	Advection (W90)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.3 The Repository MASS-5.0 BRAGFLO Geometry of the Repository	BRAGFLO	The repository comprises five regions separated by panel closures: the waste panel, a north Rest of Repository (RoR), a south RoR and the access drifts (separated by panel closures), the operations region, and the experimental region. A single shaft region is also modeled, and a borehole region is included for a borehole that intersects the separate waste panel. The dimensions of these regions are constant (see the CRA-2004, Appendix MASS, Figure MASS-4).	Disposal Geometry (W1)	R-C
	BRAGFLO	Long-term flow up plugged and abandoned boreholes modeled as if all intrusions occur into a downdip (southern) panel.	Disposal Geometry (W1)	C
	BRAGFLO	For each repository region, the model geometry preserves design volume.	Disposal Geometry (W1)	R
	BRAGFLO	Pillars, individual drifts, and rooms are not modeled for long-term performance, and containers provide no barrier to fluid flow.	Disposal Geometry (W1)	C
	BRAGFLO	Long-term flow is radial to and from the borehole that intersects the waste disposal panel during disturbed performance.	Waste-Induced Borehole Flow (H32)	R
	BRAGFLO	DRZ provides a pathway to MBs.	—	R
	BRAGFLO	Grid and material properties are consistent with the Option D panel closure design.	—	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.3.1 Creep Closure MASS-6.0 Creep Closure Appendix PORSURF	SANTOS	Creep closure is modeled using a two-dimensional model of a single room. Room interactions are insignificant.	Salt Creep (W20) Changes in the Stress Field (W21) Excavation-Induced Changes in Stress (W19)	R
	SANTOS	The amount of creep closure is a function of time, gas pressure, and waste-matrix strength.	Salt Creep (W20) Changes in the Stress Field (W21) Consolidation of Waste (W32) Pressurization (W26)	R
	BRAGFLO	Porosity of operations and experimental areas is fixed at a value representative of consolidated material.	Salt Creep (W20)	R
CRA-2004, Chapter 6.0, Section 6.4.3.2 Repository Fluid Flow MASS-7.0 Repository Fluid Flow	BRAGFLO	General assumptions 1 to 8.	—	See above
	BRAGFLO	The waste disposal region is assigned a constant permeability representative of average consolidated waste without backfill.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24)	R
MASS-7.1 Flow Interactions with the Creep Closure Model	BRAGFLO	The experimental and operations regions are assigned a constant permeability representative of unconsolidated material and a constant porosity representative of consolidated material.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24) Salt Creep (N20)	C
MASS-7.2 Flow Interactions with the Gas Generation Model	BRAGFLO	For gas generation calculations, the effects of wicking are accounted for by assuming that brine in the repository contacts waste to an extent greater than that calculated by the Darcy Flow model used.	Wicking (W41)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.3.3 Gas Generation MASS-8.0 Gas Generation CRA-2004 Appendix TRU WASTE	BRAGFLO	Gas generation occurs by anoxic corrosion of steel containers and Fe and Fe-base alloys in the waste, giving H_2, and by microbial consumption of cellulosics and, possibly, plastics and rubbers, giving mainly CO_2 and H_2S. Radiolysis, oxic reactions, and other gas generation mechanisms are insignificant. Gas generation is calculated using the average-stoichiometry model, and is dependent on brine availability.	Container Material Inventory (W5) Waste Inventory (W2) Degradation of Organic Material (W44) Gases from Metal Corrosion (W49)	R
	BRAGFLO	The anoxic corrosion rate is dependent on liquid saturation. Anoxic corrosion of steel continues until all the steel is consumed. Steel corrosion will not be passivated by microbially generated gases (CO_2 or H_2S). The water in brine is consumed by the corrosion reaction.	Brine Inflow (W40) Gases from Metal Corrosion (W49) Degradation of Organic Material (W44)	R
	BRAGFLO	Laboratory-scale experimental measurements of gas generation rates at expected room temperatures are used to account for the effects of biofilms and chemical reactions.	Effects of Biofilms on Microbial Gas Generation (W48) Effects of Temperature on Microbial Gas Generation (W45) Chemical Effects of Corrosion (W51)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	BRAGFLO	The rate of microbial gas production is dependent on the amount of liquid present. It is assumed that microbial activity neither produces nor consumes water. Significant microbial activity occurs in all the simulations. In 75% of the simulations, microbes may consume all of the cellulosics but none of the plastics and rubbers. In the remaining 25% of the simulations, microbes may consume all of the cellulosics and all of the plastics and rubbers. Microbial production will continue until all biodegradable CPR materials are consumed if brine is present. The MgO backfill will react with all of the CO_2 and remove it from the gaseous phase.	Brine Inflow (W40) Degradation of Organic Material (W44) Waste Inventory (W2)	R
	BRAGFLO	Gas dissolution in brine is of negligible consequence.	Fluid Flow Due to Gas Production (W42)	R
	BRAGFLO	The gaseous phase is assigned the properties of hydrogen (General Assumption 7).	Fluid Flow Due to Gas Production (W42)	See above
CRA-2004, Chapter 6.0, Section 6.4.3.4 Chemical Conditions in the Repository SOTERM-2.0 Conceptual Framework of Chemical Conditions	NUTS PANEL	Chemical conditions in the repository will be constant. Chemical equilibrium is assumed for all reactions that occur between brine in the repository, waste, and abundant minerals, with the exceptions of gas generation and redox reactions.	Speciation (W56) Reduction-Oxidation Kinetics (W66)	R
	NUTS PANEL	Brine and waste in the repository will contain a uniform mixture of dissolved and colloidal species. All actinides have instant access to all repository brine.	Heterogeneity of Waste Forms (W3) Speciation (W56)	C

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	NUTS PANEL	No microenvironments that influence the overall chemical environment will persist.	Speciation (W56)	R
	NUTS PANEL	For the undisturbed performance and E2 scenarios, brine in the waste panels has the composition of Salado brine. For E1 and E1E2 (Appendix PA-2009, Section PA-2.3.2.2) scenarios, all brine in the waste panel intersected by the borehole has the composition of Castile brine.	Speciation (W56)	R
	NUTS PANEL	Chemical conditions in the waste panels will be reducing. However, a condition of redox disequilibrium will exist between the possible oxidation states of the An elements.	Reduction-Oxidation Kinetics (W66) Speciation (W56) Effects of Metal Corrosion (W64)	R
	NUTS PANEL	The pH and CO_2 fugacity in the waste panels will be controlled by the equilibrium between $Mg(OH)_2$ and $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$. (A result of this assumption is low CO_2 fugacity and mildly basic conditions.)	Speciation (W56) Backfill Chemical Composition (W10)	R
CRA-2004, Chapter 6.0, Section 6.4.3.5 Dissolved Actinide Source Term SOTERM-3.3 The Fracture Matrix Transport Computer Code	NUTS PANEL	Radionuclide dissolution to solubility limits is instantaneous.	Dissolution of Waste (W58)	C
	NUTS PANEL	Of the 29 isotopes considered as inputs, 6 actinides (Th, U, Np, Pu, Am, and Cm) are used in PANEL for calculations of radionuclide transport of brine (up a borehole). Four actinides (Th, U, Pu, and Am) are explicitly considered in NUTS for calculations of radionuclide transport in brine (porous materials) (Leigh and Trone 2005a). Choice of radionuclides is discussed in Leigh and Trone (2005b), Leigh, Trone, and Fox (2005), and Leigh et al. (2005).	Waste Inventory (W2)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	NUTS PANEL	The reducing conditions in the repository will eliminate significant concentrations of Np(VI), Pu(V), Pu(VI), and Am(V) species. Am and Cm will exist predominantly in the III oxidation state; while Th will exist in the IV oxidation state. It is assumed that the solubilities and K_ds of U, Np, and Pu will be dominated by one of the remaining oxidation states: U(IV) or U(VI), Np(IV) or Np(V), and Pu(III) or Pu(IV) (See Appendix SOTERM-2009, Table SOTERM-15).	Speciation (W56) Reduction-Oxidation Kinetics (W66)	R
	NUTS PANEL	For a given oxidation state, the different actinides have similar solubilities.	Speciation (W56)	R
	NUTS PANEL	For undisturbed performance and for all aspects of disturbed performance, except for cuttings and cavings releases, radionuclides in the waste are distributed evenly throughout the disposal panel.	Waste Inventory (W2) Heterogeneity of Waste Forms (W3)	R
	NUTS PANEL	Mobilization of actinides in the gas phase is negligible.	Dissolution of Waste (W58)	R
	NUTS PANEL	An concentrations in the repository will be inventory limited when the mass of an An becomes depleted such that the predicted concentrations cannot be achieved.	Dissolution of Waste (W58)	R
CRA-2004, Chapter 6.0, Section 6.4.3.6 Source Term for Colloidal Actinides	NUTS PANEL	Four types of colloids constitute the source term for colloidal actinides: microbes, humic substances, intrinsic colloids, and mineral fragments.	Colloid Formation and Stability (W79) Humic and Fulvic Acids (W70)	R
	NUTS PANEL	The only intrinsic colloids that will form are those of Pu.	Colloid Formation and Stability (W79)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	NUTS PANEL	Concentrations of intrinsic colloids and mineral-fragment colloids are modeled as constants based on experimental observations. Humic and microbial colloidal An concentrations are modeled as proportional to dissolved An concentrations.	Colloid Formation and Stability (W79)	R
	NUTS PANEL	The maximum concentration of each An associated with each colloid type is constant.	Actinide Sorption (W61)	R
CRA-2004, Chapter 6.0, Section 6.4.4 Shafts and Shaft Seals MASS-12.0 Shafts and Shaft Seals	BRAGFLO	General Assumptions 1 to 8.	—	See above
	BRAGFLO	The four shafts connecting the repository to the surface are represented by a single shaft with a cross-section and volume equal to the total volume of the four real shafts and separated from the waste by less than the distance of the nearest real shaft.	Disposal Geometry (W1)	R
	BRAGFLO	The shaft seal system is represented by an upper and lower shaft region representing a composite of the actual materials in those regions.	Shaft Seal Geometry (W6) Shaft Seal Physical Properties (W7)	R
	BRAGFLO	The shaft is surrounded by a DRZ which heals with time. The DRZ is represented through the composite permeabilities of the shaft system itself, rather than as a discrete zone. The effective permeability of shaft materials are adjusted at 200 years after closure to reflect consolidation and possible degradation. Permeabilities are constant for the shaft seal materials through the Rustler formation.	Salt Creep (W20) Consolidation of Shaft Seals (W36) DRZ (W18) Microbial Growth on Concrete (W76) Chemical Degradation of Shaft Seals (W74) Mechanical Degradation of Shaft Seals (W37)	R
	BRAGFLO	Concrete shaft components of the lower shaft are modeled as if they degrade after emplacement.	Mechanical Degradation of Shaft Seals (W37)	C

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
1 See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	NUTS	Radionuclides are not retarded by the seals.	Actinide Sorption (W61) Speciation (W56)	C
CRA-2004, Chapter 6.0, Section 6.4.5 The Salado MASS-13.0 Salado	BRAGFLO	General Assumptions 1 to 8.	—	See above
CRA-2004, Chapter 6.0, Section 6.4.5.1 Impure Halite MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units	BRAGFLO	Intact rock and hydrologic properties are constant.	Stratigraphy (N1)	R
CRA-2004, Chapter 6.0, Section 6.4.5.2 Salado Interbeds MASS-13.3 The Fracture Model	BRAGFLO	Interbeds have a fracture-initiation pressure above which local fracturing and changes in porosity and permeability occur in response to changes in pore pressure. A power function relates the permeability increase to the porosity increase. A pressure is specified above which porosity and permeability do not change.	Disruption Due to Gas Effects (W25)	R
	BRAGFLO	Interbeds have identical physical properties; they differ only in position, thickness, and some fracture parameters.	Saturated Groundwater Flow (N23)	R
CRA-2004, Chapter 6.0, Section 6.4.5.3 Disturbed Rock Zone MASS-13.4 Flow in the Disturbed Rock Zone	BRAGFLO	The permeability of the DRZ is sampled with the low value similar to intact halite and the high value representing a fractured material. The DRZ porosity is equal to the porosity of Salado halite to plus 0.29%.	Disturbed Rock Zone (DRZ) (W18) Roof Falls (W22) Gas Explosions (W27) Seismic Activity (N12) Underground Boreholes (W39)	C-R
CRA-2004, Chapter 6.0, Section 6.4.5.4 Actinide Transport in the Salado MASS-13.5 Actinide Transport in the Salado	NUTS	Dissolved actinides and colloidal actinides are transported by advection in the Salado. Diffusion and dispersion are assumed negligible.	Advection (W90) Diffusion (W91) Matrix Diffusion (W92)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	NUTS	Sorption of actinides in the anhydrite interbeds, colloid retardation, colloid transport at higher than average velocities, coprecipitation of minerals containing actinides, channeled flow, and viscous fingering are not modeled.	Actinide Sorption (W61) Colloid Transport (W78) Colloid Filtration (W80) Colloid Sorption (W81) Fluid Flow Due to Gas Production (W42) Fracture Flow (N25)	R
	NUTS	Radionuclides having similar decay and transport properties have been grouped together for transport calculations as discussed in Leigh and Trone (2005a). See also assumptions for dissolved actinide source term.	Radionuclide Decay and Ingrowth (W12)	R
	NUTS	Sorption of actinides in the borehole is not modeled.	Actinide Sorption (W61)	C
CRA-2004, Chapter 6.0, Section 6.4.6 Units Above the Salado MASS-14.0 Geologic Units above the Salado	SECOTP2D	Above the Salado, lateral An transport to the accessible environment can occur only through the Culebra.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24) Solute Transport (W77)	R
CRA-2004, Chapter 6.0, Section 6.4.6.1 Los Medaños	MODFLOW-2000 BRAGFLO	The Los Medaños member of the Rustler Formation, Tamarisk, and Forty-niner are assumed to be impermeable.	Saturated Groundwater Flow (N23)	C
CRA-2004, Chapter 6.0, Section 6.4.6.2 The Culebra MASS-15.0 Culebra Appendix TFIELD	MODFLOW-2000 SECOTP2D	General Assumptions 1, 6, and 8.	—	See above
	MODFLOW-2000	For fluid flow, the Culebra is modeled as a uniform (single-porosity) porous medium.	Saturated Groundwater flow (N23)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	MODFLOW-2000	The Culebra flow field is determined from the observed hydraulic conditions and estimates of the effects of climate change and potash mining outside the controlled area, and does not change with time unless mining is predicted to occur in the disposal system in the future.	Saturated Groundwater Flow (N23) Climate Change (N61) Precipitation (e.g.,, Rainfall) (N59) Temperature (N60) Changes in Groundwater Flow Due to Mining (H37)	R
	BRAGFLO	The Culebra is assigned a single permeability to calculate brine flow into the unit from an intrusion borehole.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	R
	MODFLOW-2000	Gas flow in the Culebra is not modeled. Gas from the repository does not affect fluid flow in the Culebra.	Saturated Groundwater Flow (N23) Fluid Flow Due to Gas Production (W42)	R
	BRAGFLO MODFLOW-2000 SECOTP2D	Different thicknesses of the Culebra are assumed for BRAGFLO, MODFLOW-2000, and SECOTP2D calculations, although the Ts are consistent.	Effects of Preferential Pathways (N27)	R
	PEST	Uncertainty in the spatial variability of the Culebra transmissivity is accounted for by statistically generating 100 T fields for PA.	Saturated Groundwater Flow (N23) Fracture Flow (N25) Shallow Dissolution (N16)	R
	MODFLOW-2000 BRAGFLO	Potentiometric heads are set on the edges of the regional grid to represent flow in a portion of a much larger hydrologic system.	Groundwater Recharge (N54) Groundwater Discharge (N53) Changes in Groundwater Recharge and Discharge (N56) Infiltration (N55)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.6.2.1 Transport of Dissolved Actinides in the Culebra MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra	SECOTP2D	Dissolved actinides are transported by advection in high-permeability features and by diffusion in low-permeability features.	Solute Transport (W77) Advection (W90) Diffusion (W91) Matrix Diffusion (W92)	R
	SECOTP2D	Sorption occurs on dolomite in the matrix. Sorption on clays present in the Culebra is not modeled.	Actinide Sorption (W61) Changes in Sorptive Surfaces (W63)	C
	SECOTP2D	Sorption is represented using a linear isotherm model.	Actinide Sorption (W61) Kinetics of Sorption (W62)	R
	SECOTP2D	The possible effects on sorption of the injection of brines from the Castile and Salado into the Culebra are accounted for in the distribution of An K_ds.	Actinide Sorption (W61) Groundwater Geochemistry (N33) Changes in Groundwater Eh (N36) Changes in Groundwater pH (N37) Natural Borehole Fluid Flow (H31)	R
	SECOTP2D	Hydraulically significant fractures are assumed to be present everywhere in the Culebra.	Advection (W90)	C
CRA-2004, Chapter 6.0, Section 6.4.6.2.2 Transport of Colloidal Actinides in the Culebra MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra	SECOTP2D	An humic colloids are chemically retarded identically to dissolved actinides and are treated as dissolved actinides.	Advection (W90) Diffusion (W91) Colloid Transport (W78) Microbial Transport (W87)	R
	SECOTP2D	The concentration of intrinsic colloids is sufficiently low to justify elimination from PA transport calculations in the Culebra.	—	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	SECOTP2D	Microbial colloids and mineral fragments are too large to undergo matrix diffusion. Filtration of these colloids, which is modeled using an exponential decay approach, occurs in high-permeability features. Attenuation is so effective that associated actinides are assumed to be retained within the disposal system and are not transported in SECOTP2D.	Microbial Transport (W87) Colloid Sorption (W81)	R
CRA-2004, Chapter 6.0, Section 6.4.6.2.3 Subsidence Due to Potash Mining MASS-15.4 Subsidence Caused by Potash Mining in the Culebra	MODFLOW-2000	The effect of potash mining is to increase the hydraulic conductivity in the Culebra by a factor between 1 and 1,000.	Conventional Underground Potash Mining (H13) Changes in Groundwater Flow Due to Mining (H37)	Reg.
CRA-2004, Chapter 6.0, Section 6.4.6.3 The Tamarisk	MODFLOW-2000 BRAGFLO	The Tamarisk is assumed to be impermeable.	Saturated Groundwater Flow (N23)	R
CRA-2004, Chapter 6.0, Section 6.4.6.4 The Magenta	BRAGFLO	General Assumptions 1 to 8.	—	See above
	BRAGFLO	The Magenta permeability is set to the lowest value measured near the center of the WIPP site. This increases the flow into the Culebra.	Saturated Groundwater Flow (N23)	R
	NUTS	No radionuclides entering the Magenta will reach the accessible environment. However, the volumes of brine and actinides entering and stored in the Magenta are modeled.	Solute Transport (W77)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.6.5 The Forty-niner	BRAGFLO	The Forty-niner is assumed to be impermeable.	Saturated Groundwater Flow (N23)	R
CRA-2004, Chapter 6.0, Section 6.4.6.6 Dewey Lake	BRAGFLO	General Assumptions 1 to 8.	—	See above
	NUTS	The sorptive capacity of the Dewey Lake is sufficiently large to prevent any release over 10,000 years.	Saturated Groundwater Flow (N23) Actinide Sorption (W61)	R
CRA-2004, Chapter 6.0, Section 6.4.6.7 Supra-Dewey Lake Units	BRAGFLO	General Assumptions 1 to 8.	—	See above
	BRAGFLO	The units above the Dewey Lake are a single hydrostratigraphic unit.	Stratigraphy (N1)	R
	BRAGFLO	The units are thin and predominantly unsaturated.	Unsaturated Groundwater Flow (N24) Saturated Groundwater Flow (N23)	R
CRA-2004, Chapter 6.0, Section 6.4.7 The Intrusion Borehole MASS-16.0 Intrusion Borehole CRA-2004 Section 6.4.7.1 Releases during Drilling	CUTTINGS_S BRAGFLO DRSPALL	Any actinides that enter the borehole during drilling are assumed to reach the surface.	—	C
MASS-16.1 Cuttings, Cavings, and Spall Releases during Drilling	BRAGFLO PANEL CUTTINGS_S DRSPALL	Future drilling practices will be the same as they are at present.	Oil and Gas Exploration (H1) Potash Exploration (H2) Oil and Gas Exploitation (H4) Other Resources (H8) Enhanced Oil and Gas Recovery (H9)	Reg.
	CUTTINGS_S DRSPALL	Releases of particulate waste material are modeled (cuttings, cavings, and spallings). Releases are corrected for radioactive decay until the time of intrusion.	Drilling Fluid Flow (H21) Suspension of Particles (W82) Cuttings (W84) Cavings (W85) Spallings (W86)	R
	CUTTINGS_S	Degraded waste properties are based on marine clays and surrogate materials.	Cavings (W85)	C

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
1 See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	DRSPALL	A hemispherical geometry with one-dimensional spherical symmetry defines the flow field and cavity in the waste.	Spallings (W86)	C
	DRSPALL	Tensile strength, based on completely degraded waste surrogates, is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms.	Spallings (W86)	C
	DRSPALL	Shape factor is 0.1, corresponding to particles that are easier to fluidize and entrain in the flow.	Spallings (W86)	C
CRA-2004, Chapter 6.0, Section 6.4.7.1.1 Direct Brine Release During Drilling MASS-16.2 Direct Brine Releases during Drilling	BRAGFLO PANEL	Brine containing actinides may flow to the surface during drilling. DBR will have negligible effect on the long-term pressure and saturation in the waste panel.	Blowouts (H23)	R
	BRAGFLO	A two-dimensional grid (one degree dip) on the scale of the waste disposal region is used for DBR calculations.	Blowouts (H23)	R
	BRAGFLO CCDFGF	Calculation of DBR from several different locations provides reference results for the variation in release associated with location.	Blowouts (H23)	R
CRA-2004, Chapter 6.0, Section 6.4.7.2 Long-Term Releases Following Drilling MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole	BRAGFLO CCDFGF	Plugging and abandonment of future boreholes are assumed to be consistent with practices in the Delaware Basin.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	Reg.
CRA-2004, Chapter 6.0, Section 6.4.7.2.1 Continuous Concrete Plug through the Salado and Castile	BRAGFLO CCDFGF	A continuous concrete plug is assumed to exist throughout the Salado and Castile. Long-term releases through a continuous plug are analogous to releases through a sealed shaft.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	Reg.-R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.7.2.2 The Two-Plug Configuration	BRAGFLO	A lower plug is located between the Castile brine reservoir and underlying formations. A second plug is located immediately above the Salado. The brine reservoir and waste panel are in direct communication though an open cased hole.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	Reg.-R
	BRAGFLO	The casing and upper concrete plug are assumed to fail after 200 years, and the borehole is assumed to be filled with silty-sand-like material. At 1,200 years after abandonment, the permeability of the borehole below the waste panel is decreased by one order of magnitude as a result of salt creep.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	R
CRA-2004, Chapter 6.0, Section 6.4.7.2.3 The Three-Plug Configuration	BRAGFLO	In addition to the two-plug configuration, a third plug is placed within the Castile above the brine reservoir. The third plug is assumed not to fail over the regulatory time period.	Natural Borehole Fluid Flow (H31) Waste-Induced Borehole Flow (H32)	Reg.-R
CRA-2004 Section 6.4.8 Castile Brine Reservoir MASS-18.0 Castile Brine Reservoir	BRAGFLO	The Castile region is assigned a low permeability, which inhibits fluid flow. Brine occurrences in the Castile are bounded systems. Brine reservoirs under the waste panels are assumed to have limited extent and interconnectivity, with effective radii on the order of several hundred meters.	Brine Reservoirs (N2)	R
CRA-2004, Chapter 6.0, Section 6.4.9 Climate Change MASS-17.0 Climate Change	SECOTP2D	Climate-related factors are treated through recharge. A parameter called the Climate Index is used to scale the Culebra flux field.	Climate Change (N61) Temperature (N60) Precipitation (e.g., Rainfall) (N59)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
1 See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.10 Initial and Boundary Conditions for Disposal System Modeling CRA-2004, Chapter 6.0, Section 6.4.10.1 Disposal System Flow and Transport Modeling (BRAGFLO and NUTS)	BRAGFLO	There are no gradients for flow in the far-field of the Salado, and pressures are above hydrostatic but below lithostatic. Excavation and waste emplacement result in partial drainage of the DRZ.	Saturated Groundwater Flow (N23) Brine Inflow (W40)	R
	BRAGFLO	An initial water-table surface is set in the Dewey Lake at an elevation of 980 meters (m) (3,215 feet [ft]) above mean sea level. The initial pressures in the Salado are extrapolated from a sampled pressure in MB139 at the shaft and are in hydrostatic equilibrium. The excavated region is assigned an initial pressure of one atmosphere. The liquid saturation of the waste-disposal region is consistent with the liquid saturation of emplaced waste. Other excavated regions are assigned zero liquid saturation, except the shaft, which is fully saturated.	Saturated Groundwater Flow (N23)	R
	NUTS	Molecular transport boundary conditions are no diffusion or dispersion in the normal direction across far-field boundaries. Initial An concentrations are zero everywhere, except in the waste.	Radionuclide Decay and Ingrowth (W12) Solute Transport (W77)	R
CRA-2004, Chapter 6.0, Section 6.4.10.2 Culebra Flow and Transport Modeling (MODFLOW-2000, SECOTP2D)	MODFLOW-2000	Constant head and no-flow boundary conditions are set on the far-field boundaries of the flow model.	Saturated Groundwater Flow (N23)	R
	MODFLOW-2000	Initial An concentrations in the Culebra are zero.	Solute Transport (W77)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.10.3 Initial and Boundary Conditions for Other Computational Models	NUTS PANEL BRAGFLO (DBR) CUTTINGS_S	Initial and boundary conditions interpolated from previously executed BRAGFLO calculation.	—	R
CRA-2004, Chapter 6.0, Section 6.4.12 Sequences of Future Events	CCDFGF	Each 10,000-year future (random sequence of future events) is generated by randomly and repeatedly sampling (1) the time between drilling events, (2) the location of drilling events, (3) the activity level of the waste penetrated by each drilling intrusion, (4) the plug configuration of the borehole, and (5) the penetration of a Castile brine reservoir, and by randomly sampling the occurrence of mining in the disposal system.	Oil and Gas Exploration (H1) Potash Exploration (H2) Oil and Gas Exploitation (H4) Other Resources (H8) Enhanced Oil and Gas Recovery (H9) Natural Borehole Fluid Flow (N31) Waste-Induced Borehole Flow (H32)	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.12.1 Active and Passive Institutional Controls in Performance Assessment Chapter 7.0	CCDFGF	Active institutional controls are effective for 100 years and completely eliminate the possibility of disruptive human activities (e.g., drilling and mining). No credit is taken for passive institutional controls.	—	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.12.2 Number and Time of Drilling Intrusions	CCDFGF	Drilling may occur after 100 years according to a Poisson process.	Loss of Records (H57) Oil and Gas Exploration (H1) Potash Exploration (H2) Oil and Gas Exploitation (H4) Other Resources (H8)	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.12.3 Location of Intrusion Boreholes	CCDFGF	The waste disposal region is discretized into 144 regions, each with an equal probability of being intersected. A borehole can penetrate only one region.	Disposal Geometry (W1)	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
CRA-2004, Chapter 6.0, Section 6.4.12.4 Activity of the Intersected Waste Appendix TRU WASTE	CCDFGF	Six-hundred ninety waste streams are identified as contact-handled (CH) transuranic (TRU) (CH-TRU). All 77 remote-handled (RH) transuranic (TRU) (RH-TRU) waste streams were grouped (binned) together into one equivalent or average (WIPP-scale) RH-TRU waste stream.	Heterogeneity of Waste Forms (W3)	R
CRA-2004, Chapter 6.0, Section 6.4.12.5 Diameter of the Intrusion Borehole CCA Appendix DEL	CUTTINGS_S	The diameter of the intrusion borehole is constant at 12.25 inches (in.) (31.12 centimeters [cm]).	—	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.12.6 Probability of Intersecting a Brine Reservoir	CCDFGF	One brine reservoir is assumed to exist below the waste panels. The probability that a deep borehole intersects a brine reservoir below the waste panels is sampled uniformly from 0.01 to 0.60.	Brine Reservoirs (N2)	R
CRA-2004, Chapter 6.0, Section 6.4.12.7 Plug Configuration in the Abandoned Intrusion Borehole	CCDFGF	The two-plug configuration has a probability of 0.696. The three-plug configuration has a probability of 0.289. The continuous concrete plug has a probability of 0.015.	—	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.12.8 Probability of Mining Occurring in the Land Withdrawal Area	CCDFGF	Mining in the disposal system occurs a maximum of once in 10,000 years (a 10^{-4} probability per year).	—	Reg.-R
CRA-2004, Chapter 6.0, Section 6.4.13 Construction of a Single Complementary Cumulative Distribution Function (CCDF)	CCDFGF	Deterministic calculations are executed with BRAGFLO, NUTS, MODFLOW-2000, SECOTP2D, CUTTINGS_S, and PANEL to generate reference conditions. These reference conditions are used to estimate the consequences associated with random sequences of future events. These are, in turn, used to develop CCDFs.	—	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	CCDFGF	Ten thousand random sequences of future events are generated for each CCDF plotted.	—	R
CRA-2004, Chapter 6.0, Section 6.4.13.1 Constructing Consequences of the Undisturbed Performance Scenario	CCDFGF	A BRAGFLO and NUTS calculation with undisturbed conditions is sufficient for estimating the consequences of the undisturbed performance scenario.	—	R
CRA-2004, Chapter 6.0, Section 6.4.13.2 Scaling Methodology for Disturbed Performance Scenarios	CCDFGF	Consequences for random sequences of future events are constructed by scaling the consequences associated with deterministic calculations (reference conditions) to other times, generally by interpolation, but sometimes by assuming either similarity or no consequence.	—	R
CRA-2004, Chapter 6.0, Section 6.4.13.3 Estimating Long-Term Releases from the E1 Scenario	CCDFGF NUTS	Reference conditions are calculated or estimated for intrusions at 100, 350, 1,000, 3,000, 5,000, 7,000, and 9,000 years.	Waste-Induced Borehole Flow (H32)	R
CRA-2004, Chapter 6.0, Section 6.4.13.4 Estimating Long-Term Releases from the E2 Scenario	CCDFGF NUTS SECOTP2D	The methodology is similar to the methodology for the E1 scenario. For multiple E1 intrusions into the same panel, the additional source term to the Culebra for the second and subsequent intrusions is assumed to be negligible.	Waste-Induced Borehole Flow (H32) Waste Inventory (W2)	R
CRA-2004, Chapter 6.0, Section 6.4.13.5 Estimating Long-Term Releases from the E1E2 Scenario	CCDFGF PANEL	The concentration of actinides in liquid moving up the borehole assumes homogeneous mixing within the panel.	Waste-Induced Borehole Flow (H32)	C
	PANEL	Any actinides that enter the borehole for long-term flow calculations reach the Culebra.	Waste-Induced Borehole Flow (H32)	C

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

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Table MASS-5. General Modeling Assumptions (Continued)

Chapter or Section	Code	Modeling Assumption	Related FEP in Appendix SCR-2009	Assumption Considered[a]
	CCDFGF PANEL	Reference conditions are calculated or estimated for intrusion at 100, 300, 1,000, 2,000, 4,000, 6,000 and 9,000 years.	Oil and Gas Exploration (H1)	—
CRA-2004, Chapter 6.0, Section 6.4.13.6 Multiple Scenario Occurrences	CCDFGF PANEL	The panels are assumed not to be interconnected for long-term brine flow.	Saturated Groundwater Flow (N23) Unsaturated Groundwater Flow (N24)	R
CRA-2004, Chapter 6.0, Section 6.4.13.7 Estimating Releases During Drilling for All Scenarios	CCDFGF PANEL NUTS	Repository conditions will be dominated by Castile brine if any borehole connects to a brine reservoir.	Brine Reservoirs (N2) Natural Borehole Fluid Flow (H31)	R
	CUTTINGS_S PANEL CCDFGF	Depletion of actinides in parts of the repository penetrated by boreholes is not accounted for in calculating the releases from subsequent intrusions at such locations.	Waste-Induced Borehole Flow (H32) Waste Inventory (W2)	C
CRA-2004, Chapter 6.0, Section 6.4.13.8 Estimating Releases in the Culebra and the Impact of the Mining Scenario	CCDFGF	Releases from intrusions at random times in the future are scaled from releases calculated at 100 years with a unit source of radionuclides in the Culebra.	—	R
	CCDFGF	Actinides in transit in the Culebra when mining occurs are transported in the flow field used for the undisturbed case. Actinides introduced subsequent to mining are transported in the flow field used for the disturbed case (i.e., the mined case).	—	R

[a] R = Reasonable
C = Conservative
Reg. - Based on regulatory guidance
See above - Refers to assumptions 1 through 8 listed at the beginning of this table.

necessarily zero. This effect, which results in additional flux of gas above that predicted by application of Darcy's Law, is known as the slip phenomenon, or Klinkenberg effect (Bear 1972, p. 128). A correction to Darcy's Law for the Klinkenberg effect is incorporated into the BRAGFLO model (see Appendix PA-2009, Section PA-4.2).

Darcy flow for one and two phases implies that values for principal fluid and rock parameters must be specified. Fluid properties in the Darcy flow model used for the WIPP PA are density, viscosity, and compressibility, while rock properties are porosity, permeability, and

compressibility (pore or bulk). In BRAGFLO, other parameters are required to describe the interactions or interference between the gas and brine phases present in the model because those phases can occupy the same pore space. In the WIPP application of Darcy flow models, compressibility of both the liquid and rock are related to porosity through a dependence on pressure. Fluid density, viscosity, and compressibility are functions of fluid composition, pressure, and temperature. It is assumed in BRAGFLO that fluid viscosity is a function of pressure, but its density and compressibility are held constant. Fluid composition for the purposes of modeling flow and transport is assumed to be constant.

MASS-3.2 Hydrogen Gas as Surrogate for Waste-Generated Gas Physical Properties in BRAGFLO and DRSPALL

Hydrogen gas is produced as a result of the corrosion of steel in the repository by water or brine. As in the CCA, the gas phase in the BRAGFLO model is assigned the properties of hydrogen because hydrogen will, under most conditions reasonable for the WIPP, be the dominant component of the gas phase. The model for spallings, DRSPALL, also assigns the physical properties of hydrogen to the gas phase. As discussed in the following text, the effect of assuming flow of pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S, and CH_4), was shown to be minor relative to the permeability variations in the surrounding formations.

Other gases may be produced by processes occurring in the repository. If microbial degradation occurs, a significant amount of CO_2 and possibly methane (CH_4) will be generated by microbial degradation of cellulosics and, possibly, plastics and rubbers in the waste. The CO_2 produced, however, will react with the magnesium-oxide (MgO) engineered barrier and cementitious materials to form brucite ($Mg(OH)_2$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), and calcite ($CaCO_3$) thus resulting in very low CO_2 fugacity in the repository. Although other gases exist in the disposal system, BRAGFLO calculations assume these gases are insignificant and they are not included in the model.

With the average stoichiometry gas generation model, the total number of moles of gas generated will be the same whether the gas is considered to be pure H_2 or a mixture of several gases, because the generation of other gases is accounted for by specifying the stoichiometric factor y (see Appendix PA-2009, Section PA-4.2.5). Therefore, considering only the moles of gas generated, the pressure buildup in the repository will be approximately the same because the expected gases behave similarly to an ideal gas, even up to lithostatic pressures.

The effect of assuming pure H_2 instead of a mixture of gases (including H_2, CO_2, H_2S and CH_4) on flow behavior, and its resulting impact on the WIPP repository pressure, is as follows:

Radial flow in a fully saturated rock with nonideal gas is described by Darcy's Law, which, for the given problem, has a solution of the form (Amyx, Bass, and Whiting 1960, p. 78, Equation 2-33)

$$q_b = 1.988\times10^{-5}\left[\frac{T_b Z_b}{P_b}\frac{kh\left(P_e^2 - P_w^2\right)}{\mu_{avg} Z_{avg}\ln\left(\frac{r_e}{r_w}\right)}\right] \quad \text{(MASS.1)}$$

which can be rewritten as

$$P_e^2 - P_w^2 = \frac{q_b P_b}{1.988\times10^{-5} T_b Z_b}\times\frac{\mu_{avg} Z_{avg}}{kh}\ln\left(\frac{r_e}{r_w}\right) \quad \text{(MASS.2)}$$

where

- q = gas flow rate (cubic feet per day at base (reference) conditions)
- T = temperature (K)
- P = pressure (pounds per square inch absolute)
- k = permeability (millidarcys)
- h = height (feet)
- μ = viscosity (centipoises)
- Z = gas compressibility factor (defined as the ratio of the actual molar volume of a gas to the corresponding ideal gas volume *RT/P* at the same temperature and pressure)
- r = radius (consistent units)
- R = ideal gas constant
- e = denotes external boundary (repository)
- w = denotes internal boundary (wellbore)
- b = denotes base or reference conditions for gas (temperature, pressure, compressibility factor)
- avg = denotes average properties between external and internal boundaries because u and z are functions of pressure which change with time

This expression is useful for examining the effects of gas properties, specifically the viscosity (μ) and the compressibility (Z) and rock properties (namely k), on the flow rate (q) and the pressure (P).

To evaluate the effect of gas composition on q and P, SUPERTRAPP, a computer program developed by the National Institute of Standards and Technology (NIST), was used (National Institute of Standards and Technology 1992). SUPERTRAPP calculates gas properties for 116 pure fluids and mixtures of up to 20 components for temperatures to 1,000 K (726 °C, 1340 °F) and pressures to 300 megapascals (MPa). Because such small quantities of H_2S are anticipated at the WIPP, its impact is negligible.

Figure MASS-1 shows the relationship between gas viscosity and composition of H_2-CO_2 mixtures for various mole fractions of H_2 at pressures of 7 MPa and 15 MPa, as determined from SUPERTRAPP. The viscosity at 50% mole fraction H_2 is about 2.3 times greater than for 100% mole fraction H_2. As shown in Equation (MASS.1), viscosity has an inverse relationship to flow rate and, as shown in Equation (MASS.2), a direct relationship to the square of the repository

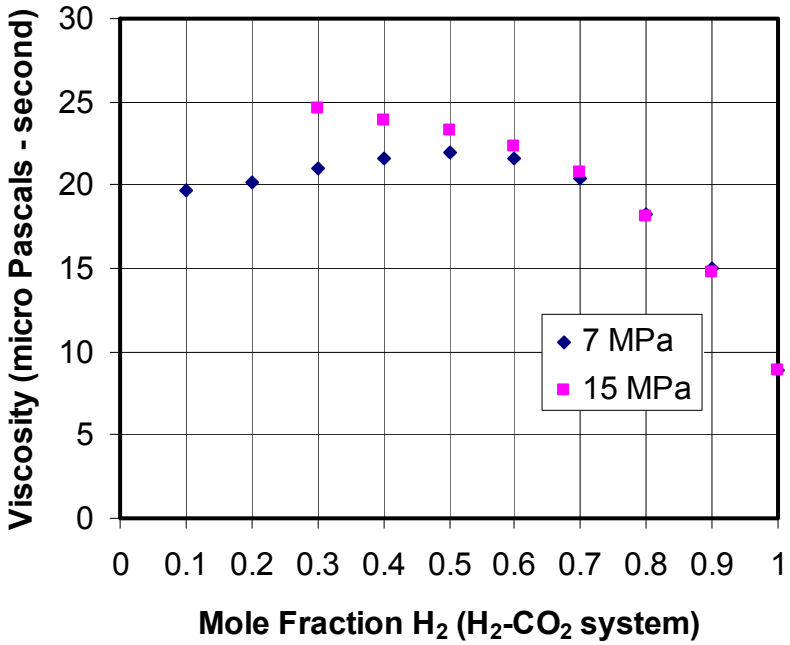


Figure MASS-1. Gas Viscosity as a Function of Mole Fraction H_2 at 7 MPa and 15 MPa Pressure

pressure. Hence, viscosity differences that would result if gas properties other than those of hydrogen were incorporated would result in a decrease in flow rate and potentially higher pressures.

As shown in Figure MASS-2, the gas compressibility at 50% mole fraction H_2 is about 0.9 times that of pure H_2. Like viscosity, the gas compressibility (actual volume/ideal volume) is inversely related to flow rate and directly related to the square of the repository pressure. Therefore, the impact of variation in gas compressibility caused by composition is considered minor and is not considered.

The viscosity and compressibility calculations described above for H_2-CO_2 mixtures were repeated for H_2-CH_4 mixtures for various mole fractions of H_2 at pressures of 7 MPa and 15 MPa (Kanney 2003). The variability of viscosity with the composition for the H_2-CH_4 mixtures is smaller than that observed for the H_2-CO_2 mixtures. For example, at 15 Mpa, the gas viscosity of H_2-CH_4 at 50% mole fraction is only 1.6 times greater than the viscosity at 100% mole fraction. The H_2-CH_4 mixtures are only slightly less compressible than the H_2-CO_2 mixtures. For example, at 15 MPa, the gas compressibility of the H_2-CH_4 at 50% mole fraction is approximately 0.94 times the compressibility at 100% mole fraction. Changing composition from 100% to 50% H_2 would result in a slight increase in flow rate and a decrease in pressure.

The permeability of each component of the formation plays a significant role in determining both flow rate and pressure. Because marker bed (MB) permeabilities and Salado impure halite permeabilities vary over three to four orders of magnitude (see Fox 2008, Table 30 and Table 31), the permeabilities of these flow pathways will have a greater influence on pressure and flow rate determinations than either uncertainty in viscosity or gas compressibility effects.

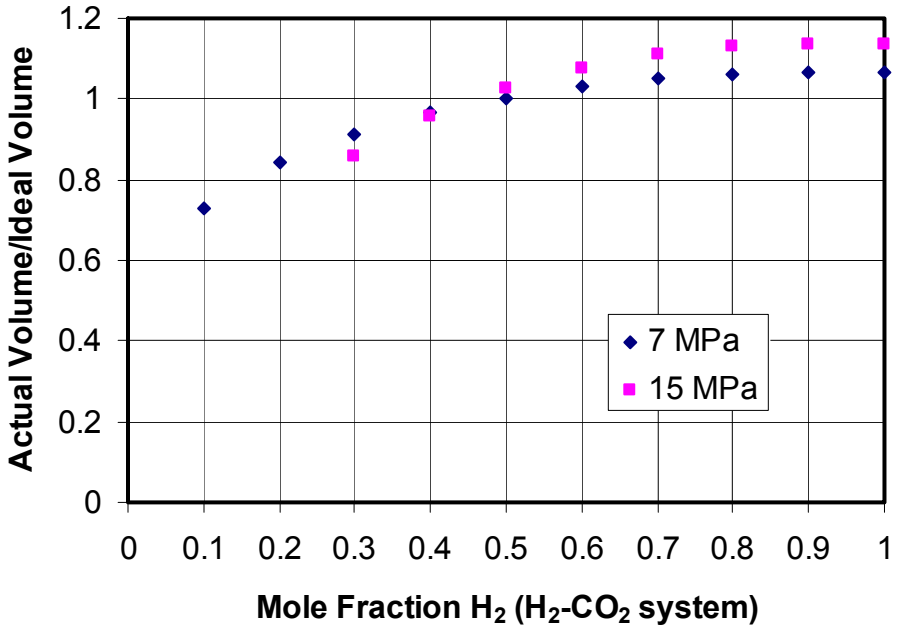


Figure MASS-2. Gas Compressibility as a Function of Mole Fraction H_2

Note that the BRAGFLO code includes a pressure-induced fracture model that will limit pressure increases in the repository (Schreiber 1997). For example, at high repository pressures, the factor of 1.5 pressure increase calculated here using the simplified Darcy's Law model is unlikely to be seen in the BRAGFLO results, since fracturing will lead to increased permeability, effectively limiting pressure increases.

MASS-3.3 Salado Brine as Surrogate for Liquid-Phase Physical Properties in BRAGFLO

BRAGFLO uses Salado Formation brine properties as the physical properties for all liquids. However, liquid in the modeled region may consist of (1) brine originally in the Salado, (2) liquid introduced in the excavation during construction, maintenance, and ventilation during the operational phase, (3) a very small amount of liquid introduced as a component of the waste, (4) liquid from overlying units, and (5) liquid from the Castile brine reservoir. However, for BRAGFLO modeling, it is assumed that the properties of all of these liquids are similar enough to Salado brine properties that the effect of any variation in properties resulting from liquids mixing is negligible. The variations in chemical properties of brine are accounted for as discussed in Appendix SOTERM-2009, Section SOTERM-2.0, Section SOTERM-2.3, and Section SOTERM-5.0.

MASS-4.0 Model Geometries

This section presents supplementary information on the disposal system geometry.

MASS-4.1 Disposal System Geometry as Modeled in BRAGFLO

Overall, the conceptual model of the disposal system geometry represents the spatial effects of process interactions in two dimensions. The geometry used to represent long-term fluid flow processes in the Salado, flow between a borehole and overlying units and flow within the repository (where processes coupled to fluid flow such as creep closure and gas generation occur), is a vertical cross-section through the repository on a north-south axis shown in Figure MASS-3 (see also Appendix PA-2009, Section PA-4.2.1). The dimension of this geometry in the direction perpendicular to the plane of the cross-section varies so that spatial effects of certain processes can be better represented.

For fluid flow and transport modeling in the Culebra, the geometry is a horizontal, two-dimensional plane (see Appendix PA-2009, Section PA-4.8, Figure PA-32). For modeling brine flow from the intruded panel to the borehole during drilling (DBR), the geometry is a two-dimensional, horizontal representation of a waste panel as described in Section MASS-16.2 (see also the CRA-2004, Chapter 6.0, Section 6.4.7.1).

Using a two-dimensional geometry to represent the three-dimensional Salado flow is based on the assumption that brine and gas flow will converge upon and diverge from the repository horizon. Grid flaring is used when flows can be represented as divergent and convergent from the center of the flaring (see Section MASS-4.2.5). The impact of this conceptual model and its implementation in a two-dimensional grid has been compared to a model that does not make the assumption of convergent and divergent flow (see the CRA-2004, Appendix PA, Attachment MASS, Attachment 4-1 for additional information). The conceptual model for the Salado also includes the slight and variable dip of beds in the vicinity of the repository, which might affect fluid flow.

Above and below the repository, it is assumed that any flow between the borehole or shaft (see the CRA-2004, Chapter 6.0, Section 6.4.3) and surrounding materials will converge or diverge. With respect to flow in units overlying the Salado, the only purpose of this conceptual model is to determine the quantity (flux) of fluid leaving or entering the borehole or shaft. Fluid movement through the units above the Salado is treated in a different conceptual model (see the CRA-2004, Chapter 6.0, Section 6.4.6). Below the repository, the possible presence of a brine reservoir is considered to be important, so a hydrostratigraphic layer representing the Castile and a possible brine reservoir in it is included (see the CCA, Appendix MASS, Section MASS-4.2 for the disposal system geometry historical context prior to the CCA).

MASS-4.2 Change to Disposal System Geometry since the CCA

Changes have been made to the disposal system geometry since the first WIPP certification. The disposal system geometry is specifically represented in BRAGFLO. This section describes the methodology used to create the two-dimensional BRAGFLO computational grid used for the

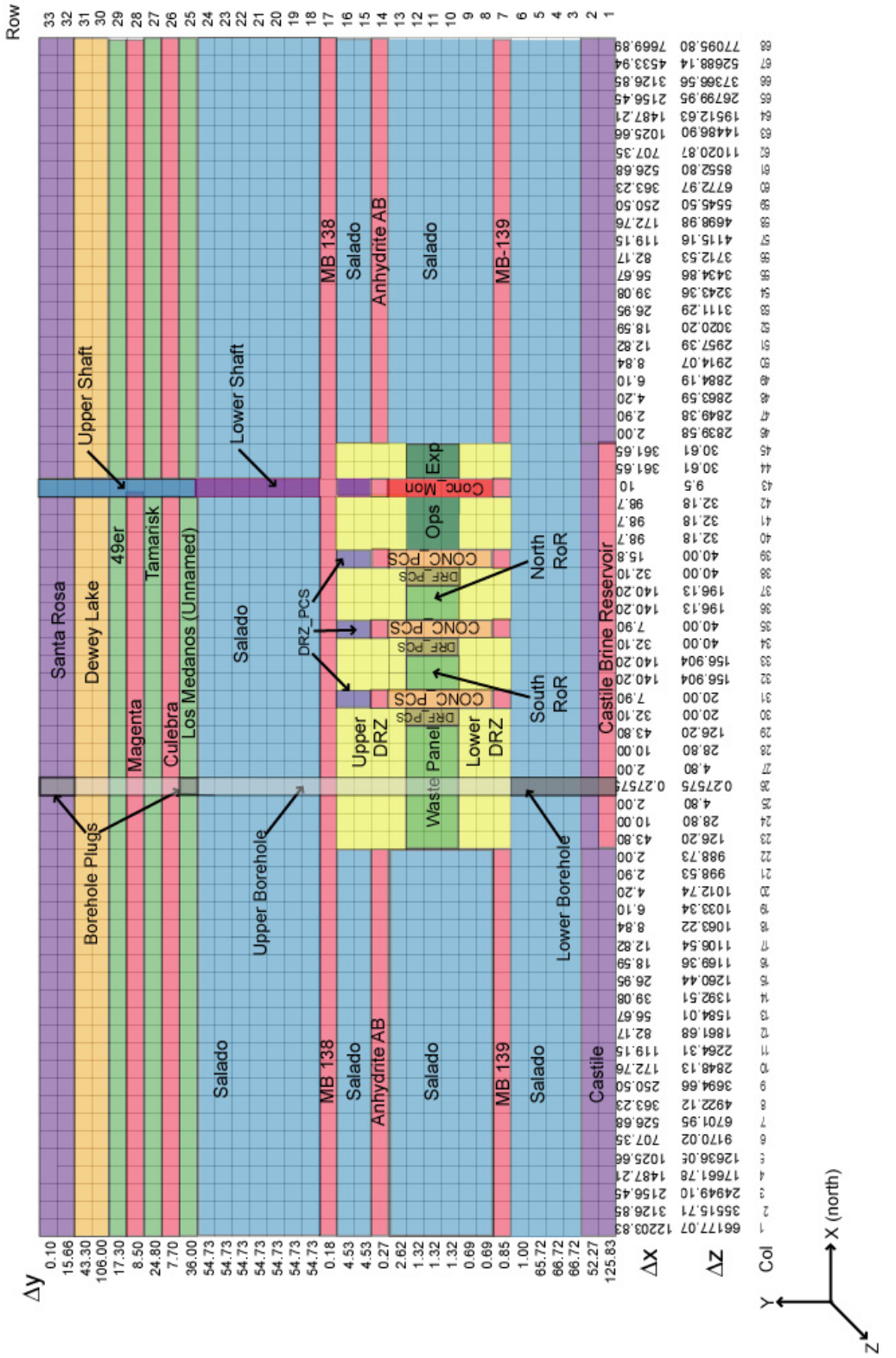


Figure MASS-3. Logical Grid Used for the CRA-2004 and 2009 PA BRAGFLO Calculations

CRA-2004 PA calculations. The CRA-2004 grid is similar to the CCA and the CCA Performance Assessment Verification Test (PAVT) grids, except for the differences described below. Since no changes have been made to the geometry since the CRA-2004 PABC, this grid was used in the CRA-2009 PA.

The most important changes affecting the CRA-2004 BRAGFLO grid were the implementation of the Option D panel closures and a simplified shaft seal model. Additional grid refinements were also made to increase numerical accuracy and computational efficiency and to reduce numerical dispersion. These changes modify the conceptual models. All conceptual model changes were approved by the Salado Flow Peer Review Panel in February 2003 (Caporuscio, Gibbons, and Oswald 2003). For completeness, all changes from the CCA PA/CCA PAVT grid are described here. These changes were made and approved by the EPA in the 2004 recertification decision (U.S. Environmental Protection Agency 2006) and are repeated here for completeness and to show the historical progression of the grid from the CCA to the CRA-2009 PA.

MASS-4.2.1 CCA to CRA-2004 Baseline Grid Changes

The baseline grid used in the CCA PA and the CCA PAVT had 33 cells in the x direction and 31 cells in the y direction, while the grid used for the CRA-2004 PA and later calculations has dimensions 68 by 33 cells. The specific changes implemented in the CRA-2004 grid are listed below and discussed in more detail in the following sections. Logical grids for the CCA PA, the CCA PAVT, and the CRA-2004 and CRA-2009 PAs are shown in Figure MASS-3 and Figure MASS-4.

The following changes have been implemented in the CRA-2004 grid:

1. A simplified shaft seal model is implemented.
2. Option D-type panel closures are implemented.
3. Segmentation of the waste regions is increased.
4. A grid-flaring method is redefined and simplified.
5. X spacing of the grid beyond the repository to the north and south is refined.
6. Layers above and below MB 139 have been made relatively thin (~1 m thick), and Y spacing in the Salado has been changed.

MASS-4.2.2 CRA-2004 Simplified Shaft Seal Model

A shaft seal model is included in the CRA-2004 grid, but it is implemented in a simpler fashion than that used for the CCA PA and the CCA PAVT. A detailed description of the parameters used to define the simplified model is discussed in AP-094 (James and Stein 2002) and the resulting analysis report (James and Stein 2003). The model used in the CRA-2004 PA is described by Stein and Zelinski (2003a and 2003b), and was approved by the Salado Flow Peer Review Panel (Caporuscio, Gibbons, and Oswald 2003).

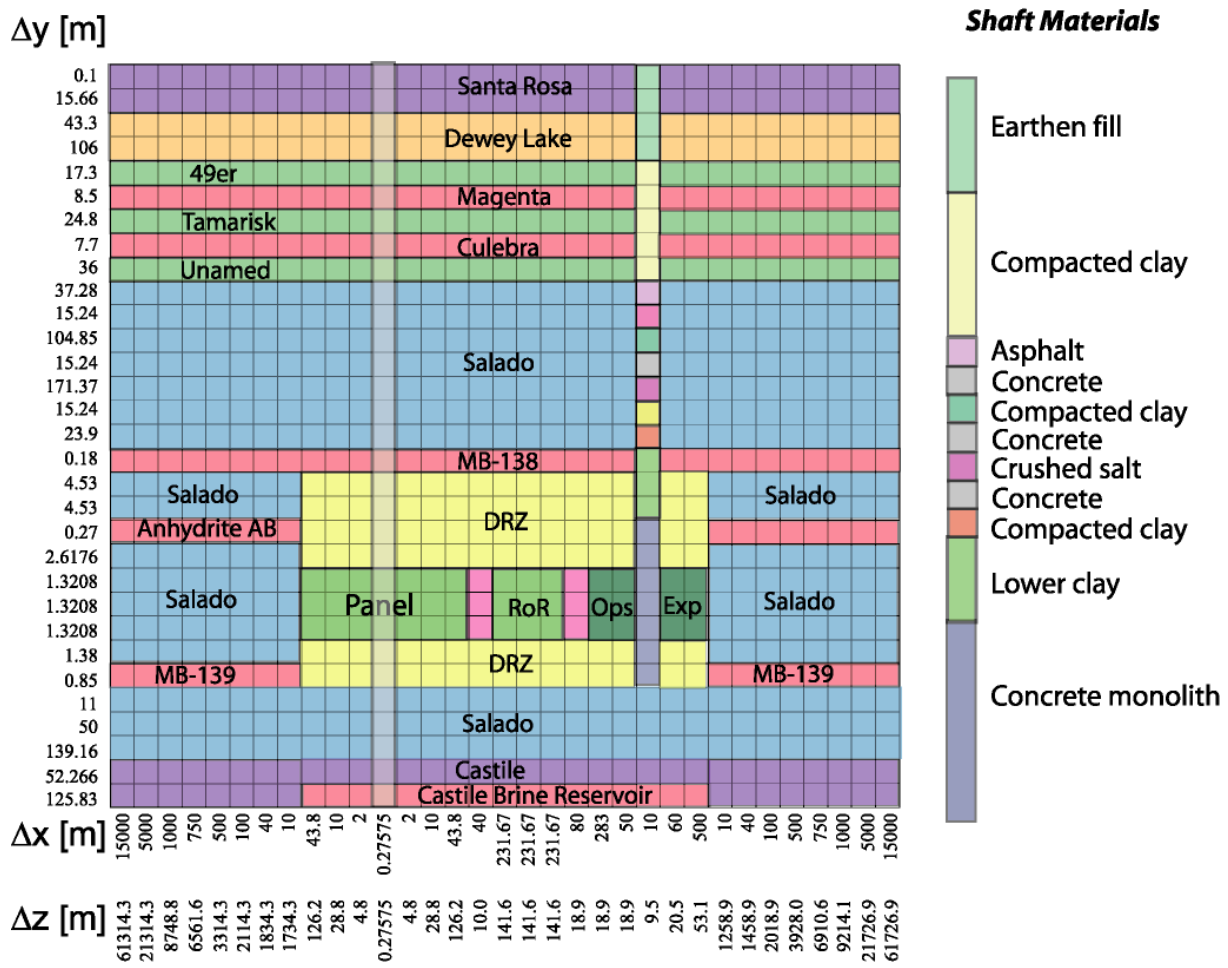


Figure MASS-4. Logical Grid Used for the CCA PA BRAGFLO Calculations

The new model does not alter the conceptual model of the shaft seal components as described in the CCA. Rather, it simplifies the representation of seal components in the repository system model. The CRA and CCA shaft models are graphically compared in Figure MASS-5. The simplified shaft model was tested in the AP-106 calculations (Stein and Zelinski 2003a and 2003b), which supported the Salado Flow Peer Review (see the CRA-2004, Chapter 9.0, Section 9.1.3.4). The results of this analysis demonstrated that brine flow through the simplified shaft model was comparable to brine flows through the detailed shaft model in the CCA PAVT calculations. The conclusion remains that the shaft seals are very effective barriers to flow throughout the 10,000-year regulatory period. The CRA-2004 PA shaft representation is used in the CRA-2009 PA.

MASS-4.2.3 CRA-2004 Implementation of Option D-Type Panel Closure

In the CCA, the DOE presented four options for panel closure designs (A through D). Upon reviewing the CCA, the EPA mandated the implementation of the Option D design. For the

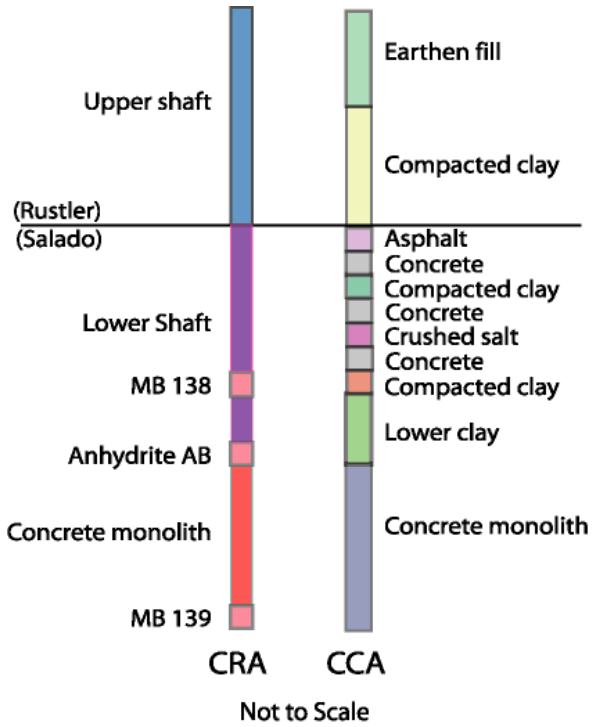


Figure MASS-5. Comparison of the Simplified Shaft (CRA-2004 and CRA-2009) and the Detailed Shaft (CCA) Models

CRA-2004, the true cross-sectional area of the Option D panel closures was represented in the flow model. In addition, to appropriately represent the effect of Option D geometry on repository fluid flow, the segmentation of the waste regions was increased in the grid. This change is described fully in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-4.2.4. The CRA-2009 PA continues to use the same panel closure representation as the CRA-2004 PA.

For CRA-2004, three sets of panel closures are included in the model domain. The southernmost set of closures represents a pair of closures separating a single waste panel from the other waste areas. The middle set of closures represents four panel closures that will be emplaced between the southern and northern extended panels. The northernmost set of panel closures represents two sets of four panel closures that will be emplaced between the waste regions and the shaft seals.

Each set of panel closures is represented in the CRA-2004 grid with four materials. Refer to Figure MASS-6.

1. CONC_PCS: This material represents the concrete monolith, which has properties of Salado Mass Concrete (SMC).

2. DRZ_PCS: This material represents the DRZ immediately above the concrete monolith that is expected to heal after the emplacement of the monolith.

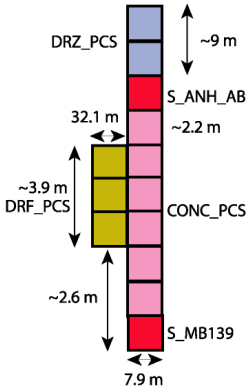


Figure MASS-6. Logical Grid Representation of the Option D Panel Closures for the CRA

3. DRF_PCS: This material represents the empty drift and explosion wall portion of the panel closure. This material has the same properties as WAS_AREA (including creep closure).

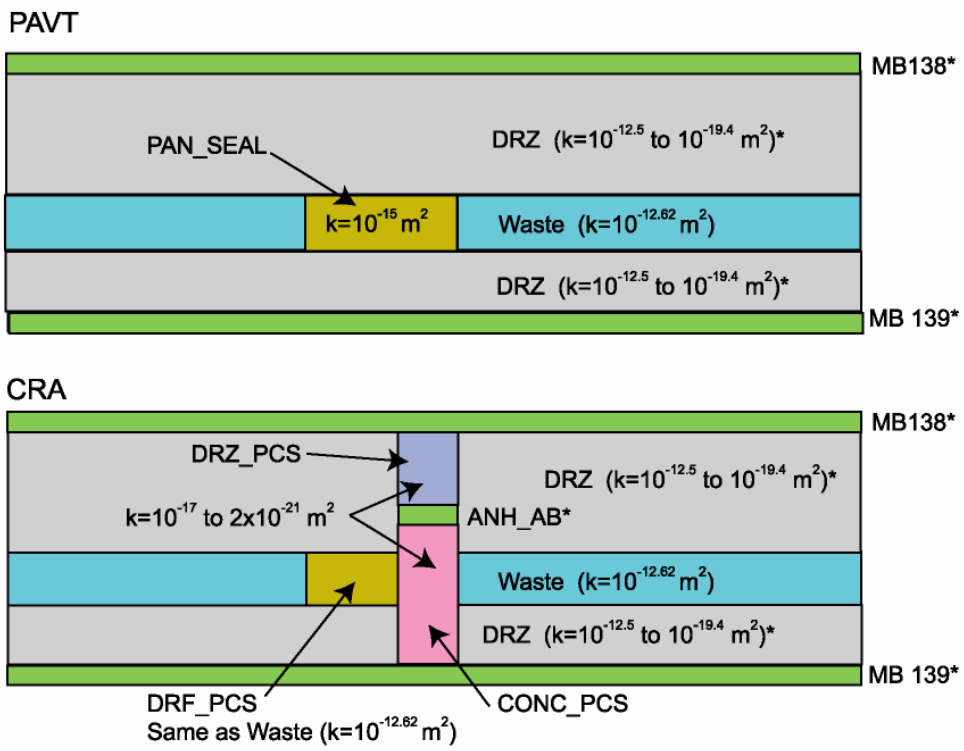
4. MB materials S_ANH_AB and S_MB 139: These materials are the same as those used to represent the anhydrite MBs in other parts of the grid. MB materials were used because they have permeability ranges very close to the material CONC_PCS and in the case when pressures near the panel closures exceed the fracture initiation pressure of the MBs, fractures could extend around the concrete monolith out of the 2-D plane represented by the numerical grid. By using MB materials to represent the parts of the panel closures that intersect MBs, both the permeability of the closure and the potential fracture behavior of MB material near the closures are represented.

Figure MASS-7 is a schematic diagram comparing the panel closure implementation in the CCA and CRA-2004 grids. Permeability ranges are indicated for all materials. Figure MASS-6 shows the 13 grid cells used to represent each set of Option D panel closures in the CRA-2004 BRAGFLO grid.

MASS-4.2.4 Increased Segmentation of Waste Regions in Grid

The CCA PA/CCA PAVT grid divided the waste region into two regions: a single panel in the southern end of the repository referred to as the Waste Panel, and a larger region containing the other nine panels referred to as the RoR. The Waste Panel is intersected by an intrusion borehole and is used to represent conditions in any panel intersected by a borehole.

It is assumed that the Option D panel closures are effective at impeding flow between panels. Therefore, it was considered necessary to divide the rest of repository (RoR) into northern and southern blocks separated by a set of panel closures. The south RoR block represents conditions in a panel directly adjacent to an intruded panel. The north RoR block represents conditions in a nonadjacent panel far from the intruded panel (i.e., it has at least two panel closures between it and the intruded panel). This representation assumes that the effects of drilling intrusions will be damped in nonintruded panels, and the degree of damping will depend on the proximity of the drilling intrusion and the number of panel closures separating the intruded panel from other regions of the repository. The CRA-2009 PA uses the same segmentation of the waste regions as in the CRA-2004 PA. (See the CRA-2004, Appendix PA, Attachment MASS, Section MASS-4.2.4 for a description of waste-region segmentation.)



[* = allowed to fracture, permeability is pressure dependant above ~12.5 MPa]

Figure MASS-7. Schematic Comparison of the Representation of Panel Closures in the CCA PAVT and CRA-2004

MASS-4.2.5 CRA-2004 Redefined and Simplified Grid Flaring Method

Grid flaring is a method to represent three-dimensional volumes in a two-dimensional grid. Flaring is used when flows can be represented as divergent and convergent from the center of flaring. The CCA PA/CCA PAVT grid used flaring at two different scales: locally around the borehole and shaft, and regionally to the north and south of the excavated regions (around a point in the northern end of the RoR). For the CRA-2004 PA, the local flaring around the borehole is the same as in the CCA PA/CCA PAVT grid. The local flaring around the shaft was eliminated because it had been demonstrated not to be a release pathway. Likewise, the manner in which the regional flaring was calculated has been simplified. The CRA-2009 PA uses the same grid flaring as in the CRA-2004 PA. (See the CRA-2004, Appendix PA, Attachment MASS, Section MASS-4.2.5 for a description of grid flaring).

MASS-4.2.6 CRA-2004 Refinement of the X-Spacing Outside the Repository

The grid blocks to the north and south of the excavated region were refined in the x-direction from the baseline grid. The x dimension of the grid cells immediately to the north and south of the repository starts at 2 m and increases by a factor of 1.45.

Exceptions to this are made to ensure that the location of the Land Withdrawal Boundary and the total extent of the grid matches that in the baseline grid. This CRA-2004 PA refinement factor was chosen to reduce numerical dispersion caused by rapid increases in cell dimensions (Anderson and Woessner 1992 and Wang and Anderson 1982). The CRA-2009 PA continues to use this refinement.

MASS-4.2.7 CRA-2004 Refinement of the Y-Spacing

During the CRA-2004 PA, the y direction grid spacing within the layers representing the Salado was changed from the CCA PA/CCA PAVT grid spacing. The Salado grid spacing used in the CCA PA was dictated by the thickness of different shaft seal materials. Since the shaft is no longer represented in the model domain, the y spacing in the Salado is now uniform. In addition, two layers were added immediately above and below MB 139 to refine the grid spacing and reduce numerical dispersion. These changes resulted in a total of 33 y divisions for the grid, and increased the numerical accuracy of flow and transport calculations.

The x and y direction refinements used in the CRA-2004 PA grid are included in the CRA-2009 PA.

MASS-5.0 BRAGFLO Geometry of the Repository

The BRAGFLO code uses a grid to represent the conceptual model of the repository geometry (see Figure MASS-3). As with the geometry of the disposal system discussed in the CRA-2004, Chapter 6.0, Section 6.4.2.1 and earlier in this appendix, the principal process considered in setting up the repository geometry is fluid flow. Several features considered to be important in fluid flow are included in the conceptual model. The first is the overall dimension of the repository along the north-south trend of the cross section, as well as the major divisions within the repository (i.e., waste disposal region, operations region, and experimental region). The second is the volume of a single panel, because fluid flow to a borehole penetrating the repository may have direct access only to the volume in a waste panel. Access to other regions of the repository may require flow through or around a panel closure. The third feature is the physical dimensions of panel closures separating the single panel and the other major divisions of the repository.

Notably absent from the conceptual model for the long-term performance of the repository are pillars and individual drifts and rooms. These are excluded from the model for simplicity, and it is assumed that they have either negligible impact on fluid-flow processes or, alternatively, that including them in the conceptual model would be beneficial to long-term performance because their presence could make flow paths more tortuous and decrease fluxes. This assumption includes lumping four and five of the 10 panels into the south RoR and north RoR regions respectively (see the CRA-2004, Appendix PA, Attachment MASS, Section MASS-4.2.4).

The BRAGFLO model of the WIPP disposal system is a two-dimensional array of three-dimensional grid blocks. Each grid block has a finite length, width, height, volume, and surface area for its boundaries with neighboring grid blocks. The BRAGFLO two-dimensional grid is similar to any other two-dimensional grid used to treat flows, except that the grid-block dimension in the z direction (perpendicular to the plane of the grid) varies from block to block as a function of the x direction (the lateral direction) (see the CRA-2004, Appendix MASS, Section MASS-4.2.5). This allows the BRAGFLO grid to treat important geometric aspects of the WIPP disposal system, such as the very small intrusion borehole, the moderate-sized shaft, and the larger controlled areas. The grid configurations used in the CCA PA and the CCA PAVT are shown in Figure MASS-4, while the grid used for the CRA-2004 PA and the CRA-2009 PA is shown in Figure MASS-3.

MASS-5.1 Historical Context of the Repository Model

Several early models of repository fluid-flow behavior—including models of radionuclide migration pathways, gas flow from the disposal area to the shaft, Salado brine flow through panel to borehole, effects of anhydrite layers on Salado brine flow through a panel, and flow from a brine reservoir through a disposal room—are summarized in Rechard et al. (1990, pp. 153–60). In the preliminary PA of 1992, all waste was lumped into a single region (WIPP Performance Assessment 1993). Because human intrusion boreholes were treated in detail for the CCA PA, it was necessary to model a single waste panel with a borehole surrounded by two-dimensional radial-flaring gridblocks. This approach is continued for the CRA-2009 PA. The CCA PA treated the remainder of the waste area as a single RoR. For the CRA-2004 PA and subsequent analyses, the RoR is divided into two areas separated by a panel closure system. As

discussed earlier, this change was made to more adequately simulate the effects of the Option D closure in impeding fluid flow between panels.

MASS-5.2 CRA-2009 Repository Model

The repository model for the CRA-2009 PA is the same model used in the CRA-2004 PABC. That model used the same features described for the CRA-2004 PA, with no changes to the representation of the repository geometry or BRAGFLO grid.

MASS-6.0 Creep Closure

The creep closure model used in the CRA-2009 is the same used in the CRA-2004 and the CRA-2004 PABC. The model used for creep closure of the repository is discussed in Appendix PORSURF-2009. Historical information on creep closure modeling is also contained in Appendix PORSURF-2009.

MASS-7.0 Repository Fluid Flow

Most repository fluid flow assumptions have not changed from those used in the CRA-2004 PABC. Those that did not change are discussed in Section MASS-7.1 and Section MASS-7.2 while those that did change are discussed in Section MASS-7.3. This model represents the long-term flow behavior of liquid and gas in the repository and its interaction with other regions in which fluid flow may occur, such as the Salado, shafts, or an intrusion borehole. This model is not used to represent the interaction of fluids in the repository with a borehole during drilling. Historical information on alternative conceptual models for brine inflow to the repository is contained in the CCA, Appendix MASS, Section MASS-7.0).

The first principle in the conceptual model for fluid flow in the repository is that gas and brine can both be present and mobile (two-phase flow), governed by conservation of energy and mass and by Darcy's Law for their fluxes (see Appendix PA-2009, Section PA-4.2). Consistent with typical concepts of two-phase flow, the phases can affect each other by impeding flow caused by partial saturation (relative permeability effects) and by affecting pressure caused by capillary forces (capillary pressure effects).

The flow of brine and gas in the repository is assumed to behave as two-phase, immiscible, Darcy flow (see Appendix PA-2009, Section PA-4.2). BRAGFLO is used to simulate brine and gas flow in the repository and to incorporate the effects of disposal-room closure and gas generation. Fluid flow in the repository is affected by the following factors:

- The geometric association of pillars, rooms, and drifts; panel closure caused by creep; and possible borehole locations
- The varied properties of the waste areas resulting from creep closure and heterogeneous contents
- Flow interactions with other parts of the disposal system
- Reactions that generate gas

The geometry of the panel around the intrusion borehole is consistent with the assumption that the fluid flow there will occur directly toward or directly away from the borehole. The geometry represents a semicircular volume north of the borehole and a semicircular volume south of the borehole (representing radial flow in a subregion of a two-dimensional representation of the repository).

Approximating convergent and divergent flow around the intrusion borehole creates a narrow neck in the otherwise fairly uniform width grid in the region representing the repository. In the undisturbed performance scenario, and under certain conditions in other scenarios, flow in the repository may pass laterally through this neck. In reality, this neck does not exist. Its presence in the model is expected to have a negligible or conservative impact on model predictions compared to predictions that would result from a more realistic model geometry. The time scale involved and the permeability contrast between the repository and surrounding rock are sufficient so that the lateral flow that may occur in the repository is restricted by the rate at which

liquid gets into or out of the repository, rather than by the rate at which it flows through the repository.

Gas generation is affected by the quantity of liquid in contact with metal. However, the distribution of fluid in the repository can only be approximated. For example, capillary action can create wicking that would increase the overall region in which gas generation occurs, but modeling this at the necessary resolution to simulate these processes would greatly increase the time required to carry out the modeling (Appendix PA-2009, Section PA-4.2.6 and CRA-2004, Section 6.4.3.3). Therefore, as a bounding measure for gas generation purposes, brine in the repository is distributed to an extent greater than estimated by the Darcy flow models or by the values of parameters chosen.

Option D panel closures and the surrounding rocks are represented by a group of materials, including

1. SMC
2. A material representing the empty drift and explosion wall
3. A material representing healed DRZ
4. MBs

SMC and healed DRZ materials are assigned permeability values sampled independently from a distribution ranging from 2×10^{-21} to 1×10^{-17} m^2. This value range is considered reasonable because the shape of the Option D closure assumes a compressive state that maintains a concrete permeability range similar to the CCA PAVT permeability. This range captures the uncertainty in the long-term performance of the Option D panel closure design.

Modeling of flow within the repository is based on homogenizing the room contents into relatively large computational volumes. The approach ignores heterogeneities in disposal room contents that may influence gas and brine behavior by causing fluid flow among channels or creating preferential paths in the waste, bypassing entire regions. Isolated regions could exist for several reasons:

- They may be isolated by low-permeability regions of waste that serve as barriers.
- Connectivity with the interbeds may occur only at particular locations within the repository.
- The repository dip may promote preferential gas flow in the upper regions of the waste.

For the CCA, the adequacy of the repository homogeneity assumption was examined in screening analyses DR-1 (Webb 1995) and DR-6 (Vaughn, Lord, and MacKinnon 1995a). These analyses used an additional parameter in BRAGFLO to specify the minimum active (mobile) brine flow saturation (pseudoresidual brine saturation). Above this saturation, the normal descriptions of two-phase flow apply (i.e., either the Brooks and Corey or van Genuchten and Parker relative permeability models). Below this minimum, brine is immobile, although it is available for reaction and may still be consumed during gas-generation reactions. The

assumption of a minimum saturation limit was justified based on the presumed heterogeneity of the waste and the slight dip in the repository. The minimum active brine saturation was treated as an uncertain parameter and sampled uniformly between the values 0.1 and 0.8 during the analysis. This saturation limit was applied uniformly throughout the disposal room to bound the impact of heterogeneities on flow (Webb 1995 and Vaughn, Lord, and MacKinnon 1995a). Results of this analysis showed that releases to the accessible environment in the baseline case (homogenization) are consistently higher.

The experimental and operations regions were represented in the CCA PA by a fixed porosity of 18.0% and a permeability of 10^{-11} m^2. The combination of low porosity and high permeability conservatively overestimated fluid flow through these regions and limited the capacity of these regions to store fluids, potentially overestimating releases to the environment. This conclusion was based on a screening analysis (Vaughn, Lord, and MacKinnon 1995b) that examined the importance of permeability varying with porosity in closure regions (waste disposal region, experimental region, and operations region). To perform this analysis, a model for estimating the change in permeability with porosity in the closure regions was implemented in BRAGFLO. A series of BRAGFLO simulations was performed to determine whether permeability varying with porosity in the closure regions could enhance contaminant migration to the accessible environment. Two basic scenarios were considered in the screening analysis: undisturbed performance and disturbed performance. To assess the sensitivity of system performance on dynamic permeability in the closure regions, CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline conditional CCDFs. The baseline model treated permeabilities in the closure regions as fixed values. Results of this analysis showed that the inclusion of dynamic closure of the waste disposal region, experimental region, and operations region in BRAGFLO resulted in computed releases to the accessible environment that are essentially equivalent to the baseline case.

A separate analysis (Park and Hansen 2003) examined the possible effects of heterogeneity in waste container and waste material strength on room closure. The analysis of room closure found that the room porosity may vary widely depending on the type of waste container and the emplacement of waste in the repository. However, analysis of a separate PA (Hansen et al. 2003) found that PA results are relatively insensitive to the uncertainty in room closure and room porosity. The conclusions of the separate PA are summarized in Section MASS-21.0 of this appendix.

MASS-7.1 Flow Interactions with the Creep Closure Model

The dynamic effect of halite creep and room consolidation on room porosity is modeled only in the waste disposal region. Other parts of the repository, such as the experimental region and the operations region, are modeled assuming fixed (invariant with time) properties. In these regions, the permeability is held at a fixed high value representative of unconsolidated material, while the porosity is maintained at relatively low values associated with highly consolidated material. This combination of low porosity and high permeability is assumed to conservatively overestimate flow through these regions and minimize the capacity of this material to store fluids, thus maximizing the release to the environment. To examine the acceptability of this assumption, a screening analysis (Vaughn, Lord, and MacKinnon 1995c) evaluated the effect of including closure of the experimental region and operations region. In this analysis, consolidation of the

experimental region and operations region was implemented in BRAGFLO by relating pressure and time to porosity using a porosity-surface method. The porosity surface for the experimental region and operations region differs from the surface used for consolidation of the disposal room and is based on an empty excavation (see Appendix PORSURF-2009). The screening analysis showed that disregarding dynamic closure of the experimental region is acceptable because it is conservative: lower releases occur when closure of the experimental region and operations region is computed compared to simulations with time-invariant high permeability and low porosity.

MASS-7.2 Flow Interactions with the Gas Generation Model

Gas generation affects repository pressure, which in turn is an important parameter in other processes such as two-phase flow, creep closure, and fracturing of the interbeds and DRZ. Gas-generation processes considered in PA calculations include anoxic corrosion and microbial degradation. Radiolysis is excluded from PA calculations on the basis of laboratory experiments and a screening analysis (Vaughn et al. 1995) that concluded that radiolysis does not significantly affect repository performance.

In modeling gas generation, the effective liquid in a computational cell is the computed liquid in that cell plus an adjustment for the uncertainty associated with wicking by the waste (see Appendix PA-2009, Section PA-4.2.6). Capillary action (wicking) is the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. Because the current gas-generation model computes substantially different gas-generation rates depending on whether the waste is wet or merely surrounded by water vapor, the physical extent of wetting could be important. A screening analysis (Vaughn, Lord, and MacKinnon 1995d) examined wicking and concluded that it should be included in PA calculations.

The baseline gas-generation model in BRAGFLO accounts for corrosion of iron and microbial degradation of cellulose and possibly plastics and rubber. The net reaction rate of these processes depends directly on brine saturation: an increase in brine saturation will increase the net reaction rate by weighting the inundated portion more heavily and the slower humid portion less heavily. To simulate the effect of wicking on the net reaction rate, an effective brine saturation, which includes a wicking saturation contribution, is used to calculate reaction rates rather than the actual brine saturation. To account for uncertainty in the wicking saturation contribution, this contribution was sampled from a uniform distribution from 0.0 to 1.0 for each BRAGFLO simulation in the analysis.

MASS-7.3 CRA-2009 Flow Interactions with the Gas-Generation Model Changes

The assumptions for brine availability were changed in BRAGFLO Version 6.0 to account for brine-consuming reactions. Brine-consuming reactions such as anoxic corrosion tend to dry out the waste-filled regions of the repository. The former BRAGFLO code and underlying models could not simulate completely dry cells in the grid. To accommodate brine-consuming reactions and allow the code to run, BRAGFLO Version 6.0 includes a lower cut off in brine saturation for waste-filled regions in the repository, representing a numerically dry condition. At this cut-off saturation, biodegradation and iron corrosion ceases. This modification is explained fully in

Section 5.2.2 of Nemer and Clayton (2008). BRAGFLO version 6.0 was used in the CRA-2009 PA; older versions of the code were used in previous PAs.

MASS-8.0 Gas Generation

The gas generation model represents the possible generation of gas in the repository by corrosion of steel and microbial degradation of CPR materials. The CRA-2009 uses the CRA-2004 PABC gas generation modeling assumptions. Although the amount of the excess MgO engineered barrier emplaced in the repository has been reduced from 1.67 to 1.2, the PA methodology does not account for any excess material in the modeling assumption and therefore no changes to these assumptions are necessary. Additional discussion of this topic may be found in Appendix PA-2009, Section PA-4.2.5 and Appendix SCR-2009 (FEPs W44 through W48, W53, and N71) and the CRA-2004, Chapter 6.0, Section 6.4.3.3.

MASS-8.1 Historical Context of Gas Generation Modeling

See the CCA, Appendix MASS, Section MASS-8.1 for historical information on the development of the CCA gas-generation conceptual model.

MASS-9.0 Chemical Conditions

The chemical conditions modeling assumptions have not changed from those in the CRA-2004 PABC. The models used for chemical conditions in the repository are discussed in Appendix MgO-2009 and Appendix SOTERM-2009.

MASS-10.0 Dissolved Actinide Source Term

The dissolved An source term modeling assumptions have not changed from those in the CRA-2004 PABC. The models used for the dissolved An source term in the repository are discussed in Appendix SOTERM-2009, Section SOTERM-4.0 and Section SOTERM-5.0.

MASS-11.0 Colloidal Actinide Source Term

The colloidal An source term modeling assumptions have not changed from those in the CRA-2004 PABC. The models used for the colloidal An source term are discussed in Appendix SOTERM-2009, Section SOTERM-3.8.

MASS-12.0 Shafts and Shaft Seals

The shafts and shaft seals modeling assumptions have not changed from those in the CRA-2004 PABC. The models used for shafts and shaft seals are discussed in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-12.0.

MASS-13.0 Salado

The far-field Salado modeling assumptions used in the CRA-2009 are the same as those used in the CRA-2004 PABC. No changes have been made to these modeling assumptions for the CRA-2009 PA. The purpose of this model is to reasonably represent the effects of fluid flow in the Salado on long-term performance of the disposal system. The conceptual model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.5. The Salado fluid flow model represented in the CRA-2004 PABC is also used in the CRA-2009 PA (Nemer and Clayton 2008).

Fluid flow in the Salado is considered in the conceptual model of long-term disposal system performance for several reasons. First, some liquid could move from the Salado to the repository because of the considerable gradients that can form for liquid flow inward to the repository. This possibility is important because such fluid can affect creep closure, gas generation, An solubility, and other processes occurring in the repository. Second, gas generated in the repository is thought to be capable of fracturing the Salado interbeds under certain conditions, creating increased permeability channels that could be pathways for lateral transport. The lateral transport pathway in intact Salado is also modeled, but it is considered unlikely to result in any significant radionuclide transport to the accessible environment boundary.

The fundamental principle in the conceptual model for fluid flow in the Salado is that it is a porous medium within which gas and brine can both be present and mobile (two-phase flow), governed by conservation of energy and mass and by Darcy's Law for their fluxes (see Appendix PA-2009, Sections PA-4.2). Consistent with typical concepts of two-phase flow, each phase can affect the other by impeding flow because of partial saturation (relative permeability effects) and by affecting pressure by capillary forces (capillary pressure effects). It was originally assumed that no waste-generated gas is present before repository closure. However, during the EPA completeness review of the CRA-2004, the representation of the gas-generation rate was changed for the CRA-2004 PABC (Cotsworth 2005). The repository was precharged after closure to represent the short-term, but initially faster, microbial gas-generation rate (see Section MASS-8.0 and Leigh et al. 2005, Section 2.3). Future states are modeled as producing gas by corrosion and microbial activities. Should high pressure develop over the regulatory period, it is allowed to access MBs in the Salado.

Some variability in composition exists between different horizons of the Salado. The largest differences occur between the anhydrite-rich layers called interbeds and those dominated by halite. Within horizons dominated by halite, composition varies from nearly pure halite to halite plus several percent other minerals, in some instances including clay (see the CCA, Chapter 2.0, Section 2.1.3.4). The Salado is modeled as impure halite except for those interbeds that intersect the DRZ near the repository. This conceptual model and an alternative model that explicitly represented all stratigraphically distinct layers of the Salado near the repository (Christian-Frear and Webb 1996) produced similar results.

From other modeling and theoretical considerations, flow between the Salado and the repository is expected to occur primarily through interbeds that intersect the DRZ. Because of the large surface areas between the interbeds and surrounding halite, the interbeds serve as conduits for the flow of brine in two directions: from halite to interbeds to the repository, or, for brine flowing out of the repository, from the repository into interbeds and then into halite. Because the

repository is modeled as a relatively porous and permeable region, brine is considered most likely (but not constrained) to leave the repository through MB 139 below the repository because of the effect of gravity. If repository pressures become sufficiently high, gas is modeled to exit the repository via the MBs.

The effect of gravity may also be important in the Salado because of the slight and variable natural stratigraphic dip. For long-term performance modeling, the dip in the Salado within the domain is taken to be constant and 1 degree from north to south.

Fluid flow in the Salado is conceptualized as occurring either convergently into the repository or divergently from it, as discussed in detail in the CRA-2004, Chapter 6.0, Section 6.4.2.1. Because the repository is not conceptualized as homogeneous, implementing a geometry for the conceptual model of convergent or divergent flow in the Salado is somewhat complicated and is discussed in the CRA-2004, Chapter 6.0, Section 6.4.2.1.

The conceptual model for Salado fluid flow has primary interactions with three other conceptual models. The interbed fracture conceptual model allows porosity and permeability of the interbeds to increase as a function of pressure. The repository fluid flow model is directly coupled to the Salado fluid flow model by the governing equations of flow in BRAGFLO (in the governing equations of the mathematical model, they cannot be distinguished), and it differs only in the region modeled and the parameters assigned to materials. The Salado model for An transport is directly coupled to the conceptual model for flow in the Salado through the process of advection. Additional information on the treatment of the Salado in PA is found in Appendix PA-2009, Section PA-4.2.

MASS-13.1 High Threshold Pressure for Halite-Rich Salado Rock Units

An important parameter used to describe the effects of two-phase flow is threshold pressure, which helps to determine the ease with which gas can enter a liquid-saturated rock unit. For a brine-saturated rock, the threshold pressure is defined as "equal to the capillary pressure at which the relative permeability to the gas phase begins to rise from its zero value, corresponding to the incipient development of interconnected gas flow paths through the pore network" (Davies 1991, p. 9).

The threshold pressure, as well as other parameters used to describe two-phase characteristics, has not been measured for halite-rich rocks of the Salado. The Salado, however, is thought to be similar in pore structure to rocks for which threshold pressures have been measured (Davies 1991). Based on this observation, Davies (1991) postulated that the threshold pressure of the halite-rich rocks in the Salado could be estimated if an empirical correlation exists between rocks postulated to have similar pore structure.

Davies developed a correlation between threshold pressure and intrinsic permeability applicable to the Salado halites. A similar correlation was developed for Salado anhydrites; subsequent testing confirmed that the correlation predicted threshold pressures accurately. The correlation developed by Davies predicts threshold pressures in intact Salado halites on the order of 20 MPa or greater (Davies 1991). This threshold pressure predicted by correlation is much higher than

that expected to persist in the repository, so that for all practical and predictive purposes, no gas will flow into intact Salado halites (see the CRA-2004, Chapter 6.0, Section 6.4.5.1).

Because threshold pressure helps control the flow of gas, and because the greatest volume of rock in the Salado is rich in halite, a high threshold pressure effectively limits the volume of gas that can be accommodated in the pore spaces of the intact host formation. Thus, high threshold pressure is considered conservative, because if gas could flow into the pore spaces of intact Salado halite, repository pressures could be reduced dramatically.

MASS-13.2 Historical Context of the Salado Conceptual Model

See the CCA, Appendix MASS, Section MASS-13.2 for the historical information relating to the CCA Salado conceptual model. The Salado conceptual model is unchanged for the CRA-2009 PA.

MASS-13.3 The Fracture Model

The fracture model assumptions have not changed from those in the CRA-2004 PABC. The purpose of this model is to alter the porosity and permeability of the anhydrite interbeds and the DRZ if their pressure approaches lithostatic, simulating some of the hydraulic effects of fractures with the intent that unrealistically high pressures (in excess of lithostatic) do not occur in the repository or disposal system. The conceptual model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.5.2. The fracture model assumptions have not changed from those in the CRA-2004 PABC.

In the 1992 preliminary PA, repository pressures were shown to greatly exceed lithostatic pressure if a large quantity of gas was generated. Pressures within the waste repository and surrounding regions were predicted to be roughly 20 to 25 MPa. It was expected that fracturing within the anhydrite MBs would occur at pressures slightly above lithostatic pressure. An expert panel on fractures was convened to develop the conceptual bases for the fracturing within the anhydrite MBs.

Two parametric behaviors must be quantified in the conceptual model. First, the change of porosity with pressure in the anhydrite MBs must be specified. This is done with a relatively simple equation, described in Appendix PA-2009, Section PA-4.2.4, that relates porosity change to pressure change using an assumption that the fracturing can be thought of as increasing the compressibility of interbeds. Parameters in the model are treated as fitting parameters and have little relation to physical behavior except that they affect the porosity change. The second parametric behavior is the change of permeability with pressure, which is incorporated by a functional dependence on the porosity change. It is assumed that a power function is appropriate for relating the magnitude of permeability increase to the magnitude of porosity increase. The parameter in this power function, an exponent, is also treated as a fitting parameter and can be set so that the behavior of permeability increase with porosity increase fits the desired behavior.

The fracture enhancement model assumes fracture propagation is uniform in the lateral direction to flow within the MBs in the absence of dip. The 1-degree dip modeled in BRAGFLO may affect fracture propagation direction; however, within the accuracy of the finite difference grid, a

fracture will develop radially outward. This would not account for fracture fingering or a preferential fracturing direction; however, no existing evidence supports heterogeneous anhydrite properties that would contribute to preferential fracture propagation. This evidence is discussed in the CCA, Appendix MASS, Attachment 13-2.

The maximum enhanced fracture porosity controls the storativity within the fracture. The extent of the migration of the gas front into the MB is sensitive to this storativity. The additional storativity caused by porosity enhancement will mitigate gas migration within the MB. The enhancement of permeability by MB fracturing will make the gas more mobile and will contribute to longer gas-migration distances. Thus the effects of porosity enhancement at least partially counteract the effects of permeability enhancement in affecting the gas-migration distances.

Because intact anhydrite is partially fractured, the pressure at which porosity or permeability changes are initiated is close to the initial pressure within the anhydrite. The fracture treatment within the MBs will not contribute to early brine drainage from the MB because the pressures at these times are below the fracture initiation pressure.

The input data to the interbed fracture model (see Fox 2008, Table 30, Table 31, and Table 32) were chosen deterministically to produce the appropriate pressure and porosity response as predicted by a linear elastic fracture mechanics model, as discussed in Mendenhall and Gerstle (1993).

MASS-13.4 Flow in the DRZ

Modeling assumptions relating to flow in the DRZ have not changed from those in the CRA-2004 PABC. The conceptual model for the DRZ around the waste disposal, operations, and experimental regions has been chosen to provide a reasonably conservative estimate of fluid flow between the repository and the intact halite and anhydrite MBs. The conceptual model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.5.3.

The conceptual model implemented in the CCA PA used values for the permeability and porosity of the DRZ that did not vary with time. A screening analysis examined an alternative conceptual model for the DRZ in which permeability and porosity changed dynamically in response to changes in pressure (Vaughn, Lord, and MacKinnon 1995e). This analysis implemented a fracturing model in BRAGFLO for the DRZ. This fracturing model is used in the existing anhydrite interbed model. In this model, formation permeability and porosity depend on brine pressure, as described by Freeze, Larsen, and Davies (1995, pp. 2-16 through 2-19) and Appendix PA-2009, Section PA-4.2.4. This model permits the representation of two important formation-alteration effects. First, pressure buildup caused by gas generation and creep closure within the waste will slightly increase porosity within the DRZ and offer additional fluid storage with lower pressures. Second, the accompanying increase in formation permeability will enhance fluid flow away from the DRZ. Because an increase in porosity tends to reduce outflow into the far field, parameter values for this analysis were selected so that the DRZ alteration model greatly increases permeability while only modestly increasing porosity.

Two basic scenarios were considered in the screening analysis by Vaughn, Lord, and MacKinnon (1995e): undisturbed repository performance and disturbed repository performance. Both scenarios included a 1-degree formation dip downward to the south. Intrusion event E1 is considered in the disturbed scenario and consists of a borehole that penetrates the repository and pressurized brine in the underlying Castile. Two variations of intrusion event E1 were examined: E1 updip and E1 downdip. In the E1 updip event, the intruded panel region was located on the north end of the waste disposal region, whereas in the E1 downdip event, the intruded panel region was located on the south end of the disposal region. These two different geometries permitted evaluation of the possibility of increased brine flow into the panel region and the potential for subsequent impacts on contaminant migration. To incorporate the effects of uncertainty in each case (E1 updip, E1 downdip, and undisturbed), a Latin hypercube sample (LHS) size of 20 was used, for a total of 60 simulations. To assess the sensitivity of system performance on formation alteration of the DRZ, conditional CCDFs of normalized contaminated brine releases were constructed and compared with the corresponding baseline model conditional CCDFs that were computed with constant DRZ permeability and porosity values. Based on comparisons between conditional CCDFs, computed releases to the accessible environment were determined to be essentially equivalent between the two treatments. Since the two configurations were determined to have essentially equivalent impacts on releases, the intrusion borehole was assumed to intrude in the down-dip or south side of the repository where it is assumed brine would more readily accumulate (see Figure MASS-3).

Preliminary PAs considered alternative conceptual models that allowed for some lateral extent of the DRZ into the halite surrounding the waste disposal region and for the development of a transition zone between anhydrites A and B and MB 138 (WIPP Performance Assessment 1993, Volume 4, Figure 4.1-2 and Figure 5.1-2; and Davies, Webb, and Gorham 1992; and Gorham et al. 1992). The transition zone was envisioned as a region that had experienced some hydraulic depressurization and perhaps some elastic stress relief because of the excavation, but probably no irreversible rock damage and no large permeability changes. Modeling results indicated that including the lateral extent of the DRZ had no significant effect on fluid flow. Communication vertically to MB 138 was thought to be a potentially important process, however, and the model adopted for PA assumes that the DRZ extends upward to MB 138 and permeability is sampled over the same range used in the CCA PAVT. This representation continues to be used in the CRA-2009 PA.

MASS-13.5 Actinide Transport in the Salado

The An transport modeling assumptions have not changed from those in the CRA-2004 PABC. The purpose of this model, implemented in the code NUTS, is to represent the transport of actinides in the Salado. This model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.5.4 and Appendix PA-2009, Section PA-4.3.4.

Actinide transport in the Salado is conceptualized as occurring only by advection, or movement of material through the bulk flow of a fluid, through the porous medium described in the Salado hydrology conceptual model. Advection is a direct function of fluid flow, which is discussed in the conceptual model for Salado fluid flow. Other processes that might disperse actinides, such as diffusion, hydrodynamic dispersion, and channeling in discrete fractures, are not included in

the conceptual model. Since these processes will reduce An transport, it is conservative to ignore these processes.

To model radionuclide transport in the Salado, NUTS takes as input BRAGFLO's velocity field, pressures, porosities, saturations, and other model parameters (including geometrical grid, residual saturation, material map, brine compressibility, and time step) averaged over a given number of time steps (20 for the CRA-2009 PA calculations). NUTS then models the transport of radionuclides within all the regions for which BRAGFLO computes brine and gas flow. The brine must pass through some part of the repository at some point during the 10,000-year regulatory period if it is to become contaminated. Radioactive constituents of the waste in the repository are assumed to dissolve into the brine while the brine is in the repository; the radionuclides are then transported by advection to other regions outside the repository. Consequently, the results of NUTS are subject to all the uncertainties associated with BRAGFLO's conceptual model and parameterization, and are presented in Appendix PA-2009. Details of the source term, which specifies the types and amounts of radionuclides that are assumed to come into contact with the waste, are discussed in Appendix SOTERM-2009, Section SOTERM-3.1 and Table SOTERM-6.

NUTS neglects molecular dispersion. For materials of interest in the WIPP repository system, molecular diffusion coefficients are, at most, on the order of 4×10^{-10} m^2 per second. Thus, the simplest scaling argument using a time scale of 10,000 years leads to a molecular diffusion (that is, mixing) length scale of approximately 33 ft (10 m), which is negligible compared to the lateral advection length scale of roughly 7,874 ft (2,400 m) (the lateral distance from the repository to the accessible environment).

NUTS also neglects mechanical dispersion (see the CRA-2004, Chapter 6.0, Section 6.4.5.4.2). Dispersion is quantified by dispersivities, which are empirical tensor factors proportional to flow velocity (to within geometrical factors related to flow direction). They account for both the downstream and cross-stream spreading of local extreme values in concentration of dissolved constituents. Physically, the spreading is caused by the fact that both the particle paths and velocity histories of once-neighboring particles can be vastly different because of material heterogeneities characterized by permeability variations. These variations arise from the irregular cross-sectional areas and tortuous inhomogeneous, anisotropic connectivity between pores. Because of its velocity dependence, the transverse component of mechanical dispersivity tends to transport dissolved constituents from regions of relatively rapid flow (where mechanical dispersion has a larger effect) to regions of slower flow (where mechanical dispersion has a smaller effect). In the downstream direction, dispersivity merely spreads constituents in the flow direction. Conceptually, ignoring lateral spreading assures that dissolved constituents will remain in the rapid part of the flow field, which assures their transport toward the boundary. Similarly, ignoring longitudinal dispersivity ignores the elongation of a feature in the flow direction, which would delay the arrival of radionuclide constituents at the accessible environment. However, because the EPA release limits are time-integrated measures, the exact time of arrival is unimportant for constituents that arrive at the accessible environment, so long as arrival occurs within the assessment period (10,000 years).

NUTS conservatively disregards sorptive and other retarding effects throughout the entire flow region even though retardation must occur at some level within the repository, the MBs, and the

anhydrite interbeds, and especially in zones with clay layers or clay as accessory minerals. Advection is, therefore, the only transport mechanism considered in NUTS. Because the Darcy flows are given by BRAGFLO to NUTS as input, the maximum solubility limits for combined dissolved and colloidal components are the most important NUTS parameters. These components are described in Appendix SOTERM-2009, Section SOTERM-5.0.

MASS-14.0 Geologic Units above the Salado

The modeling assumptions of the geologic units above the Salado have not changed from those in the CRA-2004 PABC. The model for geologic units above the Salado was developed to provide a reasonable and realistic basis for simulations of fluid flow within the disposal system and detailed simulations of groundwater flow and radionuclide transport in the Culebra. The conceptual model for these units is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.

The conceptual model used in PA for the geologic units above the Salado is based on the overall concept of a groundwater basin, as introduced in the CRA-2004, Chapter 2.0, Section 2.2.1.1 and in the CCA, Appendix MASS, Section MASS-14.2. The computer code SECOFL3D was originally used to evaluate the effect on regional-scale fluid flow by recharge and rock properties in the groundwater basin above the Salado (see the CCA, Appendix MASS, Attachment 17-2). However, simpler models for this region are implemented in codes used in PA. For example, in the BRAGFLO model, layer thicknesses, important material properties including porosity and permeability, and hydrologic properties such as pressure and initial fluid saturation are specified, but the model geometry and boundary conditions are not suited to groundwater basin modeling (nor is the BRAGFLO model used to make inferences about groundwater flow in the units above the Salado). In PA, the Culebra is the only subsurface pathway modeled for radionuclide transport above the Salado, although the groundwater basin conceptual model includes other flow interactions. The Culebra model implemented in PA includes spatial variability in hydraulic conductivity and uncertainty and variability in physical and chemical transport processes. Thus, the geometries and properties of units in the different models applied to the units above the Salado by the DOE are chosen to be consistent with the purpose of the model.

The MODFLOW-2000 and SECOTP2D codes are used directly in PA to model fluid flow and transport in the Culebra. The assumptions made in these codes are discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.2 and the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.0.

With respect to the units above the Salado, the BRAGFLO model is used only for determination of fluid fluxes between the shaft or intrusion borehole and hydrostratigraphic units. For this purpose, it does not need to resolve regional or local flow characteristics.

The basic stratigraphy and hydrology of the units above the Salado are described in the CRA-2004, Chapter 2.0, Section 2.1.3.5, Section 2.1.3.6, Section 2.1.3.7, Section 2.1.3.8, Section 2.1.3.9, and Section 2.1.3.10 and Section 2.2.1.4. Additional supporting information is contained in the CCA, Appendices GCR, HYDRO, and SUM. Details of the conceptual model for each unit are described in the CRA-2004, Chapter 6.0, Section 6.4.6.1, Section 6.4.6.2, Section 6.4.6.3, Section 6.4.6.4, Section 6.4.6.5, Section 6.4.6.6, and Section 6.4.6.7 and additional information on units above the Salado is found in Appendix HYDRO-2009.

The representation of units above the Salado used in the CRA-2009 PA has not changed from that used in the CRA-2004 PA.

MASS-14.1 Historical Context of the Units above the Salado Model

See the CCA, Appendix MASS, Section MASS-14.1 for historical information relating to the conceptual models for units above the Salado for the CCA. The conceptual models for the units above the Salado are unchanged for CRA-2009 PA.

MASS-14.2 Groundwater-Basin Conceptual Model

The groundwater-basin conceptual model and associated modeling assumptions have not changed from those of the CRA-2004 PABC. For a discussion on the groundwater-basin conceptual model, see the CCA, Appendix MASS, Section MASS-14.2.

MASS-15.0 Flow Through the Culebra

The Culebra flow modeling assumptions have not changed from those in the CRA-2004 PABC. The conceptual model for groundwater flow in the Culebra (1) provides a reasonable and realistic basis for simulating radionuclide transport in the Culebra and (2) allows evaluation of the extent to which uncertainty about groundwater flow in the Culebra may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. See the CRA-2004, Chapter 6.0, Section 6.4.6.2 for additional references to other relevant discussions on this conceptual model.

The conceptual model used in PA for groundwater flow in the Culebra treats the Culebra as a confined two-dimensional aquifer with constant thickness and spatially varying transmissivity (see the CCA, Appendix MASS, Attachment 15-7). Flow is modeled as single-phase (liquid) Darcy flow in a porous medium.

Basic stratigraphy and hydrology of the units above the Salado are described in the CRA-2004, Chapter 2.0, Section 2.1 and Section 2.2. Additional supporting information is contained in the CCA, Appendices GCR, HYDRO, and SUM.

The conceptual model for flow in the Culebra is discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.2. Details of the calibration of the T fields, based on available field data, are given in Appendix TFIELD-2009, Section TFIELD-4.0. Initial and boundary conditions used in the model are given in the CRA-2004, Chapter 6.0, Section 6.4.10.2. A discussion of the adequacy of the two-dimensional assumption for PA calculations is included in the CCA, Appendix MASS, Attachment 15-7.

The principal parameter used in PA to characterize flow in the Culebra is an index parameter (the transmissivity index) used to select a single T field for each LHS element from a set of calibrated fields (see Fox 2008, Table 1), each of which is consistent with available data.

MASS-15.1 Historical Context of the Culebra Model

See the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.1 for historical information relating to the Culebra conceptual model. The conceptual model for this unit is unchanged for CRA-2009.

MASS-15.2 Dissolved Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of advective transport and physical and chemical retardation on the movement of actinides in the Culebra. This conceptual model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.2.1. The same model is used in the CRA-2004 PABC and the CRA-2009 PA. For a historical presentation of this model, see the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.2.

MASS-15.3 Colloidal Actinide Transport and Retardation in the Culebra

The purpose of this model is to represent the effects of colloidal An transport in the Culebra. This model is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.2.2 and the CRA-2004, Appendix PA, Attachment MASS, Attachments 15-2, 15-8, and 15-9. No changes have been made to this model since the CRA-2004. Additional information and historical information on colloidal An transport and retardation in the Culebra can be found in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.3.

MASS-15.4 Subsidence Caused by Potash Mining in the Culebra

The mining-related modeling assumptions have not changed from those in the CRA-2004 PABC. This model incorporates the effects of potash mining in the McNutt Potash Zone on disposal system performance (see Appendix SCR-2009, FEP H13, FEP H37, and FEP H38). Provisions in Part 194 provide a conceptual model and elements of a mathematical model for these effects. The DOE has implemented the EPA conceptual model (40 CFR § 194.32(b), U.S. Environmental Protection Agency 1996) to be consistent with EPA criteria and guidance; this model is described in the CRA-2004, Chapter 6.0, Section 6.4.6.2.3. Additional information on the implementation of the mining subsidence model is available in Appendix TFIELD-2009, Section TFIELD-9.0; the CCA, Appendix MASS, Attachments 15-4 and 15-7; and Wallace (1996).

The principal parameter in this model is the range assigned to a factor by which hydraulic conductivity in the Culebra is increased (see the CCA, Appendix MASS, Attachment 15-4). As allowed in supplementary information to Part 194, it is the only parameter changed to account for the effects of mining.

Mining in the McNutt has been considered in the performance of the WIPP since the original siting activities. Siting criteria for both the site abandoned in 1975 and the current site included setbacks from active mines. (See, for example, the CCA, Appendix MASS, Section MASS-2.0.) The 1980 Final Environmental Impact Statement (FEIS) for the WIPP (U.S. Department of Energy 1980, pp. 9-145 through 9-148) considered the possibility of an indirect dose arising from the effects of solution mining for potash or halite.

Mining has been included in scenario development for the WIPP since the earliest work on this topic (see U.S. Department of Energy 1980 [pp. 9-145 through 9-148], Hunter 1989, Marietta et al. 1989, Guzowski 1990, Tierney 1991, and WIPP Performance Assessment 1991). These early scenario developments considered both solution and room-and-pillar mining. The focus was generally on effects of mining outside the disposal system. In the CCA FEPs screening, solution mining was screened out during scenario development (see Appendix SCR-2009, FEP H58 and FEP H59). The two primary effects of mining considered were (1) changes in the hydraulic conductivity of the Culebra or other units, and (2) changes in recharge as a result of surface subsidence. These mining effects were not formally incorporated into quantitative assessment of repository performance in preliminary PAs.

The inclusion of mining in PA satisfies the requirements of section 194.32(b) to consider the effects of this activity on the disposal system.

MASS-16.0 Intrusion Borehole

The intrusion borehole modeling assumptions have not been changed from those in the CRA-2004 PABC. The inclusion of intrusion boreholes in PA adds to the number of release pathways for radionuclides from the disposal system. Direct releases to the surface may occur during drilling as particulate material from cuttings, cavings, and spallings are carried to the surface. Also, dissolved actinides may be carried to the surface in brine during drilling. Once abandoned, the borehole presents a possible long-term pathway for fluid flow, such as might occur between a hypothetical Castile brine reservoir, the repository, and overlying units. This topic is also addressed in the CRA-2004, Chapter 6.0, Section 6.4.7 and Appendix SCR-2009 (FEP H1 and FEP H21).

MASS-16.1 Cuttings, Cavings, and Spallings Releases during Drilling

The cuttings, cavings, and spallings models estimate the quantity of actinides released as solids directly to the surface during drilling through the repository. The releases are caused by three mechanisms: the drill bit boring through the waste (cuttings); the drilling fluid eroding the walls of the borehole (cavings); and high repository gas pressure causing solid material failure and entrainment into the drilling fluid in the wellbore (spallings). See the CRA-2004, Chapter 6.0, Section 6.4.7.1 and references to other appendices cited in that section for additional information. Stochastic uncertainty in parameters relevant to these release mechanisms is addressed in the CRA-2004, Chapter 6.0, Section 6.4.12. The conceptual model for cuttings, cavings, and spallings is discussed in three parts because of the different processes that produce the three types of material.

Cuttings are materials removed to the surface through drilling mud by the direct mechanical action of the drill bit. The volume of waste removed to the surface is a function of the repository height and the drill bit area. The principal parameter in the cuttings model is the diameter of the drill bit (see Appendix DATA-2009, Attachment A).

Cavings are materials introduced into the drilling mud by the erosive action of circulating drilling fluid on the waste in the walls of the borehole annulus. Erosion is driven solely by the shearing action of the drilling fluid (or mud) as it moves up the borehole annulus. Shearing may be caused by either laminar or turbulent flow. Repository-pressure effects on cavings, which are negligible, are covered by the spall process. The principal parameters in the cavings model are the properties of the drilling mud, drilling rates, the drill string angular velocity, and the shear resistance of the waste. (See Fox 2008, Table 13 and Table 18, for details on the sampled parameters used in the cavings model, the drill string angular velocity, and the effective shear resistance to erosion.)

Spallings are solids introduced into the wellbore by the fluid pressure difference between the repository and the bottom of the wellbore. If the repository pressure is sufficiently high (more than about 12 MPa) relative to the well bottom hole pressure (about 8 MPa), the stress state in the repository may cause repository solids to fail in the vicinity of the wellbore. In turn, these solids may become entrained in the gas flowing toward the well, ultimately to be carried up to the land surface and constituting a release. The principal parameters in the spallings model are the gas pressure in the repository when it is penetrated and properties of the waste such as

permeability, tensile strength, and particle diameter. Because the release associated with spalling 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.

MASS-16.1.1 Historical Context of Cuttings, Cavings, and Spallings Models

Cuttings and cavings releases are straightforward. The analytical equations governing erosion (cavings) based on laminar and turbulent flow (Appendix PA-2009, Section PA-4.5) have been implemented in the code CUTTINGS_S. Using selected input based on assumed physical properties of the waste and other drilling parameters, this code calculates the final caved diameter of the borehole that intersects the waste.

The various approaches used for spallings up to the CCA PA are documented in the CCA, Appendix MASS, Section MASS-16.1.1. Since the CCA PA, the spallings model has been extensively revised and has changed fundamentally from an end-state erosional model to a mechanically based, coupled material failure and transport model (WIPP Performance Assessment 2003a). This model is implemented in the code DRSPALL. A discussion tracing the historical steps from the CCA erosional model to the current DRSPALL model can be found in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-16.1.1.

MASS-16.1.2 Waste Mechanistic Properties

Waste mechanical properties used in the CRA-2009 PA are the same as those in the CRA-2004 PA and the CRA-2004 PABC. Changes to the waste mechanistic properties for CRA-2004 were previously documented in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-16.1.2. Those changes involved the development of surrogate waste materials for the WIPP spallings model. Surrogate waste recipes for 50% and 100% corrosion of the Fe-based inventory were fabricated from the projected inventory of waste materials. The development of each surrogate product assumed extensive degradation of the modeled constituent (Hansen et al. 1997). Subsurface processes contributing to massive degradation of the waste taken into consideration include ample brine availability; extensive microbial activity and corrosion of metals; and an absence of cementation, mineral precipitation, and salt encapsulation.

The WIPP PA uses the parameter BOREHOLE:TAUFAIL to represent the hydrodynamic shear strength of the waste in the numerical code CUTTINGS_S (see Appendix PA-2009, Section PA-4.5). It is officially called the "effective shear strength for erosion," but it is more commonly known as the "waste shear strength." The parameter is treated as a sampled value in WIPP PA with a log-uniform distribution and a range of 0.05 to 77 Pa. This range of values was derived by DOE from literature reviews of incipient motion of seafloor or channel bed sediments—0.05 Pa corresponds to a San Francisco Bay mud—and consideration of the mean particle size of the WIPP waste as determined by an expert elicitation (Berglund 1996, Carlsbad Area Office Technical Assistance Contractor [CTAC] 1997). The lower limit of this range of values represents what is hypothesized as an extreme case of degradation of the waste and waste containers.

MASS-16.1.3 Mechanistic Model for Spall

The CRA-2009 PA uses the same spallings model that was used in the CRA-2004 PA and the CRA-2004 PABC. No changes were made to the model or implementation of the results in PA.

In the CRA-2004 PA, a new approach to modeling the WIPP spallings process was developed to address peer review concerns during the original certification process (see the CCA, Chapter 9.0, Section 9.3.1.2 and the CRA-2004, Appendix PEER-2004, Section PEER-2004 3.0). Instead of focusing on the end state after penetration, as was done in the original CCA erosional model, the new model sought to capture the system behavior from just before penetration through to the end state. In doing so, many more phenomena were included in the model. Considered in this new conceptual model was unsteady, convergent gas flow from the repository toward the wellbore that caused mechanical stress and potential failure of solids near the face of the wellbore. Pressure in the cavity at the point of penetration was balanced by the mud column in the wellbore and the repository pressure.

The new spall model, DRSPALL (WIPP Performance Assessment 2003a), is based on a predecessor code called GASOUT (Hansen et al. 1997, Appendix C). DRSPALL builds upon GASOUT by:

1. Adding a wellbore flow model that transports mud, repository gas, and waste solids from repository level to the land surface

2. Adding a fluidized bed model that evaluates the potential for failed particulate waste to fluidize and become entrained in the wellbore flow

The wellbore flow model in DRSPALL utilizes one-dimensional geometry with a compressible, viscous, isothermal, homogeneous mixture of mud, gas, and solids. Standard mass and momentum balance, friction loss, and slurry viscosity equations are used. Wellbore flow model results were successfully verified against those from an independent commercial code for several test problems (WIPP Performance Assessment 2003b).

DRSPALL applies the fluidized bed theory to determine the mobilization of failed material to the flow stream in the wellbore. If the escaping gas velocity exceeds the minimum fluidization velocity, failed material is fluidized and entrained for transport at the land surface. If gas velocity is too low to fluidize the bedded material, the cavity size is allowed to stabilize. The spall volumes predicted by DRSPALL are based on the following conservative assumptions for material properties and for the flow geometry within the repository:

- The particle size distribution for spallings is based on a detailed analysis (Wang 1997) of data from an expert elicitation (Carlsbad Area Office Technical Assistance Contractor [CTAC] 1997). This analysis considered several limiting cases in developing a conservative distribution for mean particle size ranging from 1 millimeter to 10 cm (Hansen, Pfeifle, and Lord 2003).

- The shape factor for fluidization of particles has a potential range from 0 to 1.0. Smaller values of the shape factor denote particles that are less spherical, and, therefore, more easily

fluidized and transported in the flow. The shape factor is conservatively set to a value of 0.1 (Lord 2003).

- The tensile strength of the waste assigned for the spalling process is uncertain, ranging from 0.12 MPa to 0.17 MPa (Hansen, Pfeifle, and Lord 2003). Tensile strength data was measured in laboratory experiments on surrogate materials chosen to conservatively represent highly degraded residuals from typical wastes. The given range is felt to represent extreme, low-end tensile strengths because it does not account for several strengthening mechanisms, such as MgO hydration and halite precipitation/cementation (Hansen et al. 1997).

- DRSPALL uses a hemispherical geometry (one-dimensional spherical symmetry) for the flow field and cavity in the waste. This conceptual model is appropriate when the drill bit first penetrates the repository. But as the drill bit passes completely through the compacted waste, the flow field transitions toward a cylindrically symmetric geometry. This transition is important because the largest spall release volumes are predicted to occur at late times, well after the drill bit has penetrated through the waste, and because the spall volumes predicted for a cylindrical geometry are less than for the hemispherical geometry (Lord, Rudeen, and Hansen 2003).

In summary, the conservative assumptions for waste properties, the waste flow geometry, and the driller's actions provide very conservative spalling release volumes (see also Appendix PA-2009, Section PA-4.6 for a description of the spallings model, and the CRA-2004, Appendix PEER-2004, Section PEER-2004 3.0 for the results of the spallings model peer review). As stated previously, the DRSPALL calculations from the CRA-2004 PABC were also used in the CRA-2009 PA (see Appendix PA-2009, Section PA-6.7.4 and Section PA-8.5.2.1).

MASS-16.1.4 Calculation of Cuttings, Cavings, and Spall Releases

The modeling assumptions relating to the calculations of cuttings, cavings and spallings releases have not changed since the CRA-2004. As detailed in Appendix PA-2009, Section PA-6.7.5, cuttings and cavings releases for intrusions into CH-TRU waste are computed by multiplying the volume released (calculated by the code CUTTINGS_S) by the radioactivity in three independently selected waste streams, consistent with the conceptual assumption that waste streams are randomly emplaced in waste stacks that are three drums high. The effect of this assumption on PA results was examined in a separate PA (Hansen et al. 2003) in which cuttings and cavings releases were computed by assuming that each intrusion encounters only a single waste stream. The differences in repository performance (determined by comparing the mean CCDFs for releases) were determined to be minor. For more details on the analysis, see the CRA-2004, Appendix PA, Attachment MASS, Section MASS-21.0.

Because spallings may release a relatively large volume of material (exceeding 4 m^3), spalling releases for intrusions into CH-TRU waste are computed by multiplying the volume of spalled material with the average concentration of radioactivity in the waste at the time of the intrusion. A separate PA (Hansen et al. 2003) compared spalling releases computed using the average concentration of radioactivity in the waste to spalling releases computed using the radioactivity of a single, randomly selected waste stream. The analysis determined that the assumption had only a minor effect on the mean CCDF for releases. For more details on the analysis, see the

CRA-2004, Appendix PA, Attachment MASS, Section MASS-21.0. During their completeness review of the CRA-2004, the EPA requested additional DRSPALL vectors be used in the CRA-2004 PABC. Minor changes were made to the implementation of spallings results that did not change the overall modeling assumptions. These implementation changes are outlined in Leigh et al. (2005, Section 7.8).

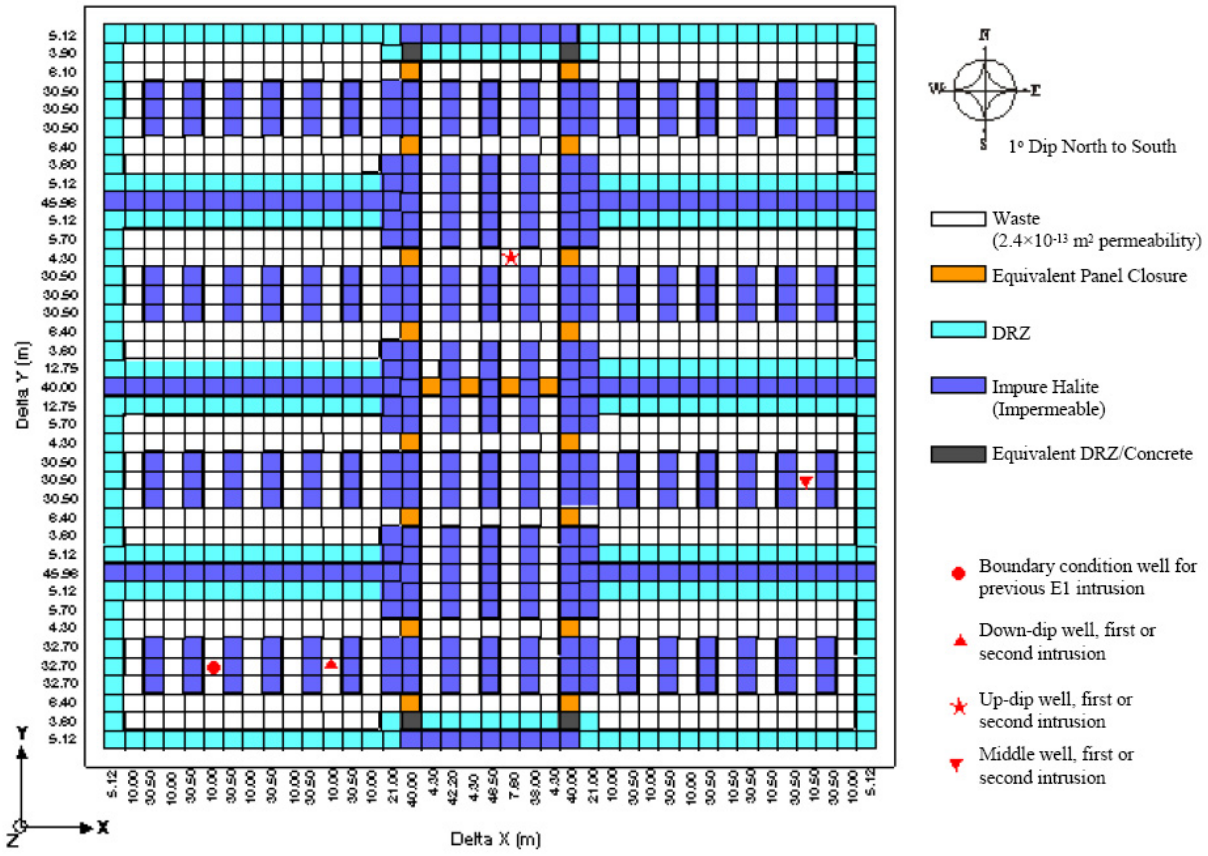
MASS-16.2 Direct Brine Releases during Drilling

The DBR modeling assumptions for the CRA-2004 PABC are used in the CRA-2009 PA. This model provides a series of calculations to estimate the quantity of brine released directly to the surface during drilling. DBRs may occur when a driller penetrates the WIPP and unknowingly brings contaminated brine to the surface during drilling (these releases are not accounted for in the cuttings, cavings, and spallings calculations, which model only the solids removed during drilling). Appendix PA-2009, Section PA-4.7 describes the DBR model used for the CRA-2009 PA. The CCA, Appendix MASS, Attachment 16-2 describes the DBR model used for the CCA PA. The conceptual model for DBRs is discussed in Appendix PA-2009, Section PA-4.7 and the CRA-2004, Chapter 6.0, Section 6.4.7.1.1.

Uncertainty in the BRAGFLO DBR calculations is captured in the 10,000-year BRAGFLO calculations from which the initial and boundary conditions are derived. The model parameters that have the most influence on DBRs are repository pressure and brine saturation at the time of intrusion. Brine saturation is influenced by many factors, including Salado and MB permeability and gas-generation rates (for undisturbed scenario calculations). For E1 and E2 intrusion scenarios, Castile brine-reservoir pressure and volume, and abandoned borehole permeabilities influence conditions for the second and subsequent intrusions. The dip in the repository (hence the location of intrusions), two-phase flow parameters (residual brine and gas saturation), time of intrusion, and duration of flow have lesser impacts on brine releases.

To account for changes in the BRAGFLO model (see Section MASS-2.0), the implementation of the DBR model was adjusted for the CRA 2004-PA. These adjustments are also used in the CRA-2009 PA. Figure MASS-8 shows the DBR grid used in the CRA-2004 PA and the CRA-2009 PA.

The grid dimensions and resolution are the same as in the CCA PA, but the material parameters assigned to the panel closures were changed during the CRA-2004 to be more consistent with the conceptual model for the Option D panel closures. In addition, the material parameters assigned to the DRZ were changed to represent the DRZ more consistently. In the CCA PA, the pillars between rooms and the halite separating panels were assigned properties consistent with the DRZ material in the BRAGFLO grid. The DRZ permeability used in the CCA PA (10^{-15} m^2) was low enough that brine did not flow between panels during the 11-day DBR calculations. When the permeability of the DRZ was changed in the CCA PAVT (from a constant value of 10^{-15} m^2 to a sampled value between $10^{-19.4}$ m^2 and $10^{-12.5}$ m^2), realizations with high DRZ permeability allowed brine flow between panels during the 11-day period for DBR calculations. It is not reasonable to model the halite between panels as DRZ, since the DRZ would extend only a few meters into the 60 m-thick pillars. Consequently, the material parameters assigned to cells separating panels were changed to be representative of undisturbed halite rather than DRZ. Stein



Note: Model cells are not to scale. The actual dimensions of the grid blocks are indicated along the edge of the diagram.

Figure MASS-8. Repository-Scale Horizontal BRAGFLO Mesh Used for DBR Calculations

(2003a) provides details on the material parameters used in the DBR calculation and the rationale for the parameter values. Note that the CRA-2009 PA uses a different DBR maximum duration of 4.5 days, based on current drilling practices (see Appendix PA-2009, Section PA-4.7.8). This parameter change does not impact the modeling assumptions discussed above.

MASS-16.3 Long-Term Properties of the Abandoned Intrusion Borehole

The long-term treatment and assumptions used to represent boreholes in the CRA-2009 PA have not changed from the treatment and assumptions used in the CRA-2004 PA. See the CRA-2004, Appendix PA, Attachment MASS, Section MASS-16.3 for the borehole modeling assumptions used in the CRA-2009 PA.

MASS-17.0 Climate Change

The purpose of this model is to allow quantitative consideration of the extent to which uncertainty about future climate may contribute to uncertainty in estimates of cumulative radionuclide releases from the disposal system. This model has not changed since the CCA and is used in the CRA-2009 PA. Consideration is limited to conditions that could result from reasonably possible natural climatic changes. The model is not intended to provide a quantitative prediction of future climate, nor is it intended to address uncertainty in system properties other than estimated cumulative radionuclide releases that may be affected by climate change. See the CRA-2004, Appendix PA, Attachment MASS, Section MASS-17.0 and Section MASS-17.1 for current and historical information on the climate change model. The implementation of this model in PA is also discussed in the CRA-2004, Chapter 6.0, Section 6.4.9 and Appendix PA, Section PA-2.1.4.6. See also the CCA, Appendix CLI for information on expected climate variability over the 10,000-year regulatory time period.

MASS-18.0 Castile Brine Reservoir

The conceptual model for the hypothetical brine reservoir is included in PA to estimate the extent to which uncertainty about the existence of a brine reservoir under the waste disposal region may contribute to uncertainty in the estimate of cumulative radionuclide releases from the disposal system. The conceptual model is not intended to provide a realistic approximation of an actual brine reservoir under the waste disposal region. Data are insufficient to determine whether such a brine reservoir exists.

The representation of the Castile brine reservoir in the CRA-2009 PA has not changed from the CRA-2004 PA. However, this model is not the same as the one used in the original CCA PA. The following describes the changes to the model since the 1996 CCA PA.

The Castile Formation is treated as an impermeable unit in PA and plays no role in the analysis except to separate the Salado from the modeled brine reservoir in the BRAGFLO grid. In human-intrusion scenarios, the hypothetical brine reservoir can be penetrated by an intrusion borehole connecting it to the repository. The amount of brine that can enter the repository from the brine reservoir is important to PA because brine is required for gas generation reactions and can transport radionuclides in solution, contributing to potential releases.

The properties of the hypothetical brine reservoir defined for PA include: permeability, porosity, pore volume, initial pressure, and various two-phase flow parameters. Values assigned for these properties were chosen to either be consistent with the available data from and analyses of borehole penetrations of brine reservoirs in the region, or provide a reasonable response in the BRAGFLO model.

The treatment of the brine reservoir for the CRA-2004 PA is different than that used in the CCA PA. The major changes to the brine reservoir representation were made by the EPA in the CCA PAVT (U.S. Environmental Protection Agency 1998b). For the CCA PAVT, the EPA defined new parameter ranges for bulk compressibility and total pore volume. The range of bulk compressibility was based on a reevaluation of field test data from the WIPP-12 borehole following the CCA (Beauheim 1997). Since the total volume of the grid cells used to represent the brine reservoir in BRAGFLO is fixed, the range of total pore volume was set by defining a range of "effective" porosity (pore volume = grid volume × effective porosity). This range of porosity values is not representative of the actual host rock. It was chosen to produce a reasonable response in the BRAGFLO model by providing a predefined range of total pore volumes based on the field tests at WIPP-12.

For the CRA-2004 PA, the DOE implemented this approach by assuming that the productivity ratio (PR) remains constant (2.0051×10^{-3} m^3/Pa). The PR is defined as:

$$PR = V\frac{C_r}{\phi},$$

where V is the grid volume of the brine reservoir (18,462,514 m^3), C_r is the bulk compressibility (2×10^{-11} to 1×10^{-10} Pa^{-1}), and ϕ is the effective porosity (0.1842 to 0.9208). To maintain a constant pore volume in the brine reservoir, the porosity range used in the CRA-2004 PA is

slightly modified from that used in the CCA PAVT because the fixed-grid volume increased slightly in the CRA-2004 BRAGFLO grid from the volume assumed in the CCA BRAGFLO grid. In this approach, bulk compressibility and effective porosity are directly proportional (Stein 2003b). See Appendix PA-2009, Section PA-4.2.10 for the details on the implementation in PA.

Basic geologic information about the Castile is given in the CRA-2004, Chapter 2.0, Section 2.1.3.3. The hydrology of the known brine reservoirs is discussed in the CRA-2004, Chapter 2.0, Section 2.2.1.2.2. The treatment of the hypothetical brine reservoir in PA is discussed in the CRA-2004, Chapter 6.0, Section 6.4.8.

MASS-18.1 Historical Context of the Castile Brine Reservoir Model

See the CCA, Appendix MASS, Attachment 18.1 for historical information on the Castile brine reservoir model.

MASS-19.0 Option D Panel Closure

The option D panel closure assumptions have not changed from those used in the CRA-2004 PABC. The certification decision by the EPA (U.S. Environmental Protection Agency 1998a) included several conditions that the DOE was required to meet. In the first of these conditions, the EPA required the DOE to implement a specific design for the panel closure system referred to as Option D and required the concrete monolith to be constructed using SMC. The DOE had included four Options (A-D) for the panel closure design using standard concrete or SMC in the CCA. The Option D design consisted of two components: a large monolith constructed of SMC and keyed into the surrounding DRZ, and an explosion wall constructed of concrete blocks, which is not keyed into the DRZ.

The PA calculations that supported the CCA and the subsequent CCA PAVT calculations included generic panel closures in the BRAGFLO grid. These generic closures were not representative of the Option D design. The generic panel closures included in the CCA PA and the CCA PAVT calculations were relatively permeable and allowed gas to flow freely between panels. In the CCA PA and the CCA PAVT calculations, a drilling intrusion into a single panel generally caused pressures in the entire repository to decrease.

Following the original certification of the repository, the DOE updated the modeling of the panel closures in PA so that the mandated Option D design was adequately represented. A new panel closure representation was developed and presented to the Salado Flow Peer Review Panel in May 2002, and again in February 2003. The peer review panel approved the new conceptual models, which included the implementation of the Option D panel closures in the grid (Caporuscio, Gibbons, and Oswald 2003).

In the CCA PA/CCA PAVT BRAGFLO grid, only two panel closures were represented. For the CRA-2004 PA and the CRA-2009, however, the DOE included an additional set of panel closures. Preliminary tests of the Option D panel closure representation (Hansen et al. 2002) concluded that Option D panel closures were effective at impeding fluid flow between panels on the order of thousands of years, but that, given enough time, pressures slowly equilibrated. These results suggest that the effect of a single intrusion event on pressures in other panels depends on the number of panel closures that lie between the intruded panel and the other panels. Therefore, the DOE decided to divide the RoR region into two regions separated by a panel closure. This panel closure represents a set of four panel closures to be located between the northern and southern internal extended panels. The south RoR represents panels directly adjacent to an intruded panel and the north RoR represents panels that are farther away from the intruded panel (two sets of panel closures lie in between).

The DOE assumes that the effect of the Option D panel closures will be to impede fluid flow through and around the closures. Only the concrete monolith portion of the closure system is assumed to remain effective over the 10,000-year regulatory period. The explosion wall is assumed to be effective for only a brief period during the operational period. The explosion wall and the open drift adjacent to the monolith are represented in the BRAGFLO grid by a column of grid cells with the properties of the waste area (e.g., high permeability) and include creep closure effects. The monolith is represented in the BRAGFLO grid by an adjacent column of grid cells with a length equal to the length of the monolith (7.9 m) multiplied by the number of panel

closures in series and a width equal to the width of the monolith (10 m) multiplied by the number of panel closures in parallel. For instance, in Figure MASS-3, the southern panel closure in the BRAGFLO grid represents a single set of two panel closures (in parallel) that separate a single external panel from one of the two internal extended panels (9 and 10). The middle panel closure in the BRAGFLO grid represents a single set of four panel closures (in parallel) that separate the internal extended panels (9 and 10) from one another. The northern panel closure in the BRAGFLO grid represents two sets (in series) of four panel closures (in parallel) that lie between the northern edge of the waste region and the shafts.

It is assumed in the modeling that the DRZ above the concrete monolith will heal and quickly attain a state of relatively low permeability. However, it is also assumed that if pressures exceed the fracture initiation pressure (~0.2 MPa above lithostatic), the DRZ and anhydrite MB materials that intersect the waste room can fracture and allow gas or brine to circumvent the panel closures by flowing around the concrete monolith. This possibility is included in the implementation of the panel closures in the BRAGFLO by replacing the concrete monolith material with MB material everywhere the monolith intersects and cuts through the MBs. This implementation is appropriate even at low pressures because the permeability range of the concrete and the MBs is nearly equivalent. In addition, fracturing is considered in these grid elements at high pressures, allowing fluids to flow and simulating the consequence of fractures extending around the monolith.

The representation of panel closures used in the CRA-2004 PABC has not changed and this representation continues to be used in the CRA-2009 PA (see Figure MASS-6 and Appendix PA-2009, Section PA-4.2.8). Additional information on panel closure effects on repository performances can be seen in the CRA-2004 BRAGFLO Analysis Package (Stein and Zelinski 2003a and 2003b).

MASS-20.0 Summary of Clay Seam G Modeling Assumptions

One of the changes to the repository design since the CCA is the raising of the repository horizon in the southern half of the waste panels. Specifically, Panels 3, 4, 5, 6, and 9 will be excavated at an elevation approximately 2.4 m above the level of Panels 1, 2, 7, 8, and 10 and the operations and experimental areas. This change in horizon will bring the roof of the raised rooms to the level of the Clay Seam G. The change is expected to improve roof conditions and enhance operations and mine safety. The DOE submitted a planned change request to the EPA describing the change and arguing that it would have minimal impact on long-term repository performance (Triay 2000). The EPA responded to the change request in a letter (Marcinowski 2000) in which they agreed with the DOE that the effects on long-term performance would be minimal. The modeling assumptions used to represent this change are described in the CRA-2004, Appendix PA, Attachment MASS, Section MASS-20.0. No changes were made to these assumptions since the CRA-2004 PA. These assumptions have also been used in the CRA-2009 PA.

MASS-21.0 Evaluation of Waste Structural Impacts, Emplacement and Homogeneity

Waste-related modeling assumptions have not changed from those used in the CRA-2004 PABC. During the development of the CCA PA, the DOE choose to assume random placement of TRU waste in the WIPP, and developed conceptual and numerical models accordingly. The EPA reviewed these models and their results and determined that the DOE had adequately modeled random placement of waste in the disposal system. Since the CCA, additional information about the waste and its emplacement has emerged, requiring the assumption of random placement to be reevaluated. The waste inventory estimates were updated since the CCA PA (see the CRA-2004, Appendix TRU WASTE and Leigh, Trone, and Fox 2005 for the CRA-2004 PABC waste updates), resulting in different estimates of important waste components, such as CPR materials. Additionally, the CCA PA assumed that all waste could be modeled as if the waste was emplaced in 55-gallon (gal) drums. However, the DOE is emplacing waste using several different types of waste containers, including standard waste boxes and pipe overpacks. Waste has been shipped to WIPP in campaigns from the generator sites, resulting in waste emplacement that appears inconsistent with the representation of the waste as a homogeneous material. Finally, the DOE is emplacing waste types, such as supercompacted waste, that were not considered in the CCA inventory (U.S. Department of Energy 2002).

Many important waste characteristics, such as the radionuclide content and the mass of CPR materials, are directly incorporated in PA by means of waste material parameters. These parameters have been updated with the inventory updates (see Leigh and Trone 2005b, and Leigh, Trone, and Fox 2005) and thus were represented in the CRA-2004 PABC and the CRA-2009 PA. However, the PAs for compliance applications have not specifically accounted for heterogeneity in waste materials or in waste containers. At the INL, for instance, debris waste is volume-reduced by supercompaction, resulting in a very dense waste form containing a high concentration of CPR material. In addition, the Pu residues from the Rocky Flats Environmental Technology Site were packaged in pipe overpacks, which are more rigid than the typical 55-gal drum assumed in the CCA. Additionally, in accordance with the requirements of 40 CFR § 194.24(d) (U.S. Environmental Protection Agency 2004), all PAs have assumed that waste is emplaced in a random or homogeneous manner. Actual waste emplacement is determined by the availability of waste at generator sites and the shipping schedules. Pipe overpacks occupy about 43% of the containers emplaced in Panel 1, suggesting that actual emplacement will not be statistically random.

As a result of this new information and these changes, the DOE performed analyses (Hansen et al. 2003) to determine if the modeling assumptions used in PA continue to adequately represent the waste. The analysis reported in Hansen et al. (2003) focused on potential effects of supercompacted waste and waste in pipe overpacks on repository performance. Both waste types are structurally stiffer than the generic waste model used in the CCA PA, and the supercompacted waste in particular has high concentrations of CPR materials. The analysis began with a systematic reevaluation of the baseline FEPs to identify specific components of PA that could be affected by supercompacted waste. The reassessment concluded that the FEPs "screened in" were adequate to represent the variety of waste types and containers, and that none of the "screened out" FEPs should be reconsidered for implementation. The FEPs assessment

concluded that creep closure of the repository, chemical conditions of the waste, gas generation models, and waste mechanical properties could be affected by heterogeneities in the waste materials and waste containers. In addition, the DOE determined that the assumption of random waste emplacement should be reevaluated.

Analysis of creep closure of waste-filled rooms, accounting for several types of waste materials and packaging, indicated that a wider range of long-term porosities could occur than that established in the CCA, given the uncertainties about the structural integrity of waste packages and their spatial arrangement in the repository (Park and Hansen 2003). For this reason, the analysis in Hansen et al. (2003) treated creep closure as an uncertain variable. Sensitivity analysis showed that this additional uncertainty did not significantly affect the results of PA.

Chemical conditions were also reexamined under a range of possible waste arrangements. The assessment found that, regardless of actual waste emplacement, the MgO would still be sufficient to maintain desired chemical conditions. Moreover, the constituents of supercompacted waste would not alter the reactions that determine chemical equilibrium and, consequently, no changes to An solubilities or to the gas-generation models were warranted to account for waste heterogeneity. This topic was addressed during the second recertification in response to comment G-12, in which the EPA requested that the DOE address potential effects of heterogeneous waste loading based on the assumption of homogeneous chemical conditions. The DOE's response indicated that the chemical conditions assumptions adequately addressed nonrandom waste loading (Piper 2004). This was again addressed during the evaluation of the MgO excess factor change from 1.67 to 1.20 (Reyes 2008). No changes were made to the chemical conditions model as a result of these investigations.

Supercompacted waste contains elevated amounts of CPR materials relative to other waste streams, and the future arrangement of this waste in the WIPP repository is uncertain. Thus, the analysis treated the spatial distribution of CPR materials as uncertain. However, sensitivity analysis demonstrated that uncertainty in the spatial distribution and quantity of CPR materials had little effect on PA results. This was also shown in an analysis performed during the 2004 recertification while responding to an EPA request for additional information (Response to Comment G-12, Dunagan, Hansen, and Zelinski 2004).

The representation of the waste properties was also considered; however, it was determined that no changes to permeability, shear strength, or tensile strength were warranted. Based on this evaluation, no changes to the models for DBRs were necessary.

DBRs as a consequence of a drilling intrusion are calculated with the assumption of random waste emplacement in the repository. In addition, releases by spallings, DBR, and long-term radionuclide transport assume that radionuclides are homogeneously distributed throughout the waste. A sensitivity analysis determined that PA results are not greatly affected by the assumption of random waste emplacement or by the assumption that radionuclides are homogeneously distributed.

Based on the analysis reported in Hansen et al. (2003), the DOE concluded that:

1. Explicit representation of the specific features of supercompacted waste and of waste in pipe overpacks, such as structural rigidity, was not warranted in modeling, since PA results were relatively insensitive to the effects of such features.

2. PA results were not affected significantly by the assumption of nonrandom waste emplacement and the representation of these waste types as a homogeneous material.

Homogeneity issues were also addressed in response to another EPA comment during the CRA-2004 completeness review. The EPA questioned in comment C-23-10 whether negating container-scale variability was a valid assumption for spallings calculations (Cotsworth 2004). In the CRA-2004 PA, spallings releases were calculated using the average radioactivity in all CH-TRU waste streams. An analysis in Vugrin (2004) compared spallings results using three randomly sampled waste streams against results using the average radioactivity over all CH-TRU waste streams. The analysis concluded that the calculation of spallings releases is not significantly affected by waste-scale variability.

The DOE continues to assume in PA that waste is randomly emplaced in the WIPP repository. The CRA-2009 PA continues to use the same waste-related modeling approaches as the CRA-2004 PABC.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix MgO-2009
Magnesium Oxide as an Engineered Barrier

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix MgO-2009
Magnesium Oxide as an Engineered Barrier

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Acronyms and Abbreviations

%	percent
μm	micrometer
AISinR	a synthetic brine representative of fluids sampled from the Culebra Member of the Rustler Formation in the WIPP air intake shaft
ALARA	as low as reasonably achievable
am	amorphous
AMWTP	Advanced Mixed Waste Treatment Program
An(III)	actinide element(s) in the III oxidation state
An(IV)	actinide(s) in the IV oxidation state
An(V)	actinide(s) in the V oxidation state
aq	aqueous
ASTM	American Society for Testing and Materials
atm	atmosphere(s)
BNL	Brookhaven National Laboratory
BRAGFLO	Brine and Gas Flow
Brine A	a synthetic brine representative of intergranular Salado brines
C	Celsius
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CH-TRU	contact-handled transuranic
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
DI	deionized
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
E. coli	*Escherichia coli*
EPA	U.S. Environmental Protection Agency
EQ3/6	a geochemical software package for speciation and solubility calculations (EQ3NR) and reaction-path calculations (EQ6)
ERDA-6	Energy Research and Development Administration (WIPP Well) 6
FMT	Fracture-Matrix Transport
ft	foot

g	gaseous or gram
gal	gallon
g/mol	grams per mole
GWB	Generic Weep Brine
HDPE	high-density polyethylene
ICP-AES	inductively coupled plasma-atomic emission spectroscopy
INEEL	Idaho National Engineering and Environmental Laboratory
K_d	matrix distribution coefficient
kg	kilogram
kg/g	kilograms per gram
kg/lb	kilograms per pound
L	liter
lb	pound
LOI	loss-on-ignition
m	meter or molal
M	molar
m/s	meters per second
m^2/s	meters squared per second
m^3	cubic meters
mL	milliliter
mm	millimeter
mM	millimolar
mol	mole
mol %	mole percent
ND	not determined
nm	nanometer
NRC	National Research Council
OECD	Organisation for Economic Cooperation and Development
PA	performance assessment
PABC	Performance Assessment Baseline Calculations
PAVT	Performance Assessment Verification Test
PCR	Planned Change Request
pH	the negative, common logarithm of the activity of H^+

RCRA	Resource Conservation and Recovery Act
RH	relative humidity
RSI	Institute for Regulatory Science
RTR	real-time radiography
s	second(s) or solid
SCA	S. Cohen and Associates
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
SPC	Salado Primary Constituents, a synthetic brine similar to Brine A
STTP	Source Term Test Program
SWB	standard waste box
TDOP	ten-drum overpack
TEA	Trinity Engineering Associates
TGA	thermal gravimetric analysis
TIC	total inorganic carbon
TRU	transuranic
VE	visual examination
vol %	volume percent
WIPP	Waste Isolation Pilot Plant
wt %	weight percent
WTS	Washington TRU Solutions, LLC
XRD	X-ray diffraction

Elements and Chemical Compounds

Al_2O_3	aluminum oxide or alumina
Am	americium
An	actinide
Br	bromine
C	carbon
Ca	calcium
$CaCl_2$	calcium chloride
Ca^{2+}	calcium ion

$CaCO_3$	calcite
$CaMg(CO_3)_2$	dolomite
$CaMg_3(CO_3)_4$	huntite
$CaMgSiO_4$	monticellite
CaO	calcium oxide or lime
CaO·MgO	dolime
$CaSO_4$	anhydrite
CH_4	methane
Cl^-	chloride ion
Cl	chlorine
CO_2	carbon dioxide
CO_3^{2-}	carbonate ion
f_{co_2}	fugacity of CO_2
Fe	iron
Fe_2O_3	Fe(III) oxide, ferric oxide, or hematite
$FeAl_2O_4$	hercynite
$FeCr_2O_4$	chromite
H^+	hydrogen ion
H_2O	water (aq or g)
H_2S	hydrogen sulfide
K^+	potassium ion
Mg	magnesium
$Mg(OH)_2$	brucite
Mg^{2+}	magnesium ion
Mg_2SiO_4	forsterite
$Mg_4(CO_3)_3(OH)_2·3H_2O$	hydromagnesite (4323)
$Mg_5(CO_3)_4(OH)_2·4H_2O$	hydromagnesite (5424)
$MgAl_2O_4$	spinel
$MgCO_3$	magnesite
$MgCO_3·3H_2O$	nesquehonite
$MgCr_2O_4$	magnesiochromite
MgO	magnesium oxide

Mn	manganese
N_2	nitrogen
Na	sodium
Na^+	sodium ion
$Na_2Ca(SO_4)_2$	glauberite
NaCl	sodium chloride or halite
NO_3^-	nitrate ion
Np	neptunium
O_2	oxygen
$O_2^{\cdot -}$	anionic dioxygenyl radical
OH^-	hydroxide ion
$OH^\bullet$	hydroxyl radical(s)
Pb	lead
periclase	pure, crystalline MgO, the primary constituent of the WIPP engineered barrier
Pu	plutonium
SiO_2	silicon dioxide or silica
SO_4	sulfate
SO_4^{2-}	sulfate ion
$Ti(Fe,Mg)_2O_4$	ulvöspinel
Th	thorium
U	uranium

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MgO-1.0 Introduction

The U.S. Department of Energy (DOE) is emplacing magnesium oxide (MgO) in the Waste Isolation Pilot Plant (WIPP) repository to provide an engineered barrier that decreases the solubilities of the actinide (An) elements in transuranic (TRU) waste in any brine present in the postclosure repository (U.S. Department of Energy 1996a, Appendix BACK; Appendix SOTERM; U.S. Department of Energy 2004, Appendix BARRIERS; Appendix PA, Attachment SOTERM). Because it will decrease An solubilities, MgO helps meet the U.S. Environmental Protection Agency's (EPA's) requirement for multiple natural and engineered barriers, one of the assurance requirements in its regulations for radioactive waste repositories at 40 CFR § 191.14(d) (U.S. Environmental Protection Agency 1993).

In 40 CFR § 191.12 (U.S. Environmental Protection Agency 1993), the EPA defined barriers as "any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form…or a material placed over and around waste provided that the material or structure substantially delays movement of water or radionuclides."

The DOE proposed four engineered barriers in its Compliance Certification Application (CCA) for the WIPP, submitted to the EPA in October 1996 (U.S. Department of Energy 1996a). The four engineered barriers proposed by the DOE were MgO, panel closures, shaft seals, and borehole plugs. The EPA, however, specified MgO as the only engineered barrier in the WIPP disposal system that meets the assurance requirement in its May 1998 certification rulemaking (U.S. Environmental Protection Agency 1998a; 1998b). The EPA specified MgO as the only engineered barrier because it considered panel closures, shaft seals, and borehole plugs to be part of the disposal-system design.

MgO as used in the WIPP will decrease An solubilities by consuming essentially all of the carbon dioxide (CO_2) that would be produced should microbial activity consume all of the cellulosic, plastic, and rubber (CPR) materials in the TRU waste, waste containers, and waste-emplacement materials in the repository. Although MgO will consume essentially all the CO_2, minute quantities (relative to the quantity that would be produced by microbial consumption of all of the CPR materials) will persist in the aqueous and gaseous phases. The residual quantities would be so small relative to the initial quantity that the adverb "essentially" is hereafter omitted in this appendix.

Consumption of CO_2 will decrease An solubilities by (1) buffering the fugacity of CO_2 (f_{CO_2}) at a value or within a range of values favorable from the standpoint of the speciation and solubilities of the An elements (the fugacity of a gaseous species, f_i, is similar to the partial pressure of that species, p_i); (2) controlling the pH at a value favorable from the standpoint of An solubilities; and (3) preventing the production of carbonate ion (CO_3^{2-}) in significant quantities. The effect of this residual CO_3^{2-} on the solubilities of An elements is described in Appendix SOTERM-2009, Section SOTERM-3.2.1 and Section SOTERM-3.3.1.3.

The effects of MgO carbonation (consumption of CO_2) have been included in WIPP performance assessment (PA) calculations by assuming that there will be no CO_2 in the repository. This assumption has been implemented in PA by (1) removing CO_2 from the gaseous phase in the

Brine and Gas Flow (BRAGFLO) calculations, thereby somewhat reducing the predicted pressurization of the repository; and (2) using the values of f_{CO_2} and pH predicted for reactions among MgO, brine, and aqueous or gaseous CO_2 to calculate An solubilities. The assumption that there will be no CO_2 has been implemented in all compliance-related WIPP PA calculations. These include (1) the CCA PA calculations (Novak et al. 1996; the CCA, Appendix SOTERM), (2) the CCA Performance Assessment Verification Test (PAVT) (Novak 1997; U.S. Environmental Protection Agency 1998c, 1998d, and 1998e), (3) the PA calculations for the 2004 WIPP Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004; the CRA-2004, Appendix PA, Attachment SOTERM), (4) the CRA-2004 Performance Assessment Baseline Calculations (PABC) (Brush and Xiong 2005a and 2005b, Brush 2005, Leigh et al. 2005), and (5) the CRA-2009 PA.

In this appendix, "MgO" refers to the bulk, granular material being emplaced in the WIPP to serve as the engineered barrier. MgO comprises periclase (pure, crystalline MgO–the main, reactive constituent of the WIPP engineered barrier) and various impurities described in Section MgO-3.0. Pure, crystalline MgO is always referred to as "periclase" in this Appendix. The term "periclase" and other mineral names used herein are, strictly speaking, restricted to naturally occurring forms of the materials that meet all the other requirements of the definition of a mineral (see, for example, Bates and Jackson 1984). However, mineral names are used in this report for convenience.

MgO-2.0 Description of the Engineered Barrier System

This section describes the emplacement of MgO in WIPP disposal rooms (Section MgO-2.2) and the vendors that provided or are providing MgO to the WIPP (Section MgO-2.2).

Washington TRU Solutions, LLC (WTS) (2005) provides the current specifications for the prepackaged MgO emplaced in the WIPP.

MgO-2.1 Emplacement of MgO

The DOE emplaced MgO in both supersacks and minisacks from the opening of the WIPP in March 1999 until January 2001. During this period, the MgO emplaced in supersacks and that emplaced in minisacks constituted about 85% and 15%, respectively, of the total quantity of MgO emplaced in the repository.

In 2000, however, the DOE requested EPA approval to eliminate the minisacks (Triay 2000, U.S. Department of Energy 2000); the EPA approved this request in 2001 (Marcinowski 2001, U.S. Environmental Protection Agency 2001). Section MgO-2.1.1 describes the supersacks; Section MgO-2.0 describes the minisacks and the reasons for their elimination; and Section MgO-2.1.2 describes changes since the CRA-2004.

MgO-2.1.1 Supersacks

The DOE is emplacing MgO in polypropylene supersacks atop each stack of 3 7-packs of 55-gallon (gal) (208-liter [L]) drums, 3 standard waste boxes (SWBs), or various combinations of these and other waste containers. Other such containers include ten-drum overpacks (TDOPs), 4-packs of 85-gal (321-L) drums, and 3-packs of 100-gal (379-L) drums. According to WTS specifications, each supersack must contain 4200 ± 50 pounds (lb) (1905 ± 23 kilograms [kg]) of MgO (WTS 2005). Forklifts are used to place the supersacks on top of the waste stacks. Figure MgO-1 shows supersacks of MgO emplaced on top of the waste stack.

Emplacement of MgO in supersacks (1) facilitates handling and emplacement of MgO, (2) minimizes potential worker exposure to dust, and (3) minimizes the exposure of periclase (the main reactive constituent of MgO) to atmospheric CO_2 and H_2O during handling and emplacement, and prior to panel closure. Washington TRU Solutions (2005) provides detailed specifications for the supersacks. In particular, Washington TRU Solutions (2005) specifies that the supersacks "shall provide a barrier to atmospheric moisture and carbon dioxide (CO_2) … equivalent to or better than that provided by a standard commercial cement bag" and "must be able to retain [their] contents for a period of two years after emplacement without rupturing from [their] own weight." The specifications also require a certificate of compliance with all requirements of Washington TRU Solutions (2005) for every shipment of MgO (see below), and a certified chemical analysis for each new lot of MgO. The supersacks are subject to random receipt inspection at the WIPP to ensure compliance with the dimensions and labeling specified by Washington TRU Solutions (2005), and to identify any damage incurred during shipping.

Figure MgO-1. Supersacks of MgO Emplaced on Top of the Waste Stack

The supersacks contain dry, granular MgO, of which less than 0.5% can exceed 3/8 inches (9.5 millimeters [mm]) in diameter (Washington TRU Solutions 2005). Emplacement of granular MgO instead of powder (1) results in a bulk density high enough that sufficient MgO can be emplaced without causing major operational difficulties, (2) reduces the likelihood of dust formation and release in the event of premature supersack rupture, and (3) ensures that the permeability of the material is high enough to promote complete reaction with aqueous or gaseous CO_2.

Creep closure of WIPP disposal rooms will rupture the supersacks and disperse the MgO among and within the ruptured waste containers. This will, in turn, expose the MgO to the room's atmosphere, to any CO_2 produced by the microbial consumption of CPR materials, and to H_2O vapor and any brine present.

MgO-2.1.2 Minisacks

Initially, the DOE emplaced MgO in both supersacks and 25-lb (11-kg) minisacks. The minisacks were emplaced among the waste containers and between the waste containers and the ribs (sides) of the disposal rooms.

In its request for EPA approval to eliminate the minisacks (Triay 2000 and U.S. Department of Energy 2000), the DOE emphasized the need to reduce the industrial and radiological hazards associated with the manual emplacement of the minisacks. The DOE (U.S. Department of Energy 2000, p. 2) stated

> Elimination of the mini-sacks will reduce the industrial hazards associated with the lifting and handling of the mini-sacks. While the bulk of the MgO backfill (85%) is contained in the

> supersacks which are emplaced using a forklift, each mini-sack of MgO must be emplaced manually. This requires that personnel emplace eighteen twenty-five pound mini-sacks around the drums for each waste stack, and 11 mini-sacks against the rib at the end of each row, a process which will be repeated for the more than 108,000 estimated waste stacks (about 2,142,000 mini-sacks) to be emplaced during the life of the facility. Handling and emplacing the mini-sacks requires excessive bending and lifting, as well as climbing ladders on an uneven surface to emplace mini-sacks in the upper tiers. Each of these actions [has] a risk of physical injury.
>
> Also, elimination of the mini-sacks will reduce the potential radiation exposure to workers. This exposure has been evaluated by timing the steps associated with emplacement and estimating the radiological exposure over this time period (WID [Westinghouse Waste Isolation Division] 1997). Although the total potential dose is not excessive, particularly when spread over the life of the facility, any potential reduction of dose supports the ALARA (As Low As Reasonably Achievable) concept, which defines [the] DOE's basic operating philosophy regarding radiation exposure. It is the installation of the mini-sacks that is responsible for most of the radiological dose associated with backfill emplacement. Elimination of the mini-sacks from the backfill system will result in the elimination of associated radiological exposure.

The DOE also demonstrated that eliminating the minisacks would (1) not affect the ability of MgO to function as an effective engineered barrier, thus meeting the EPA's assurance requirement for multiple natural and engineered barriers; and (2) "[r]etain an acceptable safety factor ..." (U.S. Department of Energy 2000, p. 3). Section MgO-6.0 defines the MgO excess factor; Section MgO-6.2.2 describes the effect of eliminating the minisacks on the MgO excess factor.

Wang (2000a and 2000b) supported the DOE's request to eliminate the minisacks by justifying the DOE assertion that doing so would not affect the ability of MgO to function as an effective engineered barrier and would not reduce the MgO excess factor to an unacceptable extent. Wang (2000a) (1) described new evidence from laboratory studies of microbial gas generation, which demonstrated that microbial methanogenesis could be an important process in the WIPP; and (2) showed that, if methanogenesis were the dominant microbial respiratory pathway, a smaller amount of CO_2 would be generated and the MgO excess factor would increase from values of 1.95 prior to and 1.67 after the proposed elimination of the minisacks to values of 3.73 prior to and 3.23 after minisack elimination. Section MgO-6.1 describes the effects of microbial respiratory pathways on the MgO excess factor; Section MgO-6.2.2 discusses the effects of eliminating the minisacks on the MgO excess factor and the laboratory results demonstrating that methanogenesis could be an important respiratory pathway.

In addition, Wang (2000b) used a bounding calculation to demonstrate that, even in the absence of the minisacks, molecular diffusion in WIPP brines would be fast enough for MgO to control chemical conditions in the repository.

In its 2001 approval of the DOE's request to eliminate the minisacks, the EPA stated, "… this change, … proposed to improve operational safety, will not significantly impact the WIPP's long-term performance" (Marcinowski 2001). After inspecting the waste emplaced in Panel 1, the EPA also "found that DOE accurately represented the steps required to attach minisacks to the waste containers and the worker safety considerations involved in this activity" (U.S. Environmental Protection Agency 2001). Furthermore, the EPA (U.S. Environmental Protection Agency 2001) noted that "DOE's conceptualization of MgO performance in the repository was very conservative," and cited the following as examples:

- The DOE did not take credit for the beneficial effects of MgO hydration on the long-term performance of the repository.

- The "DOE proposes to reduce only excess MgO, which was not used in the [PA] calculations" and "there would still be a large excess of MgO relative to any potential evolved carbon [C]."

- "Attachment 4 [Wang (2000b)] concludes that molecular diffusion alone can effectively mix brine with MgO from degraded super-sacks in a repository that has experience[d] salt creep closure.… We reviewed DOE's calculations and agree these processes will function as expected and sufficient MgO will be available to react."

MgO-2.1.3 Changes Since the CRA-2004 in Emplacement of MgO

In March 2004, the EPA approved the emplacement in the WIPP of compressed (supercompacted) waste from the Advanced Mixed Waste Treatment Project (AMWTP) at the Idaho National Engineering and Environmental Laboratory (INEEL) (Marcinowski 2004, Trinity Engineering Associates 2004, and U.S. Environmental Protection Agency 2004). However, the EPA required that the DOE maintain an MgO excess factor (Section MgO-6.0) of 1.67 on a room-by-room basis. Some of the AMWTP waste contains concentrations of CPR materials that are high relative to the average concentration of CPR materials in TRU waste, thereby necessitating the emplacement of additional MgO in the repository. To account for this, the DOE has emplaced additional MgO supersacks on racks among the waste containers. Each rack contains 5 supersacks identical to those placed on top of the waste containers, and spans the same vertical distance normally occupied by the waste stack (3 7-packs of 55-gal [208-L] drums, 3 SWBs, or various combinations of these and other waste containers) and the supersack emplaced atop the waste stack. Thus, emplacing additional MgO in the repository uses space normally occupied by contact-handled (CH) transuranic (TRU) (CH-TRU) waste. Figure MgO-2 shows a rack used to emplace additional MgO in the WIPP.

As of June 12, 2008, a total of 80 racks had been emplaced in the WIPP, comprising 30 racks in Panel 2, Room 1; 21 racks in Panel 3, Room 5; 3 racks in Panel 3, Room 4; 3 racks in Panel 4, Room 6; and 23 racks in Panel 4, Room 4.

MgO-2.2 Vendors That Provided or Are Providing MgO

National Magnesia Chemicals in Moss Landing, CA, was the first vendor to provide MgO for the WIPP. National Magnesia supplied MgO from the opening of the WIPP in March 1999 through mid-April 2000; during this period, waste was emplaced only in Panel 1, Room 7. This vendor was sometimes referred to as National Refractory Materials (e.g., Papenguth 1999). Note that in every seven-room WIPP panel, waste is emplaced in Room 7, at the back of the panel first and in Room 1 last.

After National Magnesia stopped producing MgO, WTS considered Martin Marietta Magnesia Specialties LLC, currently headquartered in Baltimore, MD, and Premier Chemicals of Gabbs, NV, as potential vendors. At the request of the DOE's Carlsbad Area Office, Papenguth (1999)

Figure MgO-2. Racks Used to Emplace Additional MgO

carried out a technical evaluation of MgO from both Martin Marietta and Premier to support WTS's selection of a new vendor. The criteria used for this evaluation included density; particle size; purity; and reactivity, quantified using a test developed by Krumhansl et al. (1997). Based on cost and the results of the technical evaluation, WTS selected Premier Chemicals. This vendor supplied MgO from mid-April 2000 (Panel 1, Room 7) through January 2005 (Panel 2, Room 2).

Section MgO-3.2 presents the results of the Premier MgO characterization.

MgO-2.2.1 Changes since the CRA-2004 in Vendors Proving MgO

Premier Chemicals informed WTS in 2004 that it would soon be unable to provide MgO that met the requirement for the minimum concentration of MgO specified by Washington TRU Solutions (2003): "The sum of MgO plus calcium oxide (CaO) shall be a minimum of 95%, with MgO being no less than 90%."

Martin Marietta Magnesia Specialties, LLC, was selected and has supplied the MgO emplaced since January 2005 (Panel 2, Room 2). Martin Marietta MgO was selected based on cost and a

technical evaluation of its suitability by Wall (2005). The results of this study and additional characterization of Martin Marietta MgO are described in more detail in Section MgO-3.3.2.

Because Martin Marietta did not begin supplying MgO until January 2005, all results reported for Martin Marietta MgO have been obtained since the CRA-2004 (Section MgO-3.3 and Section MgO-4.1.2).

MgO-3.0 Characteristics of MgO

This section describes the characteristics of the MgO provided to the WIPP by National Magnesia Chemicals (Section MgO-3.1), Premier Chemicals (Section MgO-3.2), and Martin Marietta Magnesia Specialties, LLC (Section MgO-3.3).

MgO-3.1 Production of National Magnesia MgO

This section is based on a brief description provided by Papenguth (1999).

National Magnesia produced MgO for the WIPP by mixing seawater (the source of $Mg(OH)_2$) with calcined limestone at their plant in Moss Landing, CA. Limestone is a rock that mainly comprises the mineral calcite ($CaCO_3$) or other polymorphs of $CaCO_3$. In some cases, this rock can comprise nearly pure calcite. Clay minerals and quartz commonly occur as impurities in limestone.

The calcination reaction for limestone is

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g). \quad \text{(MgO.1)}$$

The formula for limestone on the left-hand side of Reaction (MgO.1) does not include impurities such as clay minerals and quartz, which presumably occur in small quantities in the material quarried to produce National Magnesia MgO.

National Magnesia then mixed seawater with the lime (CaO) obtained from Reaction (MgO.1). Although Papenguth (1999) did not describe the reaction(s) that occurred upon mixing, brucite ($Mg(OH)_2$) presumably precipitated via a reaction similar to that discussed in Section MgO-3.3.1, except that National Magnesia used seawater instead of brine, and lime instead of dolime ($CaO{\cdot}MgO$(solid[s])). Seawater solutes, such as sodium (Na^+), calcium (Ca^{2+}), chlorine (Cl^-), and SO_4^{2-}, presumably remained mainly in solution.

After filtering and washing the precipitate to remove all the seawater, National Magnesia hard-burned (calcined at 1000-1500 ºC [1832-2732 ºF]) the brucite to convert it to periclase via the reaction

$$Mg(OH)_2(s) \rightarrow MgO(s) + H_2O(g). \quad \text{(MgO.2)}$$

Hard burning produces MgO that is more reactive than dead-burned MgO (calcined at 1500-2000 ºC [2732-3632 ºF]), but less reactive than light-burned MgO (calcined at 700-1000 ºC [1292-1832 ºF]).

MgO-3.2 Premier MgO

This section describes the process that Premier Chemicals used to manufacture MgO for the WIPP (Section MgO-3.2.1), the DOE's characterization of this product (Section MgO-3.2.2), and changes in the WIPP project's understanding of its characteristics since the CRA-2004 (Section MgO-3.2.3).

MgO-3.2.1 Production

This section is based on a brief description provided by the DOE (the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.1).

Premier Chemicals produced MgO for the WIPP by mining ore from a sedimentary magnesite ($MgCO_3$) deposit and calcining it to expel all CO_2, thereby producing periclase directly instead of from calcined brucite:

$$MgCO_3(s) \rightarrow MgO(s) + CO_2(g). \qquad \text{(MgO.3)}$$

Calcination of accessory $CaCO_3$ produced small quantities of lime. Calcination of other accessory minerals in the ore, such as clay minerals and quartz, created minor quantities of oxide and silicate minerals, such as spinel ($MgAl_2O_4$), ulvöspinel ($Ti(Fe,Mg)_2O_4$), forsterite (Mg_2SiO_4), and monticellite ($CaMgSiO_4$). Calcination also drove off any H_2O in the ore.

MgO-3.2.2 Characterization

This section is based on the summary of the DOE's characterization of Premier Chemicals MgO provided in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.1 and Section BARRIERS-2.3.2.1.

This section emphasizes the DOE's identification and quantification of the reactive constituents periclase and lime, and the nonreactive constituents of Premier Chemicals MgO. In this appendix, *reactive constituents* refers to those solids that hydrate and carbonate to a significant extent on the time scales of the accelerated or WIPP-relevant laboratory experiments described below (Section MgO-4.1 and Section MgO-4.2). It is possible that the nonreactive constituents of Premier MgO (or the MgO provided by other vendors) could significantly hydrate and carbonate during the 10,000-year WIPP regulatory period. However, these experiments were designed to investigate the hydration and carbonation of the reactive constituents of MgO, not the relatively minor nonreactive constituents. Therefore, credit is not taken for possible CO_2 uptake by the nonreactive constituents.

Bryan and Snider (2001a) reported that a typical chemical analysis of Premier Chemicals MgO yielded about 91 weight percent (wt %) MgO, 1 wt % alumina (Al_2O_3), 3 wt % silica (SiO_2), 4 wt % CaO, and 1 wt % iron(III) (Fe(III)) oxide (Fe_2O_3). These chemical analyses did not differentiate between the MgO contained in the reactive constituent periclase and that contained in the nonreactive constituents spinel, ulvöspinel, forsterite, and monticellite; or between the CaO contained in the reactive constituent lime and that contained in the nonreactive constituent monticellite. However, most of the MgO and CaO occurred as periclase and lime, respectively, in Premier Chemicals MgO. On the other hand, some of the MgO and CaO, and most, if not all, of the Al_2O_3, SiO_2, and Fe_2O_3 were present in the accessory oxide and silicate minerals described above.

Snider (2002, Figure 1, Figure 2, Figure 6, and Figure 7) observed that the hydration of Premier Chemicals MgO reached completion after formation of about 85 mole % (mol %) brucite in accelerated experiments. Snider (2003a) calculated that the average brucite concentration in this lot of Premier Chemicals MgO was 84.6 mol % after complete hydration, based on the last 8 data

points of the inundated hydration experiment with deionized (DI) H_2O at 90 ºC (194 ºF) (Snider 2002, Figure 1 and Figure 2) and the last 16 data points of the humid hydration run at 95% relative humidity (RH) and 80 ºC (176 ºF) (Snider 2002, Figure 6 and Figure 7). Therefore, it was assumed in the CRA-2004 that this lot of Premier Chemicals MgO contained 84.6 mol % periclase prior to hydration.

It is important to note that Snider (2002) determined the brucite concentration of the MgO hydration products by loss-on-ignition (LOI) analysis, which quantified the mass of H_2O released by brucite upon heating to 500 ºC (932 ºF). However, based on the results of Deng et al. (2006) and Deng, Xiong, and Nemer (2007) (Section MgO-3.3.2), it is now clear that LOI or thermal gravimetric analysis (TGA) cannot readily differentiate between the H_2O lost by brucite and portlandite. Therefore, Deng et al. (2006) and Deng, Xiong, and Nemer (2007) reported their results as mole percent brucite and portlandite or weight percent brucite and portlandite. Thus, the results of Snider (2002) are described as mole percent brucite and portlandite in this appendix, which correspond to the concentration in mole percent of periclase and lime prior to hydration.

Snider (2003b) used inductively coupled plasma-optical atomic spectroscopy (ICP-AES) and gravimetric analysis to quantify the mineralogical composition of one of the lots of Premier Chemicals MgO used for the hydration and carbonation experiments (Section MgO-6.0). Based on the assumption that the silicate in this MgO was forsterite, this lot of MgO contained 86.9 wt % periclase, 2.39 wt % lime, 2.07 wt % spinel, and 5.02 wt % forsterite. If the silicate was monticellite, this lot contained 88.7 wt % periclase, 1.27 wt % lime, 2.07 wt % spinel, and 5.76 wt % monticellite. Given the uncertainties inherent in quantifying the mineralogical composition of materials such as Premier Chemicals MgO, it is reasonable to conclude that this material contained about 90 wt % reactive constituents (periclase and lime) and 10 wt % nonreactive constituents (oxides and silicates).

Bryan and Snider (2001a) carried out particle-size analyses of two batches of MgO used for their experiments. Table MgO-1 provides the results of these analyses.

MgO-3.2.3 Results since the CRA-2004 in Characteristics of MgO

Snider and Xiong (2004) reported the results of experiments on the inundated hydration and the inundated carbonation of Premier Chemicals MgO. The objectives of this study were to determine why Snider (2002, 2003a) had observed that the hydration of Premier Chemicals MgO reached completion after formation of about 85 mol % brucite in three sets of experiments (Experiments 1, 2, and 3) and why the extent of Premier Chemicals MgO hydration in accelerated tests was less than expected (Snider 2002, 2003a, 2003b).

Snider and Xiong (2004, Section 3.1.2.1 and Section 3.3.2.1) conducted Experiment 1 to examine the effects of particle size on the extent of hydration and it yielded no useful data. The cause of the unexpectedly low extent of hydration was identified by Experiments 2 and 3 (below).

Table MgO-1. Particle-Size Distribution of Two Batches of Premier MgO (from Bryan and Snider [2001a])

Size Range (mm)	Batch 1	Batch 2
< 0.15	31.0%	9.89%
0.15 to 0.30	8.36%	29.4%
0.30 to 0.50	4.59%	29.7%
0.50 to 0.71	3.50%	15.0%
0.71 to 2.00	14.2%	14.5%
> 2.00	37.4%	1.53%

Snider and Xiong (2004, Section 3.1.2.2 and Section 3.3.2.2) conducted Experiment 2 to test the validity of LOI analysis at 500 °C (932 °F). For this experiment, 22 separate runs were conducted with 5 grams (g) of reagent grade Fisher MgO and 100 milliliters (mL) of DI water in 125-mL polypropylene bottles at 90 ºC (194 ºF) for 1 to 15 days, followed by LOI analysis at 500 ºC (932 ºF). These runs yielded results from 87 to 99 mol % brucite, with no apparent increase in the extent of hydration from 1 to 15 days (Snider and Xiong 2004, Figure 8). Snider and Xiong (2004, p. 16) concluded, "The most likely reason for why hydration of Fisher MgO did not produce 100 mol % brucite in this experiment is that LOI analysis at 500 ºC (932 ºF) did not drive off all bound H_2O (see Experiment 3 below)."

Snider and Xiong (2004, Section 3.1.2.3 and Section 3.3.2.3) performed Experiment 3 to further test the validity of LOI at 500 ºC (932 ºF) by conducting 8 runs with either 5 g of Fisher or Premier Chemicals MgO and 100 mL of DI water in 125 mL polypropylene bottles at 90 ºC (194 ºF) for 29 days, followed by LOI analysis at 500 or 750 ºC (932 or 1382 ºF). Table MgO-2 provides the results of Experiment 3. These results imply that (1) not all of the bound H_2O is released during LOI analysis at 500 ºC (932 ºF), and (2) the concentration of brucite and portlandite in their hydration products and the concentration of periclase and lime for Premier Chemicals MgO prior to reaction were about 89 mol % and 92 wt % for the LOI analysis at 750 ºC (1382 ºF), thus confirming the impact of higher temperature on the LOI analysis.

MgO-3.3 Martin Marietta MgO

This section discusses the process that Martin Marietta Magnesia Specialties LLC uses to produce MgO for the WIPP (Section MgO-3.3.1) and the DOE's characterization of this product (Section MgO-3.3.2). Because Premier Chemicals was replaced by Martin Marietta in January 2005 (Section MgO-2.2.1), all the information described in this section has been obtained since the CRA-2004.

MgO-3.3.1 Production

This section summarizes the process Martin Marietta Magnesia Specialties, LLC, uses to produce its MgO. This summary is based on information provided by Martin Marietta (Martin Marietta Magnesia Specialties 2006) and the text in Brush and Roselle (2006, Section 2.3.1).

Table MgO-2. Effects of LOI Analysis Temperature on the Extent of Hydration under Accelerated Conditions on Fisher and Premier Chemicals MgO

Type of MgO	Brucite, 500 ºC (932 ºF) (mol %)	Brucite, 500 ºC (932 ºF) (wt %)	Brucite, 750 ºC (1382 ºF) (mol %)	Brucite, 750 ºC (1382 ºF) (wt %)
Fisher	90.5	93.2	NA[a]	NA
Fisher	90.2	93.0	NA	NA
Fisher	NA	NA	97.3	98.2
Fisher	NA	NA	98.5	99.0
Premier	84.2	88.5	NA	NA
Premier	83.0	87.6	NA	NA
Premier	NA	NA	88.7	91.9
Premier	NA	NA	89.4	92.4

[a] NA = not analyzed.

Martin Marietta pumps brine from a depth of about 762 m (2,500 feet (ft)) in the Michigan Basin. According to their website, this brine consists of $CaCl_2 + MgCl_2 + H_2O$. This simplified composition of the brine does not include solutes such as Na^+, K^+, and SO_4^{2-}, which are important constituents of WIPP brines and which presumably are present at least to some extent in brines from the Michigan Basin.

Martin Marietta produces dolime by calcining dolomite ($CaMg(CO_3)_2$) quarried in Ohio. Dolomite, which is also commonly referred to as "dolomitic limestone," is a rock that mainly comprises the mineral dolomite. In some cases, this rock can comprise nearly pure dolomite.

The calcination reaction for dolomite is

$$CaMg(CO_3)_2(s) \rightarrow CaO{\cdot}MgO(s) + 2CO_2(g). \qquad \text{(MgO.4)}$$

The formula for dolomite on the left-hand side of Reaction (MgO.4) does not include impurities such as clay minerals and quartz, which presumably occur in small quantities in the rock quarried to produce Martin Marietta MgO.

Martin Marietta then mixes the brine, dolime, and water to produce a slurry containing dissolved $CaCl_2$ and particulate $Mg(OH)_2$ produced via the following reaction:

$$(CaCl_2(aq) + MgCl_2(aq) + H_2O(aq)) + CaO{\cdot}MgO(s) + 2H_2O(aq) \rightarrow 2Mg(OH)_2(s) + 2CaCl_2(aq) + H_2O(aq). \qquad \text{(MgO.5)}$$

Note that $CaCl_2$ and $MgCl_2$ are written as neutral complex species instead of ionic species in Reaction (MgO.5), and that H_2O is included on both sides of Reaction (MgO.5) to be consistent with the information on the Martin Marietta website.

Next, Martin Marietta allows the brucite to settle. They filter and wash it to remove all of the brine and the $CaCl_2$ dissolved in this brine.

Finally, Martin Marietta hard-burns (calcines at 1000-1500 ºC [1832-2732 ºF]) the brucite to convert it to periclase via Reaction (MgO.2) (Section MgO-3.1).

MgO-3.3.2 Characterization

This subsection reviews the DOE's characterization of Martin Marietta Magnesia Specialties MgO, hereafter called Martin Marietta MgO. It is based on the text in Brush and Roselle (2006, Section 2.3).

This section emphasizes the DOE's identification and quantification of the reactive and nonreactive constituents of Martin Marietta MgO. The meanings of *reactive* and *nonreactive constituents* are explained in Section MgO-3.2.

Wall (2005) carried out a technical evaluation on the suitability of Martin Marietta MgO. This evaluation, which supported the 2004 selection of Martin Marietta as the vendor of MgO for the WIPP (Section MgO-2.2.1), emphasized quantifying the concentration of the reactive phases periclase and lime, but also considered the rate at which these phases hydrate in accelerated tests.

Wall (2005) conducted accelerated hydration experiments (hydration of MgO in DI water at 90 ºC [194 ºF]) to (1) measure the concentrations of periclase and lime in these materials and compare them to those of Premier Chemicals MgO (Snider and Xiong 2004); (2) measure the accelerated hydration rates of the Martin Marietta products and compare them to those of Premier Chemicals MgO; (3) improve, if possible, the LOI technique used to measure the brucite and portlandite contents of MgO hydration products. Wall (2005) evaluated three materials from Martin Marietta: MagChem 10 WTS-20, MagChem 10 WTS-30, and MagChem 10 WTS-60. ("MagChem 10" is omitted hereafter.) All of these products are hard-burned MgO (calcined at 1000-1500 ºC [1832-2732 ºF]) with a specified MgO content of 95 wt % and a bulk density of 87 lb/cubic foot (ft^3) (1,400 kg/cubic meter (m^3)). Assay results are typically 97 wt % MgO. However, these results include MgO in phases other than periclase, such as other oxides or silicates (Section MgO-3.2.2).

Table MgO-3 compares Wall's (2005) results for sample products WTS-20, WTS-30, and WTS-60 with those obtained by Snider and Xiong (2004) for Premier Chemicals MgO. Snider and Xiong (2004) and Wall (2005) reported the results of their MgO hydration product LOI analysis as mole percent brucite or weight percent brucite. However, based on the results of Deng et al. (2006) and Deng, Xiong, and Nemer (2007) (see below), it is now clear that LOI or TGA cannot readily differentiate between the H_2O lost by brucite and portlandite. Therefore, Deng et al. (2006) and Deng, Xiong, and Nemer (2007) reported their results as mole percent brucite and portlandite or weight percent brucite and portlandite. Thus, the results of Snider and Xiong (2004) and Wall (2005) are described as mole percent brucite and portlandite or weight percent brucite and portlandite in this appendix, which corresponds to the mole percent or weight percent concentration of periclase and lime prior to hydration.

Table MgO-3 illustrates the effects of the materials used for the accelerated hydration experiments and the temperature used for LOI on the brucite and portlandite contents of the hydration products and—by assumption—the periclase and lime contents of these materials. Two important conclusions can be drawn from these results:

Table MgO-3. Effects of Temperature Used for LOI Analyses of MgO Hydration Products on the Brucite + Portlandite Concentrations of the Hydrated Samples. From Wall (2005, Table 1), Unless Otherwise Noted.

Material	Temperature Used for LOI			
	500 °C[a]		750 °C[a]	
	Mol %	Wt %	Mol %	Wt %
WTS-20	87 ± 5[b]	91 ± 4[b]	ND[c]	ND[c]
WTS-30	87 ± 5[b]	91 ± 4[b]	96 ± 5[b]	97 ± 3[b]
WTS-60	90 ± 3[b]	93 ± 2[b]	ND[c]	ND[c]
Premier	85[d]	89[d]	89[d]	92[d]

[a] Snider and Xiong (2004) and Wall (2005) reported their results of LOI analysis of MgO hydration products as mole percent brucite or weight percent brucite. However, Deng et al. (2006a) and Deng, Xiong, and Nemer (2007) report their results as mole percent brucite + portlandite or weight percent brucite + portlandite (see text). In this appendix, all of these results are reported as mole percent brucite + portlandite or weight percent brucite + portlandite.

[b] Reported uncertainties represent two standard deviations (2σ).

[c] ND = not determined.

[d] Snider and Xiong (2004).

1. All three materials from Martin Marietta have the same or higher contents of reactive constituents (periclase and lime) than Premier Chemicals MgO.

2. LOI at 750 ºC (1382 ºF) yields higher brucite and portlandite contents (and, by assumption, higher initial periclase and lime contents) than LOI at 500 ºC (932 ºF). The results obtained for Premier MgO since the CRA-2004 (Section MgO-3.2.3) imply that the 750 ºC (1382 ºF) results are more accurate than the 500 ºC (932 ºF) results.

Wall (2005) reported that LOI at 750 ºC (1382 ºF) was unsuccessful for WTS-20 and WTS-60 due to decrepitation of these samples at this temperature. Wall (2005) was unable to develop a procedure for LOI at 750 ºC (1382 ºF) that prevented decrepitation of these samples. However, the fact that LOI for WTS-60 at 500 ºC (932 ºF) yielded a higher brucite and portlandite content than LOI with WTS-30 at this temperature strongly suggested that the sample of WTS-60 tested by Wall (2005) had a periclase and lime content greater than or equal to that of WTS-30, and that the brucite and portlandite content of WTS-60 from LOI at 750 ºC (1382 ºF) would equal or exceed 96 ± 5 mol %, or 97 ± 3 wt % (see Table MgO-3). Therefore, it is reasonable to conclude based on these results that WTS-60, the MgO currently being emplaced in the WIPP, contains 96 ± 5 mol % (97 ± 3 wt %) periclase and lime.

Another important result of Wall's (2005) work is that Martin Marietta MgO hydrated significantly faster in accelerated hydration experiments than Premier Chemicals MgO at the same temperature (90 ºC [194 ºF]). Although the DOE does not have any 25 ºC (77 ºF) hydration data for Martin Marietta MgO, comparison of the 90 ºC (194 ºF) data suggests that Martin Marietta MgO will hydrate faster—and carbonate faster—than Premier MgO at 28 ºC (82 ºF), the temperature in the undisturbed Salado Formation at the repository horizon and hence the temperature expected in the repository after it is filled and sealed (Munson et al. 1987).

Deng et al. (2006) and Deng, Xiong, and Nemer (2007) carried out additional characterization of Martin Marietta WTS-60 MgO, the MgO currently being emplaced in the WIPP. Their characterization included the following analyses, all of which were conducted on Lot SL2980076 of this material:

1. Particle-size analysis
2. Analysis of the chemical composition
3. Preliminary identification of the nonreactive constituents
4. LOI analysis and TGA of the reactive constituents in Martin Marietta WTS-60

This work was part of an ongoing laboratory study on the efficacy of Martin Marietta MgO (Deng, Nemer, and Xiong [2006] and Deng, Xiong, and Nemer [2007]).

Deng, Xiong, and Nemer (2007, Section 3.1) carried out particle-size analysis of Martin Marietta WTS-60 MgO by sieving. Table MgO-4 provides the results of their analysis.

Table MgO-4. Particle-Size Distribution of 10 Samples from One Lot of Martin Marietta MgO. Adapted from Deng, Xiong, and Nemer (2007, Table 3).

Size Range (mm)	Average (wt %)	Standard Deviation (wt %)
> 2.0 mm	7.02	0.91
1.0 to 2.0 mm	32.5	1.76
600 micrometer (μm) to 1.0 mm	20.2	1.28
300 μm to 600 μm	12.7	2.19
150 μm to 300 μm	5.4	0.70
75 μm to 150 μm	3.4	0.35
< 75 μm	17.9	1.88

Deng et al. (2006, Section 3.1 and Appendix B, Section B.1) and Deng, Xiong, and Nemer (2007, Section 3.2 and Appendix B, Section B.1) determined the overall chemical composition of Martin Marietta WTS-60 MgO by dissolving it in nitric acid, analyzing the liquid by ICP-AES, and weighing the remaining solids. They reported the following concentrations of oxides (average concentrations and standard deviations) based on 12 analyses of Lot SL2980076:

1. MgO: 98.5 ± 2.5 wt %
2. Al_2O_3: 0.13 ± 0.02 wt %
3. SiO_2: 0.31 ± 0.01 wt %
4. CaO: 0.87 ± 0.03 wt %
5. Fe_2O_3: 0.12 ± 0.01 wt %

6. Total: 99.9 ± 2.5 wt %

These chemical analyses did not differentiate between the MgO and CaO contained in the reactive constituents periclase and lime and those contained in the nonreactive constituents. Preliminary characterization of the nonreactive constituents in WTS-60 suggests that they comprise (1) a spinel-group mineral that appears to be a solid solution of the four end members chromite ($FeCr_2O_4$), hercynite ($FeAl_2O_4$), magnesiochromite ($MgCr_2O_4$), and spinel; (2) hematite (Fe_2O_3); and (3) SiO_2 (polymorph was not determined). The relative proportions of these phases also have not been determined. It is possible that one or more of these nonreactive constituents could also consume significant quantities of CO_2 and H_2O in the WIPP, albeit at lower rates than periclase and lime.

Deng et al. (2006, Section 3.2; Section 4; and Appendix B, Section B.2) and Deng, Xiong, and Nemer (2007, Section 3.3; Section 4; and Appendix B, Subsection B.2) established the concentration of reactive constituents in Martin Marietta WTS-60 MgO by (1) hydrating samples of this material in DI H_2O at 90 ºC (194 ºF) for at least 3 days; (2) using LOI analysis and TGA to determine the quantity of H_2O released by hydrated MgO from 150-800 ºC (302-1472 ºF); and (3) assuming that nonreactive components did not hydrate to a significant extent, and that any unbound water was lost at temperatures below 150 °C (302 ºF). In addition, they conducted a total carbon (C) analysis on samples of WTS-60 by C coulometry before and after hydration to ensure that precipitation of $CaCO_3$, which might have occurred during hydration, did not affect the results of the LOI analyses and TGA. Based on eight LOI analyses and TGA, they reported that WTS-60 contains 96.0 ± 1.9 mol % (95.6 ± 1.7 wt %) periclase and lime (see Table MgO-5).

Table MgO-5. Results of LOI Analysis and TGA on WTS-60. From Deng et al. (2006), Table 7 and Table 8, and Deng, Xiong, and Nemer (2007), Table 8 and Table 9.

Reactive Constituent	Average (mol %)	Standard Deviation (mol %)	Average (wt %)	Standard Deviation (mol %)
Periclase	95.2[a]	1.82[a]	94.8[b]	1.72[b]
Lime	0.6[a]	0.04[a]	0.9[b]	0.02[b]
Periclase + lime	95.8[a]	1.86[a]	95.7[c]	1.74[b]

[a] From Deng et al. (2006a, Table 7).
[b] From Deng et al. (2006a, Table 8).
[c] Value corrected from the value of 95.6 provided by Deng et al. (2006a, Table 8).

MgO-4.0 Hydration and Carbonation of MgO

This section reviews the results of the DOE's studies on the hydration and carbonation of MgO (Section MgO-4.1 and Section MgO-4.2, respectively).

MgO-4.1 Hydration of MgO

The DOE carried out extensive studies on the hydration of Premier Chemicals MgO under four versions of Test Plan 00-07 (Wang and Bryan 2000; Wang, Bryan, and Wall 2001; Snider and Xiong 2002b; Snider, Xiong, and Wall 2004); Section MgO-4.1.1 describes the results of these studies obtained prior to the CRA-2004. Since then, the DOE completed its studies on the hydration of Premier Chemicals MgO and initiated new studies with MgO from Martin Marietta Magnesia Specialties LLC (Deng, Nemer, and Xiong 2006; Deng, Nemer, and Xiong 2007); Section MgO-4.1.2 discusses the results of these studies.

MgO-4.1.1 Hydration of Premier MgO

This section, which reviews the results of studies on the hydration of Premier Chemicals MgO completed prior to the CRA-2004, is based on the text in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.2.1.

Bryan and Snider (2001a and 2001b), Snider (2002 and 2003b), and Xiong and Lord (2008) studied the hydration of Premier Chemicals MgO under humid and inundated conditions. They carried out humid experiments with 3 g of uncrushed Premier Chemicals MgO at an RH of 35, 50, 75, or 95% and temperatures of 25, 40, 60, or 80 ºC (77, 104, 140, or 176 ºF) for up to 460 days (Snider 2003b). Inundated experiments were conducted with 5 g of uncrushed Premier Chemicals MgO in 100 mL of DI H_2O, 4.00 molar (M) sodium chloride (NaCl), Energy Research and Development Administration (ERDA)-6, or Generic Weep Brine (GWB) at temperatures of 25, 50, 70, and 90 °C (77, 122, 158, and 194 ºF) for up to 360 days (Snider 2003b). ERDA-6 brine is a synthetic brine representative of fluids in brine reservoirs in the Castile Formation (Popielak et al., 1983). Snider (2003c) verified that GWB is the average composition of intergranular fluids collected from the Salado at the original stratigraphic horizon of the repository and analyzed by Krumhansl, Kimball, and Stein (1991).

Based on these experiments with Premier Chemicals MgO, the most important hydration reaction expected in the WIPP is

$$MgO(s) + H_2O(aq \text{ or } g) \rightleftharpoons Mg(OH)_2(s). \qquad \text{(MgO.6)}$$

Reaction (MgO.6) was the only hydration reaction observed in the humid experiments. Reaction (MgO.6) was also the only hydration reaction observed in the inundated runs with ERDA-6 brine (Snider 2003b). In inundated experiments with GWB, hydration produced both brucite and an amorphous or crystalline Mg-OH-Cl-H_2O phase (Snider 2003b). In most of the runs with GWB, the Mg-OH-Cl-H_2O phase was amorphous and its exact composition was not determined. In a few experiments at 25 ºC (77 ºF), however, a crystalline phase with the composition $Mg_3(OH)_5Cl{\cdot}4H_2O$ was identified by X-ray diffraction (XRD) analysis (Snider 2003b). The thermodynamic speciation and solubility code Fracture-Matrix Transport (FMT)

(Babb and Novak 1997 and addenda; Wang 1998) also predicts that both brucite and a similar Mg-OH-Cl-H_2O phase, $Mg_2(OH)_3Cl{\cdot}4H_2O$, would be present in GWB and Salado Primary Constituents (SPC) brine after these brines equilibrate with the solids in WIPP disposal rooms (Section MgO-5.1). SPC brine (Novak 1997) is similar to Brine A, another synthetic fluid that was used to represent intergranular Salado brines (see Section MgO-5.1.1.2 and Molecke 1983). The FMT thermodynamic database contains the phase $Mg_2(OH)_3Cl{\cdot}4H_2O$, but not $Mg_3(OH)_5Cl{\cdot}4H_2O$; if $Mg_3(OH)_5Cl{\cdot}4H_2O$ were in the database, FMT might predict that $Mg_3(OH)_5Cl{\cdot}4H_2O$ would be present in GWB instead of or along with $Mg_2(OH)_3Cl{\cdot}4H_2O$. However, long-term experiments with GWB suggested that brucite might be replacing the amorphous Mg-OH-Cl-H_2O phase, possibly because the Mg(II)(aq) concentration of this brine was decreasing with time. Figure MgO-3 is a scanning electron microscope (SEM) image of Premier Chemicals MgO after hydration in GWB; Figure MgO-4 shows Premier Chemicals MgO after hydration in ERDA-6 brine. Figure MgO-3 and Figure MgO-4 provide visual evidence that the passivation of MgO will not occur in the repository.

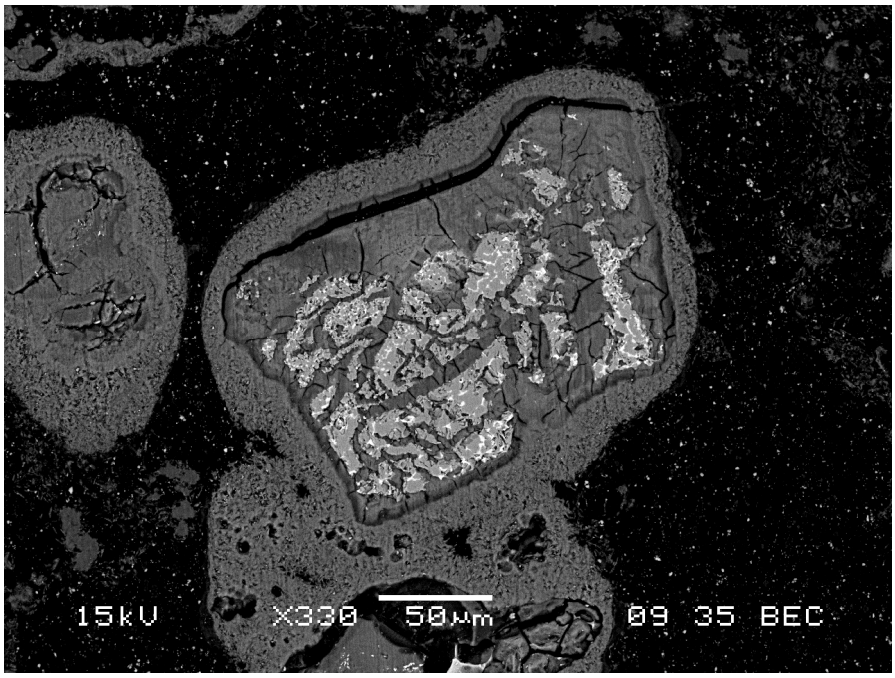

Figure MgO-3. SEM Image of Premier Chemicals MgO after Hydration in GWB at 90 ºC (194 ºF) for 21 Days (SNL Experiment CC-GW-90-30-5). The Light-Gray Phase Inside the Large Grain at the Center of This Image is Unhydrated Periclase. The Bright Inclusions in this Periclase are Oxides and Silicates Such as Spinel, Ulvöspinel, Forsterite, and Monticellite (Section MgO-3.2.1 and Section MgO-3.2.2). The Dark-Gray Material Surrounding and Penetrating the Fractures in the Periclase is a Mg-OH-Cl-H_2O Phase, Probably Amorphous or Crystalline $Mg_3(OH)_5Cl{\cdot}4H_2O$ (Section MgO-4.1.1). Abundant Fractures are Seen Penetrating the Mg-OH-Cl-H_2O Phase. The Dark-Gray Material Surrounding the Mg-OH-Cl-H_2O Phase is Brucite. This Layer of Brucite Appears to be Loosely Attached to the Mg-OH-Cl-H_2O Phase, Thus Facilitating the Continued Access of Brine to the Mg-OH-Cl-H_2O Phase and Unhydrated Periclase.

Figure MgO-4. SEM Image of Premier Chemicals MgO after Hydration in ERDA-6 Brine at 70 ºC (158 ºF) after 21 days (SNL Experiment CC-ER-70-30-5). Two Concentric Layers of Brucite Surround an Inner Core of Brucite. The Outer Layers of Brucite Appear to be Loosely Attached to the Core.

MgO-4.1.2 Results since the CRA-2004 Regarding Hydration of MgO

Deng, Xiong, and Nemer (2007, Section 5) carried out accelerated hydration experiments with Martin Marietta MgO. The primary objective of the accelerated hydration experiments was to determine which factors (see below) have a significant effect on MgO hydration and carbonation kinetics. Deng, Xiong, and Nemer (2007, Section 5) also conducted experiments to assess the advantages and disadvantages of different types of containers, and the utility of tracer dyes for their ongoing study of the efficacy of Martin Marietta MgO (Deng, Nemer, and Xiong (2006) and Deng, Nemer, and Xiong (2007)). Fernández et al. (1999) identified particle size, solid-to-solution ratio, and stirring speed as important factors that affect the kinetics of carbonation of MgO slurries.

Therefore, Deng, Xiong, and Nemer (2007, Section 5) conducted an accelerated, inundated hydration study using a fractional factorial matrix to determine which of these three factors are important enough to include in their long-term hydration and carbonation studies. For the study, they used MgO with particle sizes less than 75 µm, which constituted about 18 wt % of their as-received material (see Table MgO-4); or 1.0 to 2.0 mm, which accounted for about 32 wt % of their material (Lot SL2980076 of Martin Marietta MagChem WTS-60 MgO, the material currently being emplaced in the WIPP). These are the particle-size ranges with the most particles in this lot of Martin Marietta WTS-60 MgO. Deng, Xiong, and Nemer (2007, Section 5) used MgO-to-brine ratios of 0.05, 0.4, or 1 g/mL; these values are within the range of 0.001 to 10 g/mL expected in the WIPP (Nemer 2006). Furthermore, the previous studies of the

inundated hydration and carbonation of Premier Chemicals MgO (Section MgO-4.1.1 and Section MgO-4.2.1, respectively) were performed at an MgO-to-brine ratio of 0.05 g/mL; inclusion of this ratio in the accelerated hydration experiments with Martin Marietta MgO thus facilitated comparison with these results. Finally, the samples were placed in an oven or in a water-bath shaker at a shaking speed of 150 revolutions per minute to determine the effect of agitation. Deng, Xiong, and Nemer (2007, Section 5) carried out these experiments by placing Martin Marietta WTS-60 MgO and DI water in 30-mL high-density polyethylene (HDPE) centrifuge tubes or 125-mL HDPE serum bottles, depending on the MgO-to-brine ratio, and placed these containers in a water-bath shaker or an oven at 70 ºC (158 ºF) for periods of up to 43 days.

Deng, Xiong, and Nemer (2007, Section 5.4, p. 33) concluded,

> [T]he small-particle-size samples hydrated faster than the large particle size during the first few days, which is probably due to the larger specific surface area … of the small particles. However for the remainder of the experiment, the large-particle-size samples hydrate faster than the small particle size. There are no obvious differences between experiments that were continuously stirred in a water-bath shaker and those that were kept in the oven. The MgO-water ratio did not significantly influence the hydration rate either. These visual observations have been confirmed by the Minitab [statistical] analysis...

Finally, Deng, Xiong, and Nemer (2007, Section 5.7) fitted the results of the accelerated, inundated-hydration experiments described above to one kinetic model in which the hydration rate is controlled by the surface area of the MgO particles, and to three models in which the rate is controlled by the diffusion of H_2O through the layer of brucite that formed on the surfaces of the MgO particles. They concluded that the results obtained with the Martin Marietta WTS-60 MgO with small particle sizes (< 75 μm) are consistent with control by diffusion, but that the results obtained with the large (1.0 to 2.0 mm) particles are consistent with surface-area control.

MgO-4.2 Carbonation of MgO

The DOE also conducted extensive studies on the carbonation of Premier Chemicals MgO under Test Plan 00-07 (Wang and Bryan 2000; Wang, Bryan, and Wall 2001; Snider and Xiong 2002b; Snider, Xiong, and Nemer 2004); Section MgO-4.2.1 describes the results of these studies obtained prior to the CRA-2004. Since then, the DOE completed its carbonation studies with Premier Chemicals MgO (Section MgO-4.2.2) and started new work with Martin Marietta MgO (Deng, Nemer, and Xiong 2006 and 2007).

MgO-4.2.1 Carbonation of Premier Chemicals MgO

This section, which reviews the results of studies on the carbonation of Premier Chemicals MgO completed prior to the CRA-2004, is based on the text in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.2.2.

Bryan and Snider (2001a and 2001b), Snider (2002), Snider and Xiong (2002a), Xiong and Snider (2003), and Xiong and Lord (2008) studied the carbonation of Premier Chemicals MgO and reagent-grade materials under inundated conditions. Experiments were carried out with 5 g of uncrushed Premier Chemicals MgO in 100 mL of DI H_2O, 4.00 M NaCl, ERDA-6 brine, or GWB under an atmosphere of compressed, ambient, laboratory air at room temperature for up to

327 days (Snider and Xiong 2002a). Inundated experiments were also conducted with uncrushed Premier Chemicals MgO; crushed, prehydrated Premier Chemicals MgO; Fisher reagent-grade periclase; or prehydrated Fisher periclase in 100 mL of ERDA-6 brine or GWB under an atmosphere containing 5% CO_2 for periods up to 91 days (Snider and Xiong 2002a). Humid experiments were performed with 2.5 g of prehydrated Fisher periclase in an atmosphere consisting of compressed, ambient, laboratory air at an RH of 33, 58, 75, or 95% at room temperature and 40 ºC (104 ºF).

Based on these experiments, the carbonation reaction expected in the WIPP in the short term (a few hundred to a few thousand years) is

$$5Mg(OH)_2(s) + 4CO_2(aq \text{ or } g) \rightleftharpoons Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O(s). \qquad \text{(MgO.7)}$$

In experiments with ERDA-6 brine and atmospheric CO_2, Snider and Xiong (2002a) detected hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ by XRD analysis. This solid is referred to as "hydromagnesite (5424)" in this appendix. No other magnesium (Mg) carbonates were detected in runs with ERDA-6 brine and atmospheric CO_2. Snider and Xiong (2002a) detected both hydromagnesite (5424) and nesquehonite ($MgCO_3{\cdot}3H_2O$) by XRD analysis in the experiments with ERDA-6 brine and 5% CO_2, but hydromagnesite (5424) was clearly replacing nesquehonite as these experiments proceeded. In experiments with GWB, hydromagnesite (5424) was the only Mg carbonate detected by XRD analysis (Snider and Xiong 2002a). Therefore, there is strong evidence that hydromagnesite (5424) will be the dominant Mg carbonate for at least part of the 10,000-year regulatory period (the first few hundred to few thousand years).

There are at least two forms of hydromagnesite: hydromagnesite (5424) (see above) and hydromagnesite with the composition $Mg_4(CO_3)_3(OH)_2{\cdot}3H_2O$. The latter is referred to as "hydromagnesite (4323)" in this appendix. Thermodynamic data for both of these forms of hydromagnesite are available; geochemical modeling carried out for the WIPP project (see Section MgO-5.1) has always predicted that hydromagnesite (5424) will form under expected WIPP conditions instead of hydromagnesite (4323) if magnesite is suppressed (i.e., prevented from forming by switching off magnesite in the EQ36 or FMT input file). Moreover, hydromagnesite (5424) was the only form of hydromagnesite produced in laboratory experiments on the carbonation of Premier Chemicals MgO (i.e., hydromagnesite (4323) was not reported). However, predictions of the effects of MgO on the chemical conditions in WIPP disposal rooms and the solubilities of An elements under these conditions suggest that the effects of hydromagnesite (5424) and hydromagnesite (4323) would be similar (compare Table MgO-7 and Table MgO-8 in Section MgO-5.1).

Section MgO-4.2.2 describes the conversion of hydromagnesite (5424) to magnesite in the WIPP.

MgO-4.2.2 Formation of Magnesite in the WIPP

The DOE stated in the CCA, Appendix BACK and Appendix SOTERM, that magnesite would be the Mg carbonate present throughout the 10,000-year regulatory period. This conclusion was based on calculations by Novak et al. (1996) with the geochemical speciation component of the

FMT code (Babb and Novak 1995), which demonstrated that magnesite is thermodynamically stable with respect to hydromagnesite and other Mg carbonates under expected WIPP conditions. Because magnesite is the stable Mg carbonate, the DOE maintained that the brucite-magnesite or the hydromagnesite (5424)-magnesite carbonation reaction

$$Mg(OH)_2(s) + CO_2(aq \text{ or } g) \rightleftharpoons MgCO_3(s) + H_2O(aq \text{ or } g) \quad \text{(MgO.8)}$$

$$Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O(s) + CO_2(aq \text{ or } g) \rightleftharpoons 5MgCO_3(s) + 5H_2O(aq \text{ or } g) \quad \text{(MgO.9)}$$

would buffer f_{CO_2} in the repository at a value of 1.26×10^{-7} atmospheres (atm), and used this value of f_{CO_2} (along with other parameters) to calculate An speciation and solubilities for the CCA PA (CCA, Appendix SOTERM, p. SOTERM-6).

Recent thermodynamic calculations carried out by Brush and Xiong (2003a), Brush (2005), and Brush et al. (2006) with FMT (Babb and Novak 1997 and addenda; Wang 1998) and the EQ3/6 geochemical software package (Daveler and Wolery 1992; Wolery 1992a and 1992b; Wolery and Daveler 1992) have also predicted that magnesite is stable with respect to hydromagnesite (5424), hydromagnesite (4323), and other Mg carbonates under expected WIPP conditions.

Furthermore, magnesite is commonly observed in the Salado (Lang 1939; Adams 1944; Lowenstein 1983 and 1988; Stein 1985) and in other formations in the Delaware Basin (Garber, Harris, and Borer 1990). Lowenstein (1988, p. 598) describes the siliciclastic-carbonate mudstone, in which magnesite is most abundant, as a "non-evaporitic sediment," and attributes its origin to subaqueous "settling of fine-grained, suspended material in the center of the Salado basin where the energy of inflow waters had largely dissipated." Therefore, the magnesite observed in the Salado did not necessarily form in situ. However, Garber, Haris, and Borer (1990), who reported that magnesite "occurs pervasively" throughout an 82-meter (m) (270-ft) interval of core recovered from a stratigraphic test well located along the subsurface trend of the Capitan Reef 27 kilometers (km) (17 miles) northeast of Carlsbad, concluded, "the most likely origin for the magnesite in the core is the downward movement of dense fluids from the Ochoan Series, Salado into the underlying, and [at the time] shallowly buried Tansil and Yates formations." Clearly, magnesite either formed or persisted for long periods in the Delaware Basin.

During its review of the CCA, the EPA questioned the DOE's conclusion that magnesite will be present throughout the entire 10,000-year regulatory period. For the CCA, the DOE based this conclusion on the fact that magnesite is the thermodynamically stable Mg carbonate under expected WIPP conditions (the CCA, Appendix BACK and Appendix SOTERM). The EPA accepted the DOE's conclusion that magnesite is stable, but questioned whether the kinetics of the hydromagnesite (5424)-magnesite reaction are fast enough to produce enough magnesite in 10,000 years for the brucite-magnesite reaction to buffer f_{CO_2} at 1.26×10^{-7} atm.

A literature review on the formation of dolomite and magnesite in the natural environment and laboratory studies of the formation of magnesite was completed (Sandia National Laboratories 1997, Section 5.2.1, pp. 32-37). Section MgO-4.2.3 describes other aspects of this study. The literature review report (Sandia National Laboratories 1997, Section 5.2.1, pp. 32-35) provides several examples of naturally occurring dolomite and magnesite that may have formed in the last

several hundred to few thousand years. Nevertheless, this report states that "the most quantitative rates for precipitation kinetics of magnesite come from laboratory experiments." Therefore, the data on magnesite formation from Sayles and Fyfe (1973) and Usdowski (1989 and 1994) obtained in laboratory experiments conducted at temperatures of 60, 126, and 180 °C was used to perform an Arrhenius extrapolation to 28 °C, the temperature expected in the WIPP after it is filled and sealed (Munson et al. 1987). Based on this extrapolation, it was concluded "Under WIPP conditions, magnesite should form in several hundred years" (Sandia National Laboratories 1997, Figure 5-4).

Based on this evidence, the EPA (U.S. Environmental Protection Agency 1998f) concluded:

> The available rate data indicate that some portion, perhaps all, of the hydromagnesite will be converted to magnesite over the 10,000-year period for repository performance. The exact time required for complete conversion has not been established for all chemical conditions. However, the available laboratory and field data clearly indicate that magnesite formation takes from few hundred to, perhaps, a few thousand years. Thus, the early repository conditions can be best represented by the equilibrium between brucite and hydromagnesite. These conditions will eventually evolve to equilibrium between brucite and magnesite.

The EPA (U.S. Environmental Protection Agency 1998f) went on to describe the sequence of reactions that it expected to occur in WIPP disposal rooms:

> [T]he sequence of events resulting from brine infiltration and reaction with the MgO backfill in the repository may be conceptualized by the following reactions, in order:
>
> 1. Rapid reaction (hours to days) between the brine and MgO to produce brucite.
> 2. Rapid carbonation (hours to days) of the brucite to produce nesquehonite and possibly hydromagnesite.
> 3. Rapid conversion (days to weeks) of the nesquehonite to hydromagnesite.
> 4. Slow conversion (hundreds to thousands of years) of the hydromagnesite to magnesite"

However, the EPA (U.S. Environmental Protection Agency 1998f) also stated in the same document:

> These estimates of conversion rate are confounded by the fact that deposits of hydromagnesite are found in some evaporite basins dated as late Quaternary in age (<23.7 million years) (Stamatakis, 1995), indicating that the hydromagnesite has persisted in a metastable state for a long period with only partial conversion to magnesite and other magnesium carbonates.

Based at least in part on its interpretation of the implications of the huntite ($CaMg_3(CO_3)_4$)-hydromagnesite deposits described by Stamatakis (1995) for the kinetics of the hydromagnesite-magnesite reaction, the EPA stipulated that the brucite-hydromagnesite (5424) reaction be used to buffer f_{CO_2} for the An-solubility calculations in the CCA PAVT (Trovato 1997a; U.S. Environmental Protection Agency 1998f). This reaction would buffer f_{CO_2} at a value of 3.14×10^{-6} atm, a value somewhat higher than the value of 1.26×10^{-7} atm maintained by the brucite-magnesite reaction that was used for the CCA PA. The DOE has used a value of 3.14×10^{-6} atm for f_{CO_2} in WIPP PA since the CCA PAVT. Brush and Roselle (2006)

reconsidered the implications of Stamatakis (1995) for the kinetics of the hydromagnesite-magnesite reaction; their conclusions are described later in this section.

Experiments carried out for the WIPP project in the late 1990s by Zhang et al. (1999) imply that magnesite will replace hydromagnesite (5424) rapidly enough to be the dominant Mg carbonate for most of the 10,000-year regulatory period. Zhang et al. (1999) studied the conversion of hydromagnesite (5424) to magnesite in a saturated NaCl solution and GWB at high temperatures and used the Arrhenius equation to extrapolate the results to 25 ºC (77 ºF), close to the expected WIPP temperature of 28 ºC (82.4 ºF) (Munson et al. 1987). Zhang et al. (1999) reacted 0.3 g of reagent-grade hydromagnesite (5424) with 1.5 g of saturated NaCl solution or GWB in autoclaves (type unspecified) at 110, 150, or 200 ºC (230, 302, or 392 ºF). They then quantified the extent of conversion attained in their experiments by comparing XRD patterns for their samples with XRD calibration curves obtained by running premixed samples of their reagent-grade hydromagnesite (5424) and reagent-grade magnesite.

Conversion from hydromagnesite (5424) to magnesite took place in days to weeks at 110 and 150 ºC (230 and 302 ºF) (Zhang et al. 1999). This was preceded by an induction period that persisted for nearly half of the time required for essentially complete conversion of hydromagnesite (5424) to magnesite, during which only a few percent of the hydromagnesite (5424) reacted to form magnesite. At 200 ºC (392 ºF), conversion took place in a few hours. (At room temperature, formation of magnesite has not been observed in experiments carried out for the WIPP project, even in experiments that lasted for a few years.) Conversion of hydromagnesite (5424) to magnesite appeared to be a first-order reaction. The induction period, during which about 4-5% of the hydromagnesite (5424) formed magnesite, may have resulted from slow nucleation of magnesite, after which magnesite formed rapidly.

Zhang et al. (1999) also observed that conversion was faster in saturated NaCl than in GWB. (All experiments carried out subsequently with Premier Chemicals MgO have also shown that the rates of hydration and carbonation of periclase and brucite occurred faster in simpler, less concentrated solutions than in complex solutions with higher ionic strengths; i.e., the rates of reaction decrease in the order DI H_2O > 4 M NaCl > ERDA-6 brine > GWB.)

Based on their extrapolations to 25 ºC (77 ºF), Zhang et al. (1999) concluded that after an induction period of 18 or 200 years in saturated NaCl or GWB, respectively, the "half-life" of hydromagnesite (5424) (the time required for half of the hydromagnesite (5424) to convert to magnesite) would be 4.7 years (saturated NaCl) or 73 years (GWB). A period of about 1000 years, the approximate sum of the 200-year induction period and 730 years (10 half-lives), would result in conversion of over 99.9% of any hydromagnesite (5424) present to magnesite.

The applicability of the extrapolated results from Zhang et al. (1999) to the WIPP is probably more defensible than that of the extrapolated results in Sandia National Laboratories (1997) because Zhang et al. (1999) used high-ionic-strength brines—including one WIPP brine (GWB)—for their experiments, but SNL (Sandia National Laboratories 1997) used only low-ionic-strength (~0.05 M) results obtained from the literature.

Recently, Brush and Roselle (2006) reconsidered the implications of Stamatakis (1995) for the kinetics of the hydromagnesite (5424)-magnesite reaction and concluded the following:

1. It is unclear—based on the poorly constrained age(s) of the huntite-hydromagnesite (4323) deposits in the Kozani Basin, Greece—that the hydromagnesite (4323) there has persisted longer than expected based on the results of Zhang et al. (1999).

2. It is unclear that any conclusions regarding the kinetics of the hydromagnesite (5424)-magnesite reaction based on the hydromagnesite (4323) present in the Kozani Basin are applicable to the conversion of the hydromagnesite (5424) produced in WIPP-relevant laboratory experiments.

Stamatakis (1995) reported various ages or ranges of ages for the huntite-hydromagnesite deposits in the Kozani Basin. He referred to the sedimentary rocks that host these deposits as "late Neogene" and, on two occasions, "uppermost Neogene." He referred to the alkaline, saline, spring-fed lakes, and ponds from which these evaporite deposits precipitated as "Tertiary to Recent" and "Neogene." He did not provide any absolute (radiometric) ages for these deposits.

According to the current geologic time scale established by the International Commission on Stratigraphy, the Neogene Period has lasted from 23.03 million years ago to the present (Gradstein et al. 2005). Therefore, the ages Neogene, late Neogene, uppermost Neogene, and Tertiary to Recent do not place a lower limit on the possible range of ages of these deposits, especially in the absence of absolute (radiometric or astronomical) ages. Furthermore, the description of the deposits provided by Stamatakis (1995) is consistent with a postdepositional origin for at least some of the deposits. Therefore, it is not clear that the hydromagnesite there has persisted longer than expected based on the results of Zhang et al. (1999).

The hydromagnesite in the huntite-hydromagnesite deposits of the Kozani Basin is hydromagnesite (4323). Zhang et al. (1999) used hydromagnesite (5424) in their study on the conversion of hydromagnesite to magnesite. Therefore, any conclusions regarding the rate of the hydromagnesite-to-magnesite reaction based on the hydromagnesite (4323) present in the Kozani Basin do not apply to the conversion of the hydromagnesite (5424) used by Zhang et al. (1999) and observed in the laboratory experiments with Premier Chemicals MgO.

MgO-4.2.3 Possible Passivation of MgO in the WIPP

Laboratory studies on the carbonation of MgO were carried out to determine if (1) MgO would rapidly neutralize the mildly acidic brines that would form if microbial consumption of CPR materials in WIPP disposal rooms produces significant quantities of CO_2; and (2) reaction rims would form on periclase and prevent this phase from effectively consuming all of the CO_2 that could be produced by microbial consumption of CPR materials (Sandia National Laboratories 1997). A literature review on the formation of dolomite and magnesite in the natural environment, laboratory studies on the formation of magnesite to determine the timescale on which hydromagnesite (5424) would convert to magnesite, and the results of this activity are described above (Sandia National Laboratories 1997 and Section MgO-4.2.2). It was demonstrated that MgO would rapidly neutralize mildly acidic solutions; therefore, the remainder of this discussion focuses on whether reaction rims would form on periclase and prevent this phase from consuming CO_2 (Sandia National Laboratories 1997, Section 3.2, p. 7 and Figure 3-1, p. 8).

Short-term "scoping" experiments were carried out by placing MgO pellets in beakers containing Salado or Castile brine and bubbling CO_2 through them for "less than a week." (See Sandia National Laboratories 1997, Section 3.2, p. 7.) The report states:

> To provide as much latitude as possible in final materials selection, a material that had undergone calcination at the higher end of the [temperature] range was chosen for testing. Because reactivity typically decreases with increasing calcination temperature, selection of a material at the upper end of the range will provide a worst case.

XRD analysis indicated that nesquehonite and hydromagnesite (polymorph unspecified) rapidly formed on the surfaces of the pellets, and "After a few days of treatment, these layers coalesced to cement the pellets together." SEM analysis "suggested the presence of other phases as well." (See Sandia National Laboratories 1997, Section 3.2, p. 7)

Longer-term "final" experiments were also carried out (Sandia National Laboratories 1997, Section 3.3.1 and Section 3.3.2, pp. 7-13). The primary objective of these experiments was "to demonstrate that the formation of [Mg] carbonate surface coatings, if any, do not impact the efficacy of the MgO backfill enough to impede the backfill's ability to function as conceptualized within the CCA PA." A secondary objective was "to demonstrate that after coatings form the MgO remaining inside the pellet will still be reasonably accessible to the outside brine" (Sandia National Laboratories 1997, Section 3.3.1, p. 7). In the first set of these longer-term experiments, about 8 g of 1- to 2-mm-diameter MgO pellets were placed in beakers containing 250 mL of Salado or Castile brine and pure CO_2 was bubbled through the beakers for up to 28 days, during which individual pellets were analyzed for their C content with a C coulometer. In a larger, follow-on set of experiments, 0.5- to 1-mm and 2- to 4-mm-diameter pellets were placed in beakers containing 100 mL of Salado or Castile brine. Manifolds were used to bubble pure CO_2 through brines for up to 28 days, during which "the entire charge" was removed from the beakers and analyzed for its C content. In the follow-up experiments, triplicate experiments were run for every reaction time at which the C content was analyzed, and triplicate C analyses were carried out on the solids in every beaker.

In addition, "tea-bag" experiments were conducted, in which MgO pellets (size unspecified) were placed in porous bags about the size of a tea bag, the bottom third of the bags were immersed in Salado or Castile brine, and pure CO_2 bubbled through the brines for periods of 3-85 days. During these experiments, brine wicking moistened all of the pellets in these bags (Sandia National Laboratories 1997, Section 3.3.2, p. 14).

"Carbonation curves" (plots of the conversion of their solids to Mg carbonates versus time) that were "S-shaped" were reported (Sandia National Laboratories 1997, Section 4, pp. 17-18). The data showed (1) "an initial incubation period of slow [CO_2] uptake, which is probably preceded by a short period [during which] MgO actually dissolves to saturate the solution" and during which the surfaces of the pellets hydrate to form brucite; (2) "a period of accelerated [CO_2] uptake during which the [CO_2] content of the samples increases by several percent … in a few days"; and (3) "a long period [during which] the [CO_2] uptake rate is much slower than earlier in the test, though the process does not seem to completely stop." The incubation period was correlated to dissolution of the MgO pellets, formation of a thin layer of brucite on the pellets, and formation of "an incipient [Mg] carbonate phase … consisting of fine platy crystals," possibly "protohydromagnesite." (See Sandia National Laboratories 1997, Section 4.2, pp. 20-

29.) The period of rapid CO_2 uptake was correlated with the formation of nesquehonite needles, both on the surfaces of the pellets exposed to the brines and in the pores among the pellets. Finally, the final period of slower CO_2 uptake was correlated with reduced access of the brines to the pores caused by intergrowth of the nesquehonite needles and concomitant cementation of the pellets. However, cementation did not stop the carbonation of the pellets, even in the pores. Furthermore, "exfoliation" of nesquehonite and formation of protohydromagnesite or magnesite platy crystals was observed, possibly at the expense of nesquehonite (see Section MgO-4.2.1). Both of these processes would promote continued, albeit reduced, access of brine to the pores.

It was pointed out that, although "isolating reaction rims at high extents of conversion (15-30 mol %) were not observed," the lower values of f_{CO_2} expected in WIPP disposal rooms would result in a lower concentration gradient of dissolved CO_2-bearing species from the brine to the surfaces of the MgO pellets, which would in turn localize the precipitation of Mg carbonates in the brines instead of on the surfaces of the pellets (see Sandia National Laboratories 1997, Section 5.1, pp. 30-32, and especially Figure 5-1). The experiments bubbled pure CO_2 through their brines (Sandia National Laboratories 1997, Section 3.3.2, pp. 8-14). This, in turn, established values of f_{CO_2} in the brines that were orders of magnitude greater than those expected in the repository, currently from 3.14×10^{-6} atm (both GWB and ERDA-6) down to 1.20×10^{-7} atm (GWB) or 1.23×10^{-7} atm (ERDA-6), the values characteristic of the brucite-hydromagnesite (5425) and the brucite-magnesite carbonation reactions (see Section MgO-5.1).

In addition to the laboratory experiments described above, MgO was added to one of the liter-scale experiments (L-28) in the WIPP Source Term Test Program (STTP) with actual TRU waste (Villarreal, Bergquist, and Leonard 2001a and 2001b; Villarreal, King, and Leonard 2001; Villarreal et al. 2001). (The STTP comprised 39 L-scale and 15 drum-scale experiments.) Because the dissolved plutonium (Pu) concentration in L-28 increased after the addition of MgO, the New Mexico Environmental Evaluation Group cited this experiment as an example of the inefficacy of MgO, possibly because of passivation (Oversby 2000). The experiment in L-28 was carried out at a CO_2 pressure of 60 bars, 7 orders of magnitude higher than that expected in the WIPP (from 3.14×10^{-6} atm down to 1.20×10^{-7} atm; see Section MgO-5.1). The partial pressure of CO_2 in the WIPP will not exceed 3.14×10^{-6} atm because the rate of CO_2 consumption by the periclase and brucite in MgO is much higher than the microbial CO_2 production rate. Therefore, the conditions in L-28 were not representative of those expected in the WIPP, and the results are irrelevant to the WIPP (Brush, Moore, and Wall 2001).

Bryan and Snider (2001b, p. 5-9) and Snider (2002, pp. 3.1 through 3.15) conducted a series of "cemented-cake" experiments to determine whether lithification of MgO will occur in the WIPP and, if so, whether it would affect the rate of MgO hydration. For the experiments, 15, 30, or 45 g of Premier Chemicals MgO were placed in 125-mL plastic containers with ERDA-6 brine or GWB. This resulted in a 5-, 10-, or 15-mm thick layer of Premier Chemicals MgO at the bottom of the containers. The containers were then placed in ovens at 25, 50, 70, or 90 ºC (77, 122, 158, or 194 ºF) for periods of up to about 6 months. They were not agitated. (Agitation apparently prevented any lithification of MgO in their other inundated experiments.) Snider (2002, Figure 12, Figure 13, and Figure 14) reported results from cemented-cake experiments that lasted for periods of about four to six months. She observed lithification of some samples; however, others remained "very friable," even after inundation at 70 and 90 ºC (Snider 2002, p. 3.1 through 3.15). Snider (2002, p. 3.13) had "anticipated that the thicker layers would hydrate

at a slower rate," especially if lithification occurred. However, "MgO thickness has not affected the hydration rate under inundated conditions in ERDA-6 brine (Figure-12)" (Snider 2002, p. 3.1 through 3.13); and "in GWB at 50, 70, and 90 ºC (Snider 2002, Figure 13) thickness does not affect hydration" (Snider 2002, p. 3.1 through 3.15). Furthermore, the 5-mm-thick samples in GWB at 25 ºC (77 ºF) hydrated at the slowest rate, the 15-mm-thick samples hydrated at an intermediate rate, and the 10-mm-thick samples hydrated at the fastest rate (Snider 2002, Figure 13). Therefore, these experiments showed that lithification might occur, but, if it does, it will not decrease the MgO hydration rate.

The results obtained all imply that the periclase in MgO and the brucite that forms from the hydration of this periclase will be available to react, and will continue to react, until all CO_2 in the repository has been consumed (Sandia National Laboratories (1997), Bryan and Snider (2001b), and Snider (2002)). Nevertheless, Brush and Roselle (2006, Section 5.1 and Section 5.2) carried out a literature search for anthropogenic or natural analogs or experimental studies that provide insight into whether hydration of periclase to form brucite, and carbonation of brucite to form hydromagnesite and magnesite, will proceed to completion if H_2O or CO_2, respectively, are present in the repository. The literature they found included studies of several different types of chemical and geochemical systems:

1. Hydration of periclase in Portland cement

2. Hydration of periclase in magnesia sinters

3. Hydration of periclase formed in contact-metamorphosed dolomite and Mg-bearing limestone

4. Laboratory studies of periclase hydration in metamorphic rocks formed at high pressures and temperatures (these conditions are far from those expected in the WIPP, but provide valuable insight because of the challenges involved in preventing periclase hydration during and after "quenching" these experiments to ambient laboratory conditions)

5. Field studies of brucite carbonation during serpentinization of ultramafic rocks and the weathering of the resulting serpentinites

6. The use of brucite to scrub CO_2 from the smokestacks of power plants, or for deep-geologic sequestration of CO_2

7. The weathering of an approximately 4,000-year-old statue carved from a rock known as predazzite, a brucite- or periclase-bearing limestone marble

The results of these anthropogenic- and natural-analog studies all imply that the periclase in the MgO engineered barrier and the brucite that forms from the hydration of this periclase will be available to react—and will continue to react—until all the CO_2 in the repository has been consumed.

MgO-5.0 Effects of MgO on the WIPP Disposal System

This section reviews the effects of MgO on (1) brine composition, f_{CO_2}, pH, and An solubilities, including changes since the CRA-2004 (Section MgO-5.1); (2) colloidal An concentrations (Section MgO-5.2); (3) other near-field processes and conditions, including repository H_2O content, gas generation, and room closure (Section MgO-5.3); and (4) far-field An transport (Section MgO-5.4).

MgO-5.1 Effects of MgO on Brine Composition, f_{CO_2}, pH, and Actinide (An) Solubilities

The DOE is emplacing MgO in the WIPP to decrease the solubilities of the An elements in TRU waste by consuming all the CO_2 that would be produced by microbial activity should all the CPR materials in the repository be consumed. Consumption of CO_2 will decrease An solubilities by (1) buffering f_{CO_2} at a low value or within a low range of values, (2) maintaining a mildly basic pH, and (3) preventing the production of significant carbonate ion (CO_3^{2-}) quantities.

The effects of MgO carbonation have been included in WIPP PA by removing CO_2 from the gaseous phase in BRAGFLO calculations, and using the values of f_{CO_2} and pH predicted for reactions among MgO, brine, and aqueous or gaseous CO_2 to calculate An solubilities.

Table MgO-6 provides the initial compositions of GWB and ERDA-6 brine and their compositions predicted by FMT for the An-solubility calculations for the CRA-2004 PABC (Brush and Xiong 2005a; 2005b; Brush 2005) after equilibration with (1) the MgO hydration and carbonation products brucite ($Mg(OH)_2$) and hydromagnesite (5424), respectively; (2) halite (NaCl) and anhydrite ($CaSO_4$), two of the most abundant minerals in the Salado; and (3) the An-bearing solids $Am(OH)_3$; hydrous, amorphous ThO_2; and $KNpO_2CO_3$. In addition to these solids, which are specified in the input files, FMT predicted that (1) the solids $Mg_2(OH)_3Cl{\cdot}4H_2O$ and whewellite (Ca oxalate hydrate, or $CaC_2O_4{\cdot}H_2O$) would precipitate from GWB; and (2) glauberite ($Na_2Ca(SO_4)_2$) and whewellite would precipitate from ERDA-6 brine if these brines equilibrate with brucite, hydromagnesite (5424), halite, and anhydrite. Note that, although FMT predicted that $Mg_2(OH)_3Cl{\cdot}4H_2O$ would precipitate from GWB, $Mg_3(OH)_5Cl{\cdot}4H_2O$ has been observed in experiments with GWB (see Section MgO-4.1.1 and Figure MgO-3X). Note also that because these calculations were performed for the CRA-2004 PABC, oxalate (and other organic ligands) were added to these brines, which resulted in the prediction that whewellite would precipitate.

FMT predicts equilibration of these brines with the solids listed above will (1) establish a total inorganic C (TIC) concentration of 0.350 millimolar (mM) in GWB, and decrease the TIC concentration from 16 to 0.428 mM in ERDA-6 brine; (2) buffer f_{CO_2} at 3.14×10^{-6} atm in both brines; and (3) establish a pH of 8.69 in GWB and increase the pH from 6.17 to 8.94 in ERDA-6 brine.

Equilibration of GWB and ERDA-6 brine with these solids will also change the concentrations of the major and other minor elements in these brines. In particular, the concentration of Mg in

GWB will decrease from 1.02 to 0.578 M, but will increase from 0.019 to 0.157 M in ERDA-6 brine (Table MgO-6).

Table MgO-6. Compositions of GWB and ERDA-6 Brine Predicted by FMT for the An-Solubility Calculations for the CRA-2004 PABC (Brush and Xiong 2005a; 2005b; Brush 2005) (M, Unless Otherwise Noted) before and after Equilibration with Brucite, Hydromagnesite, Halite, Anhydrite, and Other Solids

Element or Property	GWB before Reaction with Solids[a]	GWB after Reaction with Solids[b]	ERDA-6 Brine before Reaction with Solids[c]	ERDA-6 Brine after Reaction with Solids[d]
B(III)(aq)	0.158	0.166	0.063	0.0624
Na(I)(aq)	3.53	4.35	4.87	5.24
Mg(II)(aq)	1.02	0.578	0.019	0.157
K(I)(aq)	0.467	0.490	0.097	0.0961
Ca(II)(aq)	0.014	0.00895	0.012	0.0107
S(VI)(aq)	0.177	0.228	0.170	0.179
Cl(-I)(aq)	5.86	5.38	4.8	5.24
Br(-I)(aq)	0.0266	0.0278	0.011	0.0109
TIC	—	0.350 mM	16 mM	0.428 mM
Ionic strength	—	7.66 m	—	6.80 m
f_{CO_2} (atm)	—	3.14×10^{-6}	—	3.14×10^{-6}
pH	—	8.69	6.17	8.94
RH	—	0.732	—	0.748
Specific gravity	1.2	1.23	1.216	1.22

[a] From Krumhansl et al. (1991) and Snider (2003c).
[b] FMT Run 7 (Brush and Xiong 2005a; 2005b; Brush 2005).
[c] From Popielak et al. (1983).
[d] FMT Run 11 (Brush and Xiong 2005a; 2005b; Brush 2005).

Table MgO-7 and Table MgO-8 show the effects of the Mg-carbonate solid produced by the carbonation of brucite on the TIC concentration, f_{CO_2}, pH, and the solubilities of An elements in the III, IV, and V oxidation states (An(III), An(IV), and An(V)) in GWB and ERDA-6 brine, respectively. Brush and Xiong (2003a; 2003b; 2003c; 2003d) carried out this sensitivity study as part of the An speciation and solubility calculations for the CRA-2004 PA. These calculations were superseded by those conducted for the CRA-2004 PABC (Brush and Xiong 2005a; 2005b; Brush 2005), which are now part of the WIPP PA baseline. However, Brush and Xiong (2005a, 2005b) and Brush (2005) did not redo this sensitivity study for the CRA-2004 PABC. Therefore, Table MgO-7 and Table MgO-8 provide the results from the CRA-2004 PA, along with the results of the CRA-2004 PABC Runs 7 and 11, respectively (fourth column of Table MgO-7 and Table MgO-8). Runs 7 and 11 were also used for the CRA-2009 PA. Comparison of the CRA-2004 PA results in the third column of Table MgO-7 and Table MgO-8 with the CRA-2004

Table MgO-7. Effect of the Mg-Carbonate Solid on the f_{CO_2} (atm), TIC Concentration (M), pH (Standard Units), and An Solubilities (M) in GWB after Equilibration with Brucite, Halite, Anhydrite, and Other Solids

Element or Property	Magnesite[a]	Hydro-magnesite$_{5424}$[b]	Hydro-magnesite$_{5424}$[c]	Hydro-magnesite$_{4323}$[d]	Nesquehonite[e]
f_{CO_2}	1.20×10^{-7}	3.14×10^{-6}	3.14×10^{-6}	4.08×10^{-6}	1.42×10^{-4}
TIC	1.36×10^{-5}	3.50×10^{-4}	3.50×10^{-4}	4.56×10^{-4}	1.59×10^{-2}
pH	8.69	8.69	8.69	8.69	8.69
An(III)	3.06×10^{-7}	3.07×10^{-7}	3.87×10^{-7}	3.07×10^{-7}	2.12×10^{-6}
An(IV)	1.17×10^{-9}	1.19×10^{-8}	5.64×10^{-8}	1.52×10^{-8}	5.68×10^{-7}
An(V)	2.37×10^{-5}	1.02×10^{-6}	3.55×10^{-7}	8.06×10^{-7}	2.28×10^{-7}

[a] CRA-2004 PA Run 14 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[b] CRA-2004 PA Run 18 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[c] CRA-2004 PABC Run 7 (Brush and Xiong 2005a; 2005b; Brush 2005).
[d] CRA-2004 PA Run 16 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[e] CRA-2004 PA Run 20 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).

Table MgO-8. Effect of the Mg-Carbonate Solid on the f_{CO_2} (atm), TIC Concentration (M), pH (Standard Units), and An Solubilities (M) in ERDA-6 Brine after Equilibration with Brucite, Halite, Anhydrite, and Other Solids

Element or Property	Magnesite[a]	Hydro-magnesite$_{5424}$[b]	Hydro-magnesite$_{5424}$[c]	Hydro-magnesite$_{4323}$[d]	Nesquehonite[e]
f_{CO_2}	1.23×10^{-7}	3.14×10^{-6}	3.14×10^{-6}	4.08×10^{-6}	1.36×10^{-4}
TIC	1.87×10^{-5}	4.68×10^{-4}	4.28×10^{-4}	6.08×10^{-4}	2.00×10^{-2}
pH	9.02	9.02	8.94	9.02	9.00
An(III)	1.68×10^{-7}	1.69×10^{-7}	2.88×10^{-7}	1.70×10^{-7}	5.45×10^{-7}
An(IV)	1.72×10^{-9}	2.47×10^{-8}	6.79×10^{-8}	3.19×10^{-8}	1.01×10^{-6}
An(V)	1.19×10^{-4}	5.08×10^{-6}	8.24×10^{-7}	4.00×10^{-6}	1.10×10^{-6}

[a] CRA-2004 PA Run 24 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[b] CRA-2004 PA Run 28 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[c] CRA-2004 PABC Run 11 (Brush and Xiong 2005a; 2005b; Brush 2005).
[d] CRA-2004 PA Run 26 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).
[e] CRA-2004 PA Run 30 (Brush and Xiong 2003a; 2003b; 2003c; 2003d).

PABC results in the fourth column shows that the TIC concentration, log f_{CO_2}, and pH predicted for GWB by the CRA-2004 PA and PABC calculations are identical to three significant figures. The TIC content, log f_{CO_2}, and pH predicted for ERDA-6 by the CRA-2004 PA and PABC calculations are not identical, but are similar. The An(III), An(IV), and An(V) solubilities predicted for the CRA-2004 PA and PABC calculations are different for both brines because of changes in the thermodynamic databases for the An(III), An(IV), and An(V) models between these calculations. Although the CRA-2004 PA results were not part of the WIPP PA baseline,

the results of this sensitivity study still provide a reasonably accurate assessment of the effects of the Mg carbonate formed in the WIPP.

Table MgO-7 and Table MgO-8 show that both the TIC content and the f_{CO_2} predicted for each Mg-carbonate solid increase by about three orders of magnitude from magnesite to hydromagnesite (5424), to hydromagnesite (4323), to nesquehonite. This is because magnesite is the thermodynamically stable Mg carbonate under expected WIPP conditions; hydromagnesite (5424) is metastable with respect to magnesite, hydromagnesite (4323) is metastable with respect to hydromagnesite (5424), and nesquehonite is metastable with respect to hydromagnesite (4323). The brucite carbonation Reactions (MgO.8), (MgO.7), as well as

$$4Mg(OH)_2(s) + 3CO_2(aq \text{ or } g) \rightleftharpoons Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O(s), \text{ and} \qquad \text{(MgO.10)}$$

$$Mg(OH)_2(s) + 2H_2O(aq \text{ or } g) + CO_2 \text{ (aq or g)} \rightleftharpoons MgCO_3 \cdot 3H_2O(s), \qquad \text{(MgO.11)}$$

would buffer f_{CO_2} at values of 1.20×10^{-7} atm (Reaction [MgO.8]) to 1.42×10^{-4} atm (Reaction [MgO.11]) in GWB (Table MgO-7), or 1.23×10^{-7} atm (Reaction [MgO.8]) to 1.36×10^{-4} atm (Reaction [MgO.11]) in ERDA-6 brine (Table MgO-8), depending on which of these reactions is dominant. The TIC concentrations corresponding to these fugacities would be 1.36×10^{-5} M (Reaction [MgO.8]) to 1.59×10^{-2} M (Reaction [MgO.11]) in GWB (Table MgO-8), or 1.87×10^{-5} M (Reaction [MgO.8]) to 2.00×10^{-2} M (Reaction [MgO.11]) in ERDA-6 brine (Table MgO-8).

Although nesquehonite was observed in some of the DOE's carbonation experiments with Premier Chemicals MgO (Section MgO-4.2.1), hydromagnesite (5424) was clearly replacing nesquehonite as these experiments proceeded (Section MgO-4.2.1). Therefore, carbonation of brucite to form hydromagnesite (5424) (Reaction [MgO.7]) will be the dominant carbonation reaction for at least part of the 10,000-year regulatory period (the first few hundred to few thousand years). The DOE has not observed the formation of hydromagnesite (4323), and has not observed magnesite, except in some accelerated experiments (e.g., Zhang et al. 1999; Zhang, Hardesty, and Papenguth 2001). However, these accelerated experiments (and other considerations) imply that carbonation of brucite to form magnesite (Reaction [MgO.8]) will be the dominant carbonation reaction for much, if not most, of the 10,000-year regulatory period (Section MgO-4.2.3). Therefore, f_{CO_2} would be 3.14×10^{-6} atm in the WIPP initially while hydromagnesite (5424) is the dominant Mg carbonate, but would decrease to $(1.20\text{-}1.23) \times 10^{-7}$ atm as magnesite replaces hydromagnesite (5424) and becomes dominant. Similarly, the TIC concentration would be about $(3.50\text{-}4.28) \times 10^{-4}$ M initially, but would decrease to about $(1.36\text{-}1.87) \times 10^{-5}$ M.

Appendix SOTERM-2009, Section SOTERM-2.3.2 describes how MgO will control the pH of brines in WIPP disposal rooms.

MgO-5.1.1 Changes Since the CRA-2004 in Effects of MgO on Brine Composition, f_{CO_2}, pH, and Actinide (An) Solubilities

This section describes the two changes in the predicted effects of MgO on chemical conditions in the WIPP since the CRA-2004: MgO-5.1.1.1 describes the elimination of chemical conditions

predicted for nonmicrobial PA vectors, and MgO-5.1.1.2 discusses the substitution of GWB for Brine A.

The reduction of the MgO excess factor that was approved by the EPA since the CRA-2004 will not affect chemical conditions in the WIPP. Therefore, it is described in Section MgO-6.2.4.

MgO-5.1.1.1 Elimination of Chemical Conditions for Nonmicrobial Vectors

There are large uncertainties as to whether significant microbial consumption of the CPR materials emplaced in the WIPP will occur during the 10,000-year WIPP regulatory period. Therefore, Brush (1995) assumed that "significant microbial consumption of CPR materials is possible, but by no means certain." To incorporate these uncertainties in the CCA PA and PAVT, Wang and Brush (1996a and 1996b) developed a conceptual model for microbial activity in the repository. According to this model, there is a probability of 0.50 for significant microbial activity. In the event of significant microbial activity, microbes could consume 100% of the cellulosic materials in the repository. Furthermore, there is a conditional probability of 0.50 that microbes could consume all of the plastic and rubber materials after consumption of all of the cellulosic materials. Thus, in the CCA PA and PAVT, there was no microbial activity in about 50% of the PA realizations (vectors); microbes could consume all of the cellulosic materials, but no plastic or rubber materials, in about 25% of the vectors; and microbes could consume all of the CPR materials in the remaining ~25% of the vectors. (Note that even if significant microbial activity could occur in a vector, microbes did not necessarily consume 100% of the cellulosic materials or 100% of the CPR materials because the quantities of these materials that the PA code BRAGFLO predicted would be consumed depended on several sampled parameters.) This conceptual model for microbial activity was also used in the CRA-2004 PA.

For the CCA PA and PAVT, it was assumed that the chemical conditions in WIPP disposal rooms would be identical whether or not significant microbial activity and gas generation occur. (See Brush and Xiong 2003c, Section 5, for a detailed review of how near-field chemical conditions were predicted for the CCA PA and PAVT.) For the CRA-2004 PA, however, Brush and Xiong (2003c, Section 5.3.2) concluded that, for the vectors without microbial activity, the reaction that would buffer f_{CO_2} is

$$Mg(OH)_2(s) + Ca^{2+}(aq) + CO_2(aq \text{ or } g) \rightleftharpoons CaCO_3(s) + Mg^{2+}(aq) + H_2O(aq \text{ or } g) \quad \text{(MgO.12)}$$

not the brucite-hydromagnesite (5424) carbonation reaction (Reaction [MgO.7]) (Section MgO-4.2.1 and Section MgO-5.1).

Brush and Xiong (2003a) used FMT to establish chemical conditions for the nonmicrobial vectors in the CRA-2004 PA that were slightly different than those calculated for the microbial vectors. They calculated that the f_{CO_2} would be 3.31×10^{-6} and 7.08×10^{-7} atm in GWB and ERDA-6 brine, respectively, for the nonmicrobial vectors; and 3.14×10^{-6} atm in both brines for the microbial vectors. They also predicted that the pH would be 8.69 and 8.99 in GWB and ERDA-6 brine, respectively, for the nonmicrobial vectors and 8.69 and 9.02 for the microbial vectors. Despite these differences, Brush and Xiong (2003a, Table 7) calculated An solubilities that were nearly identical for the nonmicrobial and microbial vectors in most cases. The only exceptions were the solubilities of An(IV) in ERDA-6 brine (5.84×10^{-9} M for the nonmicrobial

and 2.47×10^{-8} M for the microbial vectors) and An(V) in ERDA-6 brine (2.13×10^{-5} M in the nonmicrobial and 5.08×10^{-6} M in the microbial vectors).

During its completeness review of the CRA-2004 PA, however, the EPA (Cotsworth 2005, Enclosure 1, p. 1) stated

> In the CRA performance assessment [the CRA-2004 PA], DOE assumes that the probability that microbial degradation will occur and thus produce significant gas is 50 percent [*sic*]. However, based on our review to date, including DOE's response to EPA comments …, EPA believes that there are reasonable alternative interpretations to DOE's responses. It is EPA's position that microbes will survive over the regulatory period and be able to produce some gas, albeit with the possibility that sometimes the resulting gas generation rate may be low or near zero. The revised performance assessment [the CRA-2004 PABC] must implement a change so that the modeled probability of microbial degradation is 1. DOE may propose different ranges of gas production or microbe effectiveness as long as it is supported by data…

To incorporate this change in the CRA-2004 PABC, there is now a probability of 1 that significant microbial activity could occur and that microbes could consume 100% of the cellulosic materials in the repository. Furthermore, there is a probability of 0.25 that microbes could consume all of the CPR materials. Therefore, microbes could consume all of the cellulosic materials, but no plastic or rubber materials, in about 75% of the vectors; and microbes could consume all of the CPR materials in the remaining ~25% of the vectors. The microbial gas generation model for the CRA-2004 PABC is the one used for CRA-2009.

The separate chemical conditions established for the nonmicrobial vectors were used only once in WIPP PA, for the CRA-2004 PA (the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.2.4; the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-2.2.2 and Section SOTERM-3.5).

MgO-5.1.1.2 Substitution of GWB for Brine A

Brush and Xiong (2003c, Section 5.3.1) proposed to the EPA that GWB (Krumhansl et al. 1991; Snider 2003c) be substituted for Brine A (Molecke 1983) in future An speciation and solubility calculations for WIPP PA because "this brine resembles the average composition of intergranular Salado brines at or near the stratigraphic horizon of the WIPP more closely than Brine A." The synthetic solution Brine A was used extensively for laboratory and modeling studies of WIPP chemistry (e.g., Brush 1990; Brush 1996; Brush and Storz 1996) prior to the establishment of GWB as a more representative Salado brine (Krumhansl, Kimball, and Stein 1991; Snider 2003c).

For the CRA-2004, Brush and Xiong (2003a) calculated chemical conditions and An solubilities in both Brine A and GWB, as well as in ERDA-6 brine (used to represent fluids from Castile brine reservoirs). The conditions and solubilities predicted for Brine A and GWB were very similar, as were those predicted for Brine A or GWB and ERDA-6 brine. The solubilities calculated in GWB were used for the CRA-2004 PA (the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-3.5).

The EPA approved the use of GWB for An-solubility calculations for WIPP PA (U.S. Environmental Protection Agency 2006). Therefore, the conditions predicted for GWB in WIPP

disposal rooms are now considered the baseline conditions for Salado brine. The solubilities calculated in GWB were used for the CRA-2004 PABC (Leigh et al. 2005) and the CRA-2009 PA.

MgO-5.2 Effects of MgO on Colloidal Actinide (An) Concentrations

This section is based on the text in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.3.

Colloids could affect the long-term performance of the WIPP because of their potential ability to bind cationic metals such as the An elements in TRU waste, and because of their potential mobility under expected repository conditions (Choppin 1988). Colloids are typically defined as phases intermediate in size between dissolved ionic or molecular species and suspended particles large enough to settle by gravity. The size range of colloids is typically on the order of 1 nanometer to 1 μm.

Humic substances, microbes, and mineral fragments could bind An elements in the WIPP. Under some conditions, An elements could also form intrinsic colloids without binding to humics, microbes, or minerals. Even if one or more of these four types of colloids form(s) in the WIPP, they would not transport An elements out of the repository unless they remain suspended in brine. If coagulation occurs, any An elements bound to these colloids would be immobilized, at least with respect to direct brine releases or injection of brine into the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra).

Chemical conditions in the repository will affect the colloidal An source term. The small variations in pH within the narrow range imposed by MgO will not affect the concentrations of An-bearing colloids significantly. Studies carried out to quantify the colloidal source term included experiments under the conditions that will be established by MgO (the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-6.0 and Appendix SOTERM-2009).

MgO-5.2.1 Results since the CRA-2004

The results of Wall and Matthews (2005) imply that colloids formed by the association of actinides and humic substances are highly unstable in the presence of MgO, and that these colloids dissociate rapidly (i.e., within hours).

MgO-5.3 Effects of MgO on Other Near-Field Processes and Conditions

Section MgO-5.3.1, Section MgO-5.3.2, and Section MgO-5.3.3 are based on the text in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.4.1, Section BARRIERS-2.3.4.2, and Section BARRIERS-2.3.4.3.

MgO-5.3.1 Effects of MgO on Repository H_2O Content

The hydration of periclase could consume significant quantities of H_2O in the WIPP (Reaction [MgO.6]). The carbonation of brucite to form hydromagnesite (5424) (Reaction [MgO.7]) or, less likely, hydromagnesite (4323), will not release this H_2O unless hydromagnesite (5424) or (4323) goes on to form magnesite. Furthermore, even if large quantities of magnesite form

during the 10,000-year regulatory period (Reaction [MgO.8]), there will still be large quantities of periclase available for hydration because the DOE is emplacing more MgO than necessary to consume all the CO_2 that would be produced by microbial activity should all the CPR materials in TRU waste and waste containers be consumed.

MgO hydration is not included in PA at this time.

MgO-5.3.2 Effects of MgO on Gas Generation

The two gas-producing processes included in WIPP PA are anoxic corrosion of steels and other Fe-base alloys, which will produce H_2, and microbial consumption of CPR materials, which will produce mainly CO_2, hydrogen sulfide (H_2S), and methane (CH_4).

MgO-5.3.2.1 Gas Generation from Anoxic Corrosion

Telander and Westerman (1993 and 1997) studied anoxic corrosion of various metals and concomitant H_2 production under expected WIPP conditions. Wang and Brush (1996a and 1996c) used results from three types of experiments carried out by Telander and Westerman (1993 and 1997) to establish ranges and probability distributions of H_2 production rates for the CCA PA:

1. Experiments with low-C steels in or above Brine A under atmospheres consisting of initially pure CO_2, nitrogen (N_2), or hydrogen sulfide (H_2S) in inert (noncorroding), metallic containers at low-to-intermediate pressures (about 1 to 20 atm).

2. Experiments with low-C steels in Brine A under H_2, CO_2, or N_2 in autoclaves at high pressures (35 to 127 atm).

3. Runs with low-C steels in ERDA-6 brine at pH values of 2.8 to 10.6 under N_2. All these experiments were conducted at 30 ± 5 ºC (86 ± 9 ºF). Brine A and ERDA-6 brine are described above (Section MgO-4.1.1)

Anoxic corrosion of low-C steels in Brine A under initially pure N_2 resulted in a pH of 8.3, 8.3, and 8.4 after 6, 12, and 24 months, respectively (see Telander and Westerman 1993, Table 6-3, Test Containers 10, 17, and 25). Wang and Brush (1996a; 1996c) used the 12-to-24-month data from these experiments to establish a range and probability distribution of inundated, anoxic-corrosion rates of steels and other Fe-base alloys of 0 to 0.5 μm/year for the CCA PA. This is equivalent to a range of $(0\text{-}1.59) \times 10^{-14}$ meters per second (m/s). Data on the effects of pH on corrosion rates (Telander and Westerman 1997, Table 6-5) have demonstrated that rates obtained at a pH of 8.3 or 8.4 are somewhat higher than those at a pH of 8.69, 8.99, or 9.02, the values expected for the brucite dissolution reaction (see Reaction [MgO.3], above). Therefore, the anoxic-corrosion rates established by Wang and Brush (1996a and 1996c) for the CCA incorporated the effects of MgO on pH.

For the CCA PAVT, the EPA specified that the upper limit of the inundated anoxic-corrosion rate range be increased from 1.59×10^{-14} m/s to 3.17×10^{-14} m/s (Trovato 1997b, Enclosure 2; U.S. Environmental Protection Agency 1998e, Table ES-4, Section 5.15, and Table 6.3 and

Table 6.4; Hansen and Leigh 2003). A range of (0-3.17) × 10^{-14} m/s was also used for the CRA-2004 PA (CRA-2004, Appendix PA, Section PA-5.2) and the CRA-2004 PABC (Leigh et al. 2005).

MgO-5.3.2.2 Microbial Gas Generation

Francis and Gillow (1994 and 2000), Francis, Gillow, and Giles (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b, and 2003) did not include MgO or the effects of pH in their study of microbial gas generation under expected WIPP conditions. Instead, they included bentonite in about half of their experiments because a backfill consisting of 70 wt % crushed salt and 30 wt % bentonite had been proposed as an alternative to a backfill consisting entirely of crushed salt, the design-basis backfill in January 1992 when these microbial gas-generation experiments were started. No microbial experiments have been carried out with MgO since the use of this material to consume CO_2 and control f_{CO_2} and pH in the WIPP was proposed in 1996.

Dissolution of brucite (Section MgO-5.1, Reaction [MgO.11]) will prevent the pH of any brine present from decreasing below a value of about 9. This mildly basic value is somewhat higher than the mildly acidic pH values produced by dissolution of microbial CO_2 in the experiments described by Francis and Gillow (1994 and 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b, and 2003). However, emplacement of MgO in the WIPP and a consequent, mildly basic pH of 9 will not in and of itself preclude significant microbial activity in the repository. This conclusion is based on the common observation of viable alkalohalophilic microbes in alkaline lakes with pH values of 9 to 10. Such alkaline lakes occur frequently in arid and semiarid environments, such as southeastern New Mexico and adjacent areas of west Texas, and could be one source of the halophilic microbes observed in the WIPP. However, several investigators have reported that MgO and compounds derived from MgO possess inhibitory or even biocidal properties (Asghari and Farrah 1993; Chapman et al. 1995; Koper et al. 2002; Sawai 2003; Sawai et al. 1995a, 1995b, 1996, 2000a, and 2000b; Stoimenov et al. 2002; Yamamoto et al. 1998). Some of the results of these studies may be applicable to the WIPP.

First, the inhibitory or biocidal effects of MgO probably result from the presence of brucite, not periclase (Sawai et al. 1995a), because most of the experiments cited above were conducted in aqueous solutions or in growth media that contained H_2O, and most of these experiments were long enough for significant nucleation and growth of brucite on periclase surfaces exposed to these solutions or media.

Second, the inhibitory or biocidal effects of MgO do not seem to be caused by the mildly basic pH that results from the presence of brucite in aqueous solutions or growth media. Sawai et al. (2000b) reported that the survival of *Escherichia coli* (*E. coli*) was unaffected by a MgO-free, alkaline growth medium at pH values of 10, 10.25, and 10.5, but that *E. coli* survival decreased significantly in the same medium at pH values of 10.75 and 11. This result agrees with the conclusion that a mildly basic pH of about 9 (Section MgO-5.1) will not by itself preclude microbial activity in the WIPP.

Third, inhibition of microbial activity seems to require contact between MgO particles and microbes (Sawai et al. 2000a). This conclusion is based on the observation that increased shaking speed of an MgO-bearing slurry increased the mortality of *E. coli* in the slurry.

Fourth, the inhibitory effect is inversely proportional to the size of the MgO particles (Sawai et al. 1996; Koper et al. 2002; Stoimenov et al. 2002) and the temperature at which the MgO was prepared (Sawai et al., 1996).

Application of these results to microbial activity in the WIPP is difficult in the absence of long-term experiments under expected repository conditions. Biocides are often used for sterilization of solid materials, but become ineffective as the volume of the material(s) to be sterilized increases. This is because it becomes progressively more difficult to ensure uniform distribution of the biocide throughout these materials, and hence to ensure contact between the biocide and the microbes, as the volume increases. Therefore, sterilization methods such as autoclaving and radiation are used for materials with large volumes. In the case of MgO, Sawai et al. (2000a) reported that inhibition of microbial activity seems to require contact between MgO particles and microbes. Although room closure will rupture the supersacks and disperse the MgO into the interstices among and within the ruptured waste containers, this will not ensure contact between MgO particles and microbes. Furthermore, survival of microbes in samples subjected to treatment with an inhibitory or biocidal agent such as MgO, especially those that have had some contact with particulate MgO, would probably result in the development of increased resistance to MgO.

The results described above suggest that MgO might reduce the rate of microbial gas generation in the WIPP. However, in the absence of repository-specific experiments, the potential inhibitory or biocidal effects of MgO on the microbial gas-production rates are not included in PA.

MgO-5.3.3 Effects of MgO on Room Closure

In the CCA PA, the CCA PAVT, the CRA-2004 PA, and the CRA-2004 PABC calculations, room closure initially proceeded as if the rooms were open. The free air space was eliminated early in the calculations by unmitigated creep closure. Eventually, the salt contacted the waste and deformed it according to the waste response model. At the same time, corrosion and gas production pressurized the rooms. The coupled processes involved compression owing to the superincumbent rock counterbalanced by gas production, which was obtained from sampled parameters. Thus, room closure was caused by salt creep modified by the structural response of the waste and by gas production. MgO was not explicitly included in the PA room closure calculations, and is not expected to have a significant effect on room closure.

MgO-5.4 Effects of MgO on Far-Field An Transport

This section is based on the text in CRA-2004, Appendix BARRIERS, Section BARRIERS-2.4.

MgO could affect the matrix distribution coefficients (K_ds) used to predict transport of dissolved thorium (Th), uranium (U), Pu, and americium (Am) through the Culebra (see Brush 1996 or Brush and Storz 1996 for a definition of matrix K_ds). For the CCA PA, data from an empirical sorption study, a mechanistic sorption study, and a column-transport study were used to establish ranges and probability distributions of K_ds for Th, U, Pu, and Am.

Most of these K_ds were obtained from 6-week, empirical sorption experiments carried out with 1 g of dolomite-rich rock crushed to a size range of 75 to 500 μm; 20 mL of Brine A, ERDA-6 brine, AISinR, or H-17 with dissolved Th(IV), U(VI), Np(V), Pu(V), or Am(III); and a controlled atmosphere containing 0.24, 1.4, or 4.1% CO_2 to simulate the expected range of f_{CO_2} in the Culebra, about 3.16×10^{-4} to 3.16×10^{-2} atm (see Brush 1996; Brush and Storz 1996). Brine A and ERDA-6 brine are described above (Section MgO-4.1.1); AISinR is a synthetic brine representative of fluids sampled from the Culebra in the WIPP air intake shaft; and H-17 simulates Culebra brine from the H-17 Hydropad.

Brush (1996) and Brush and Storz (1996) extended the empirical K_ds obtained with Brine A and ERDA-6 brine to a pH of about 9 or 10 with data from a mechanistic sorption study that quantified the effects of f_{CO_2}, pH, and ionic strength on the sorption of Th(IV), U(VI), neptunium(V) (Np(V)), Pu(V), and Am(III) from synthetic NaCl solutions by well-characterized, pure dolomite. Therefore, the K_ds for Brine A and ERDA-6 brine used for the CCA PA included the effects of MgO on pH. The K_ds for the Culebra brines, however, did not include the effects of MgO on pH because it was assumed that if mixing is sufficient to produce fluids with compositions similar to those of Culebra brines, the pH of these mixtures will also be similar to those of Culebra brines (Brush 1996; Brush and Storz, 1996).

For the CCA PAVT, the EPA specified that the probability distributions for the K_ds be changed from uniform to loguniform (Trovato 1997a, Enclosure 2; U.S. Environmental Protection Agency 1998a, Table ES-3 and Table ES-4, Section 5.34, Section 5.3.5, Section 5.36, Section 5.37, and Section 5.38 and Table 6.3 and Table 6.4; Hansen and Leigh 2003). However, the EPA did not change any of the K_ds.

Brush and Storz (1996) corrected some of the ranges of K_ds established by Brush (1996) for the CCA PA. These corrections were too late for the far-field transport calculations for the CCA PA, and were not included in the far-field transport calculations for the CCA PAVT. Hansen and Leigh (2003), however, incorporated them in the PA database, and the CRA-2004 PA and the CRA-2004 PABC used the corrected K_ds along with the loguniform probability distributions specified by the EPA (see the CRA-2004, Appendix PA, Section PA-5.2). The K_ds for Brine A and ERDA-6 brine used for the CRA-2004 PA and the CRA-2004 PABC included the effects of MgO on pH, but the K_ds for the Culebra brines do not (Brush 1996; Brush and Storz 1996).

MgO-6.0 The MgO Excess Factor

The MgO excess factor is defined as the ratio of the total amount of MgO to be emplaced in the WIPP divided by the total amount required to consume all of the CO_2 produced by microbial activity should all of the CPR materials in the repository be consumed, calculated as specified by the EPA (Marcinowski 2004; U.S. Environmental Protection Agency 2004). The EPA's specifications for calculating the excess factor are described below.

Previously, the DOE referred to the MgO excess factor as the "MgO safety factor," and the EPA still uses "MgO safety factor." In this appendix, "MgO excess factor" is used exclusively. For the purposes of the discussions below, these terms are synonymous.

MgO-6.1 Effects of Microbial Respiratory Pathways on the MgO Excess Factor

The conceptual model of sequential use of electron acceptors is based on the common observation that, at any given time, (1) microbes use the best available electron acceptor (oxidant) (i.e., the one that yields the most free energy per mole of organic C consumed); (2) after depletion of the best available electron acceptor, these microbes—or other microbes—begin to consume the next-best available electron acceptor; and (3) this process continues with successively less favorable electron acceptors until all of the substrates (CPR materials in the case of the WIPP) are consumed, an essential nutrient is consumed, or some other limiting condition is attained. Sequential use of electron acceptors has been observed in a diverse array of natural and anthropogenic environments, such as lacustrine, riverine, estuarine, and oceanic sediments; soils; and landfills. In these environments, the order of use observed is oxygen (O_2) (referred to as aerobic respiration), NO_3^- (denitrification), Mn(IV) oxides and hydroxides (Mn reduction), Fe(III) oxides and hydroxides (Fe reduction), SO_4^{2-} (SO_4^{2-} reduction), and CO_2 (fermentation and methanogenesis) (Froelich et al. 1979; Berner 1980; Criddle, Alvarez, and McCarty 1991; Chapelle 1993; Wang and Van Cappellen 1996; Schlesinger 1997; Hunter, Wang, and P. Van Cappellan 1998; Fenchel, King, and T.H. Blackburn 2000). (In the following discussion, fermentation and methanogenesis are usually referred to as "methanogenesis" for simplicity.) Sequential use of electron acceptors by microbes is included in the conceptual model for gas generation in the WIPP, one of the four conceptual models for long-term chemical evolution of WIPP disposal rooms implemented in WIPP PA (Sandia National Laboratories 1996; U.S. Department of Energy 1996a, Chapter 6, Section 6.4.3.3; CRA-2004, Chapter 6.0, Section 6.4.3.3).

In the WIPP, the quantities of O_2, Mn(IV) oxides and hydroxides, and Fe(III) oxides and hydroxides will be small relative to that of CPR materials (Brush 1990 and 1995; Wang and Brush 1996a). Therefore, aerobic respiration, manganese (Mn) reduction, and Fe reduction can be ignored from the standpoint of their potential effects on the long-term chemical behavior of the repository.

However, several potentially useful electron acceptors will be present in and/or around WIPP disposal rooms: (1) some NO_3^- and SO_4^{2-} will be present in the waste; (2) SO_4^{2-} is present in SO_4^{2-}-bearing minerals such as anhydrite, gypsum ($CaSO_4 \cdot 2H_2O$), and polyhalite

($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$) in the Salado surrounding the repository, and dissolved in Salado and Castile Formation brines; and (3) CO_2 could be produced by denitrification, SO_4^{2-} reduction, and even methanogenesis (Brush 1990 and 1995; Wang and Brush 1996a). Therefore, denitrification, SO_4^{2-} reduction, and methanogenesis are potentially important microbial respiratory pathways in the repository.

The overall reactions used to represent possible denitrification, SO_4^{2-} reduction, and methanogenesis in the WIPP (Wang and Brush 1996a) are, respectively,

$$C_6H_{10}O_5(s) + 4.8H^+(aq) + 4.8NO_3^-(aq) \rightarrow 7.4H_2O(aq \text{ or } g) + 6CO_2\ (aq \text{ or } g) + 2.4N_2,(aq \text{ or } g) \quad \text{(MgO.13)}$$

$$C_6H_{10}O_5(s) + 6H^+(aq) + 3SO_4^{2-}(aq) \rightarrow 5H_2O(aq \text{ or } g) + 6CO_2(aq \text{ or } g) + 3H_2S(aq \text{ or } g) \quad \text{(MgO.14)}$$

$$C_6H_{10}O_5(s) + H_2O(aq \text{ or } g) \rightarrow 3CH_4(aq \text{ or } g) + 3CO_2(aq \text{ or } g) \quad \text{(MgO.15)}$$

For these reactions, the CO_2 yields are 1 mol of CO_2 per mol of organic C consumed from denitrification and SO_4^{2-} reduction, and 0.5 mol of CO_2 per mol of C from methanogenesis. Therefore, the MgO excess factor that would be calculated assuming that methanogenesis is the only or the dominant respiratory pathway would be double or approximately double that calculated assuming denitrification or SO_4^{2-} reduction is the only or the dominant respiratory pathway.

The total quantity of CPR materials in the WIPP TRU waste inventory—including the waste, the waste containers, and various waste emplacement materials—exceeds the quantity of NO_3^- and SO_4^{2-} in the waste. This was the case at the time of the CCA PA and the CCA PAVT (U.S. Department of Energy 1996b), the CRA-2004, Appendix DATA, Attachment F, and the CRA-2004 PABC (Crawford 2005a and 2005b). Therefore, it appeared that (1) the quantity of CPR materials consumed by methanogenesis could exceed that consumed by denitrification and SO_4^{2-} reduction, should all of the CPR materials be consumed; and (2) the overall CO_2 yield calculated assuming that methanogenesis would be dominant could be close to 0.5 mol of CO_2 per mol of C consumed (the CCA, Appendix SOTERM; the CRA-2004, Appendix BARRIERS). (Note that the conservative assumption that all of the CPR materials in the inventory would be consumed provides a lower bound on the MgO excess factor because partial consumption of the CPR materials would produce less CO_2 and consume less MgO.)

Thus, Wang (2000a) used the masses of CPR materials, NO_3^-, and SO_4^{2-} in the WIPP TRU waste inventory used for the CCA PA and the CCA PAVT (U.S. Department of Energy 1996b) to calculate that, should microbes consume all the CPR materials, denitrification would consume about 3 mol % of these materials, SO_4^{2-} reduction would consume 2 mol %, and methanogenesis would consume 95 mol %. The overall CO_2 yield would be 0.525 mol of CO_2 per mol of organic C consumed. Snider (2003d) used the CRA-2004 PA inventory (CRA-2004, Appendix DATA, Attachment F) to calculate that denitrification would consume 4.72 mol % of the CPR materials, SO_4^{2-} reduction would consume 0.82 mol %, methanogenesis would consume 94.46 mol %, and the overall CO_2 yield would be 0.528 mol of CO_2 per mol of organic C consumed. Based on the CRA-2004 PABC inventory (Crawford 2005a and 2005b), Brush et al. (2006) calculated that

denitrification, SO_4^{2-} reduction, and methanogenesis would consume 4.89, 0.84, and 94.27 mol %, respectively, of the CPR materials in the repository; the overall CO_2 yield would be 0.529 mol of CO_2 per mol of organic C.

However, it is possible that microbial SO_4^{2-} reduction could continue after microbes consume all the SO_4^{2-} in the waste. Microbial SO_4^{2-} reduction could continue by using the SO_4^{2-} dissolved in Salado or Castile brines, or by using SO_4^{2-} released by the dissolution of anhydrite, gypsum, and polyhalite in the disturbed rock zone (DRZ) surrounding WIPP disposal rooms (Section MgO-6.2.3.1, Section MgO-6.2.3.2, and Section MgO-6.2.3.3).

MgO-6.2 History of the MgO Excess Factor

This section reviews (1) the establishment of the MgO excess factor (Section MgO-6.2.1); (2) the reduction of the MgO excess factor from 1.95 to 1.67 (Section MgO-6.2.2), which occurred concomitantly with the EPA's approval of the DOE's request to eliminate the emplacement of minisacks (Section MgO-2.1.2); (3) additional developments relevant to the MgO excess factor prior to the CRA-2004 (Section MgO-6.2.3); and (4) changes since the CRA-2004 (Section MgO-6.2.4), which included the EPA's approval of the DOE's request to reduce the MgO excess factor from 1.67 to 1.2.

MgO-6.2.1 Establishment of the MgO Excess Factor

Just prior to the submittal of the CCA, Peterson (1996) calculated the quantity of MgO required to consume all of the CO_2 produced should microbes consume all of the CPR materials in the WIPP. Peterson (1996) assumed that (1) microbes would consume all of the CPR materials in the WIPP TRU waste inventory (U.S. Department of Energy 1996b), and (2) the CO_2 yield would be 1 mol of CO_2 per mol of organic C in the CPR materials (i.e., there would be no methanogenesis).

The DOE stated in the CCA that it would emplace 85,600 short tons (77,640 metric tons) of MgO in the WIPP (U.S. Department of Energy 1996a, Chapter 3, Section 3.3.3). However, it did not specify an MgO excess factor. Instead, it said that "Since the MgO backfill is being added in large excess, any quantity of brine that may enter the repository will be saturated with respect to the appropriate MgO reaction products" (the CCA, Appendix BACK, p. BACK-3).

The MgO excess factor was first established by an EPA request for additional information during its review of the CCA, and by the DOE's response to that request. The portion of the EPA request relevant to the establishment of the MgO excess factor was that the DOE "… provide information which demonstrates that the excess volume proposed to be emplaced can actually be accommodated and whether it covers the uncertainties in the actual geochemical process" (Nichols 1996, Enclosure 2, p. 11). The pertinent portion of the DOE's response (Dials 1997) was the following:

> The quantity of MgO required to be emplaced to assure removal of CO_2 from the gas phase is based on calculations that consider all processes that might contribute to CO_2 production. These calculations are very conservative in that they utilize a maximum extent of CO_2 production, a quantity that is unlikely to be attained. Based on the [Baseline Inventory Report, or BIR] and memoranda in the Records Center, the total number of moles of MgO required to react with the

> maximum possible amount of CO_2 generated is 9.85×10^8 mol. Using the appropriate conversion factors (40.3 g/mol, 0.001 kg/g, 2.202 kg/lb, 0.0005 lb/ton) a total of 43,700 tons of MgO are required to react with this maximum estimate of [CO_2] production. Section 3.3.3 of the CCA documents that approximately 85,600 tons of backfill will be emplaced in the repository. Therefore, by dividing the mass of backfill to be emplaced (85,600 tons) by the maximum mass of MgO required to react with the maximum possible [CO_2] production (43,700 tons), a 1.95 factor of safety results. In other words, 95% more MgO will be emplaced than is required to react with a conservative estimate of the maximum quantity of CO_2 production.

The EPA included this calculation of the MgO excess factor in its review of the CCA (U.S. Environmental Protection Agency 1998a, Section 44.A.5 and Section 44.A.6).

This excess factor of 1.95 is consistent with the conservative assumptions that (1) microbes would consume all of the CPR materials in the inventory (U.S. Department of Energy 1996b), and (2) the CO_2 yield would be 1 mol of CO_2 per mol of organic C in the CPR materials (i.e., there would be no methanogenesis even if all of the CPR materials in the repository were consumed).

The DOE assumed that the CO_2 yield would be 1 mol of CO_2 per mol of organic C in the CPR materials because at the time that Wang and Brush (1996a and 1996b) established the conceptual model and parameters for microbial gas generation in the CCA PA, Francis and Gillow (1994) and Francis, Gillow, and Giles (1997) had observed aerobic respiration and denitrification, but not methanogenesis, in their microbial gas-generation experiments at Brookhaven National Laboratory (BNL). By the time Wang and Brush (1996a and 1996b) established the model and parameters for the CCA PA, BNL had carried out their experiments for up to 1,228 days (3.36 years). Therefore, there was no experimental evidence at the time of the CCA PA or the CCA PAVT that methanogenesis would actually occur in the WIPP. There were at least four possible reasons why methanogenesis had not been observed by the time of the CCA and the CCA PAVT:

1. Halophilic methanogens capable of metabolizing complex, organic substrates such as cellulosic materials under expected WIPP conditions do not exist.

2. Halophilic methanogens capable of metabolizing complex, organic substrates exist, but were not present in the materials used to inoculate these experiments (laboratory dust; brine and mud from the salt lakes in Nash Draw; and brine collected from G Seep in G Drift, a drift located in the northern end of the WIPP underground workings).

3. Methanogens were present in the materials used to inoculate these experiments, but had not survived collection, storage, and inoculation of the BNL experiments.

4. Methanogens had survived collection, storage, and inoculation of these experiments, but there had not been enough time for other microbes to consume all of the NO_3^- and SO_4^{2-} and allow the methanogens to become active.

MgO-6.2.2 Reduction of the MgO Excess Factor from 1.95 to 1.67

In 2001, the MgO excess factor decreased from 1.95 to 1.67 when the EPA approved the DOE's 2000 request to eliminate the emplacement of minisacks among the waste containers and

between the waste containers and the ribs (Triay 2000; U.S. Department of Energy 2000; Marcinowski 2001; U.S. Environmental Protection Agency 2001). Section MgO-2.1.2 describes the DOE's request to eliminate the minisacks and the EPA's approval of this request.

The DOE's 2000 request to eliminate the minisacks proposed a less-conservative assumption for the calculation of the MgO excess factor: that methanogenesis would be the dominant microbial respiratory pathway in the WIPP should all of the CPR materials in the repository be consumed, and therefore, microbes would not convert all of the organic C in the CPR materials to CO_2.

The DOE proposed this less-conservative assumption because Francis and Gillow (2000, pp. 2, 3, and 10) observed CH_4 in the headspaces of their long-term, inundated microbial gas-generation experiments carried out at BNL for 2,718 days (7.44 years) under most combinations of conditions. However, Francis and Gillow (2000) did not observe CH_4 in the inundated experiments to which excess NO_3^- had been added at the start of the experiments. The addition of excess NO_3^- to some of the experiments appears to have prevented the onset of methanogenesis. Wang (2000a) used the results of Francis and Gillow (2000) to support the DOE's request to eliminate the minisacks (Section MgO-2.1.2).

Therefore, it was clear that the absence of experimental evidence for methanogenesis at the time of the CCA was because microbial activity in the initially aerobic inundated experiments had not progressed through aerobic respiration, denitrification, and SO_4^{2-} reduction to methanogenesis; and that microbial activity in the initially anaerobic inundated experiments had not progressed through denitrification and SO_4^{2-} reduction to methanogenesis. The requirement that these steps be completed prior to the onset of methanogenesis is a consequence of the observation of the sequential use of electron acceptors (Section MgO-6.1), according to which methanogenesis does not start until any and all NO_3^- and SO_4^{2-} are depleted. Although methanogenesis had not been observed by the time of the CCA in experiments carried out for up to 1,228 days (3.36 years), Francis and Gillow observed CH_4 in inundated experiments after 2,718 days (7.44 years).

It was also clear from these results by the time of the DOE's 2000 request to eliminate the minisacks that (1) there exist communities of halophilic methanogens capable of metabolizing complex organic substrates, such as cellulosic materials, under expected WIPP conditions; (2) these microbes are present and viable in one or more of the materials used to inoculate these experiments; and (3) these microbes are capable of surviving exposure to O_2. Methanogens are obligate anaerobes and, as such, are extremely sensitive to exposure to O_2. The fact that they produced CH_4 after exposure to O_2 implies that they are capable of producing resistant forms that can survive initially oxic conditions in these experiments.

Furthermore, results from the BNL microbial gas-generation study have confirmed that viable halophilic methanogens capable of metabolizing cellulosic materials under expected near-field conditions are present in the WIPP underground workings. Francis and Gillow (2000, pp. 2 and 10) detected CH_4 in initially oxic, unamended, and uninoculated experiments, and in initially anoxic, unamended, and uninoculated experiments. The most likely explanation for microbial gas production in these uninoculated experiments is that G Seep, the brine used for these inundated experiments, was collected from the WIPP underground workings. This brine contained a small but viable microflora, including methanogens, and was not sterilized prior to use. The fact that these microbes produced CH_4 after exposure to O_2 in the air used to ventilate

G Drift and in initially oxic experiments implies that they are capable of producing resistant forms that can withstand initially oxic conditions in the repository.

However, the presence of viable halophilic methanogens in the WIPP does not preclude the possibility that similar communities of microbes are also present in the other materials used to inoculate these experiments, especially brine and mud from the salt lakes in Nash Draw. It is quite possible that methanogens in these lakes are also capable of producing resistant forms that can survive the oxic conditions encountered during eolian transport from Nash Draw to the WIPP air intake shaft, and initially oxic conditions in the repository. Therefore, the presence of viable methanogens in the WIPP does not depend on the claim that microbes have survived in the Salado since the Permian Period (Vreeland, Rosenzweig, and Powers 2000) a claim that is controversial (see, for example, Hazen and Roedder 2001; Parkes 2000; Powers, Vreeland, and Rosenzweig 2001; Satterfield et al. 2005).

Based on the results of Francis and Gillow (2000) and the analysis of Wang (2000a), the DOE's 2000 request to eliminate the minisacks proposed that, if methanogenesis were the dominant respiratory pathway, it would increase the MgO excess factor from values of 1.95 prior to and 1.67 after the proposed elimination of the minisacks to values of 3.73 prior to and 3.23 after minisack elimination (U.S. Department of Energy 2000, Table 1).

The EPA's approval of the DOE's request to eliminate the minisacks included the results of several of the DOE's calculations regarding excess MgO, but did not acknowledge the proposed excess factors of 3.73 prior to and 3.23 after minisack elimination (U.S. Environmental Protection Agency 2001, Table 1).

MgO-6.2.3 Additional Developments Relevant to the MgO Excess Factor Prior to the CRA-2004

In March 2004, the EPA approved emplacing supercompacted waste from the AMWTP at the INEEL in the WIPP (Marcinowski 2004; Trinity Engineering Associates 2004; U.S. Environmental Protection Agency 2004). However, the EPA specified that the DOE maintain an MgO excess factor of 1.67. Because much of the AMWTP waste contains high concentrations of CPR materials, the DOE anticipated the need to emplace additional MgO in the repository, and began to explore various possible approaches to support a Planned Change Request (PCR) for EPA approval of a reduction in the MgO excess factor.

MgO-6.2.3.1 Additional Evidence for Microbial Methanogenesis under Expected WIPP Conditions

Gillow and Francis (2001b) reported additional CH_4 in the inundated, initially anaerobic experiments in which Francis and Gillow (2000, pp. 2, 3, and 10) had first detected this gas. Furthermore, Gillow and Francis (2001b, pp. 3-4 and 3-5) detected CH_4 in experiments to which excess NO_3^- had been added at the start of these experiments. These results were from experiments sampled after 3462 days (9.48 years). After 2,718 days (7.44 years), Francis and Gillow (2000, pp. 2, 3, and 10) had not observed CH_4 in the experiments to which excess NO_3^- had been added. Therefore, this excess NO_3^- had delayed, but did not permanently prevent, the

onset of methanogenesis. This seemed to make the case stronger for methanogenesis as a potential microbial respiratory pathway in the WIPP.

Consequently, the DOE emphasized the likely dominance of methanogenesis during microbial consumption of the CPR materials in the WIPP (CRA-2004, Appendix BARRIERS, Section BARRIERS-2.5.1). Based on the CRA-2004 PA inventory (CRA-2004, Appendix DATA, Attachment F) and calculations by Snider (2003d), the DOE concluded that (1) 4.72 mol % of the CPR materials would be consumed by denitrification, 0.82 mol % by SO_4^{2-} reduction, and 94.46 mol % by methanogenesis; (2) the overall CO_2 yield would be 0.528 mol of CO_2 per mol of organic C consumed; and (3) the MgO excess factor would be 2.45.

However, during a DOE-EPA technical exchange in January 2004, the EPA expressed concern that naturally occurring SO_4^{2-} could delay or even prevent methanogenesis in the WIPP after microbes consume the SO_4^{2-} in the waste. Dissolved SO_4^{2-} is present in both Salado and Castile brines (see Table MgO-6), so advective transport of SO_4^{2-} into WIPP disposal rooms via seepage of intergranular Salado brines (i.e., GWB) from the DRZ, or inflow of brines from the Castile (i.e., ERDA-6 brine) could delay or prevent methanogenesis. Furthermore, diffusive transport of dissolved SO_4^{2-} from DRZ minerals such as anhydrite, gypsum, and polyhalite—all of which contain SO_4^{2-}—to WIPP disposal rooms could become important as microbial consumption of SO_4^{2-} in the waste creates a concentration gradient from the DRZ to the repository.

MgO-6.2.3.2 The DOE's Analysis of Transport of Naturally Occurring SO42- into WIPP Disposal Rooms

Kanney et al. (2004) analyzed the effects of CPR materials in a panel and transport of naturally occurring SO_4^{2-} on the extent of microbial methanogenesis in the WIPP and the MgO excess factor for different assumed loadings of AMWTP supercompacted waste in a panel.

Kanney et al. (2004) used the four loadings of AMWTP supercompacted waste in a hypothetical "Panel X" developed by Leigh (2003, 2004a, and 2004b) for the DOE's analysis of the effects of this waste on the long-term performance of the WIPP (Hansen et al. 2004). The four loadings assumed for Panel X were (1) the "DOE homogeneous Panel X," based on the assumption that the AMWTP supercompacted waste would be homogeneously emplaced throughout the entire 10-panel repository (Panel X would comprise ~11-12 volume % (vol %) AMWTP supercompacted waste, the same as the other 9 panels); (2) the "DOE realistic Panel X," which would comprise 14 vol % AMWTP supercompacted waste; (3) the "DOE conservative Panel X," which would consist of 27 vol % AMWTP supercompacted waste; and (4) the "EPA conservative Panel X," which would contain 50 vol % AMWTP supercompacted waste. In all four cases, the remaining waste in the WIPP inventory was assumed to be distributed homogeneously throughout the other nine panels.

Kanney et al. (2004, Section 3.2.1, pp. 20-22, and especially Figure 4 and Figure 5) used the BRAGFLO results from the PA calculations of Hansen et al. (2004) to demonstrate that

> In all but a few vectors, CPR biodegradation has ceased after about 2000 years. In most vectors, this is because all of the CPR has been consumed. For a few vectors the consumption of CPR [materials] has ceased even though there [are] CPR [materials] remaining. This is likely caused by very low brine saturations. For those few vectors that still show some activity, the rate of …

> consumption is only a fraction of the inundated rate. Thus, a value [of] 2000 years for the biodegradation time scale T_{bio} is appropriate for this analysis.

Kanney et al. (2004, Section 3.1.1, p. 19; and Section 3.2.2, p. 22) then used a dissolved SO_4^{2-} concentration of 182 mM, the highest concentration predicted by Brush and Xiong (2003a) for GWB or ERDA-6 brine before or after equilibration with the solids in WIPP disposal rooms (see Section MgO-5.1), and a brine volume of 7.74×10^4 m^3, the largest volume predicted after 2,000 years in all of the 100 vectors of Replicate 1 of Hansen et al. (2004), to calculate the quantity of SO_4^{2-} that could enter the repository via advective transport.

To calculate the quantity that could enter via diffusive transport in 2,000 years, Kanney et al. (2004, Section 2.2.2, pp. 5-7; Section 3.1.2, p. 18) used a concentration of 1.7 wt % each for anhydrite, gypsum, and polyhalite (Stein 1985; Brush 1990) to calculate the concentration of SO_4^{2-} in the Salado at or near the stratigraphic horizon of the WIPP. Kanney et al. (2004, Section 2.3.3, pp. 13-16; Section 3.2.3, p. 23) then assumed that all the SO_4^{2-} in these minerals within 1.06 m (3.5 ft) of the excavated surfaces of a panel would diffuse into the repository in 2000 years. They calculated this "effective diffusion length" using (1) a value of 9.84×10^{-10} meters squared per second (m^2/s) for the free-solution tracer diffusion coefficient of SO_4^{2-} (Li and Gregory 1974), (2) a value of 0.05 for the porosity of the Salado DRZ, (3) a value of 1.8 for the cementation factor (Deal et al. 1989), (4) a tortuosity of 0.091, and (5) a value of 4.48×10^{-12} m^2/s for the effective diffusion coefficient of SO_4^{2-}.

For these parameter values, Kanney et al. (2004) predicted that a maximum quantity of 1.35×10^6 kg of SO_4^{2-} would be advected into Panel X in Castile brine and a total of 2.37×10^6 kg of SO_4^{2-} would dissolve from anhydrite, gypsum, and polyhalite and diffuse into Panel X from the DRZ surrounding Panel X. These quantities are much greater than those in this panel's waste, just $(1.40\text{-}4.40) \times 10^4$ kg. Therefore, the total quantity of SO_4^{2-} available to SO_4^{2-}-reducing microbes would be $\sim 3.74 \times 10^6$ kg (1.35×10^6 kg + 2.37×10^6 kg + 1.4×10^4 kg).

Finally, Kanney et al. (2004, Section 3.3, pp. 24-26) used the waste-material parameters from Leigh (2004a, 2004b), the CRA-2004 PA inventory (the CRA-2004, Appendix DATA, Attachment F), and the methods of Snider (2003d) to predict the quantities of CPR materials in the DOE homogeneous Panel X, the DOE realistic Panel X, the DOE conservative Panel X, and the EPA conservative Panel X that would be consumed by microbes in 2000 years via denitrification, SO_4^{2-} reduction using SO_4^{2-} in the waste, SO_4^{2-} reduction using naturally occurring SO_4^{2-} (Castile-brine SO_4^{2-} and SO_4^{2-} in DRZ minerals), and methanogenesis. They also determined the MgO excess factors for these panels.

Table MgO-9 provides the results of these calculations. They show that, for a given panel loading (i.e., for a given quantity of CPR materials), including naturally occurring SO_4^{2-} decreased the MgO excess factor relative to that calculated using only the SO_4^{2-} in the waste (e.g., the MgO safety factor for the DOE homogeneous Panel X decreased from 2.45 to 1.37). Kanney et al. (2004, Section 3.3, pp. 25-26) also concluded,

Table MgO-9. Effects of Panel Loading and the Source of SO_4^{2-} on Microbial Respiratory Pathways and the MgO Excess Factor—Base Case. Adapted from Kanney et al. (2004).

Loading of Panel X and Source of SO_4^{2-}	Denitrification (% of CPR Materials Consumed)	SO_4^{2-} Reduction (% of CPR Materials Consumed)	Methanogenesis (% of CPR Materials Consumed)	MgO Excess Factor
DOE Homogeneous:[a]				
Waste SO_4^{2-}	4.75	0.82	94.46	2.45
Waste + Natural SO_4^{2-}	4.75	70.57	24.68	1.37
DOE Realistic:[b]				
Waste SO_4^{2-}	4.48	0.66	94.87	2.44
Waste + Natural SO_4^{2-}	4.48	63.27	32.26	1.40
DOE Conservative:[c]				
Waste SO_4^{2-}	3.00	0.16	96.84	1.71
Waste + Natural SO_4^{2-}	3.00	42.98	54.03	1.13
EPA Conservative:[d]				
Waste SO_4^{2-}	1.03	0.23	98.75	1.21
Waste + Natural SO_4^{2-}	1.03	32.31	66.66	0.94

[a] Panel X would comprise ~11-12 vol % AMWTP supercompacted waste.
[b] Panel X would comprise 14 vol % AMWTP supercompacted waste.
[c] Panel X would consist of 27 vol % AMWTP supercompacted waste.
[d] Panel X would contain 50 vol % AMWTP supercompacted waste.

> In spite of the decreases noted above, these results show that the MgO [excess]F[1]F factor is not very sensitive to the amount of [SO_4^{2-}]. For the DOE homogeneous [P]anel X, the amount of [SO_4^{2-}] increased by about 8500% while the … [excess] factor decreased by about 44%. For the DOE realistic [P]anel X, the amount of [SO_4^{2-}] increased by about 9500% and the [MgO excess] factor decreased by about 43%. For the DOE conservative case, the amount of [SO_4^{2-}] increased by about 26,500% and the [excess] factor decreased by about 34%. For the EPA conservative scenario, the amount of [SO_4^{2-}] increased by about 14000% and the ... [excess] factor decreased by about 22%.
>
> The MgO [excess] factor is much more sensitive to the amount of CPR [materials]. Keeping in mind that there is roughly the same amount of [SO_4^{2-}] available in each [panel], one can observe how the [excess] factor change[d] as more CPR [materials were] added by comparing [excess] factors for different [loadings]. In going from the DOE realistic [Panel X] to the EPA conservative [Panel X], the [mass of] CPR [materials] increase[d] by about 95% and the MgO safety factor decrease[d] by about 33%.
>
> Note that the fraction of CPR [materials consumed] by [SO_4^{2-}] reduction in the EPA conservative [P]anel X … [was] actually less than for the DOE conservative [P]anel X, while the MgO [excess] factor [was] lower than that of [the] DOE conservative [P]anel X. This [was] caused by the larger amount of CPR [materials] in the EPA conservative [P]anel X....

Kanney et al. (2004, Section 4, pp. 27-34) also carried out an uncertainty analysis of the effects of the brine volume that enters a panel following a human intrusion, the time required for

[1] Explanatory text appears in brackets.

microbial consumption of all of the CPR materials, and the effective diffusion coefficient for SO_4^{2-} on these results.

Kanney et al. (2004, Section 4, Table 13) pointed out that the probability of a large volume of brine flowing into a panel from a reservoir in the Castile (the only way that large volumes of brine can enter the repository) is quite low; about 0.006. Therefore, Kanney et al. (2004, Section 4.1, pp. 27-29) recalculated the effects of panel loading and the source of SO_4^{2-} on microbial methanogenesis in the absence of Castile brine. This change (1) decreased the maximum volume of brine that could enter Panel X by about 75%, from 7.74×10^4 to 1.91×10^4 m^3; (2) decreased the maximum quantity of SO_4^{2-} advected into this panel by the same percentage, from 1.35×10^6 to 3.34×10^5 kg; and (3) decreased the total quantity of SO_4^{2-} available to microbes in the panel by 27%, from $(3.74\text{-}3.77) \times 10^6$ to $(2.72\text{-}2.75) \times 10^6$ kg. The absence of Castile brine from Panel X increased the percentage of CPR materials consumed by methanogenesis by about 13% in the case of the EPA conservative Panel X to 77% for the DOE homogeneous Panel X, and increased the MgO excess factor for the same panels by about 6-11% (see Table MgO-10).

Table MgO-10. Effects of Panel Loading and the Source of SO_4^{2-} on Microbial Methanogenesis and the MgO Excess Factor—Effects of Having no Castile Brine Intrude Panel X. Adapted from Kanney et al. (2004).

Loading of Panel X and Source of SO_4^{2-}	Denitrification (% of CPR Materials Consumed)	SO_4^{2-} Reduction (% of CPR Materials Consumed)	Methanogenesis (% of CPR Materials Consumed)	MgO Excess Factor
DOE Homogeneous:[a]				
Castile brine present	4.75	70.57	24.68	1.37
No Castile brine	4.75	51.47	43.77	1.52
DOE Realistic:[b]				
Castile brine present	4.48	63.27	32.26	1.40
No Castile brine	4.48	46.13	49.40	1.55
DOE Conservative:[c]				
Castile brine present	3.00	42.98	54.03	1.13
No Castile brine	3.00	31.26	65.75	1.22
EPA Conservative:[d]				
Castile brine present	1.03	32.31	66.66	0.94
No Castile brine	1.03	23.53	75.44	1.00

[a] Panel X would comprise ~11-12 vol % AMWTP supercompacted waste.
[b] Panel X would comprise 14 vol % AMWTP supercompacted waste.
[c] Panel X would consist of 27 vol % AMWTP supercompacted waste.
[d] Panel X would contain 50 vol % AMWTP supercompacted waste.

Kanney et al. (2004, Section 4.2, pp. 29-32) then predicted the effects of doubling the time required for microbial consumption of all CPR materials from 2,000 to 4,000 years. This change

1. Increased the maximum volume of Castile brine that could enter Panel X by about 32%, from 7.74×10^4 to 1.02×10^5 m^3
2. Increased the maximum quantity of SO_4^{2-} advected into this panel by the same percentage, from 1.35×10^6 to 1.78×10^6 kg
3. Increased the effective diffusion length by 42%, from 1.06 to 1.50
4. Increased the quantity of SO_4^{2-} that diffused into the panel by 41%, from 2.37×10^6 to 3.35×10^6 kg
5. Increased the total quantity of SO_4^{2-} available in this panel by 37%, from $(3.74\text{-}3.77) \times 10^6$ to $(5.14\text{-}5.17) \times 10^6$ kg

Doubling the time required for microbial consumption of all of the CPR materials decreased the percentage of CPR materials consumed by methanogenesis by about 18% in the case of the EPA conservative Panel X to 100% for the DOE homogeneous Panel X, and decreased the MgO excess factor for the same panels by about 9-12% (Table MgO-11).

Table MgO-11. Effects of Panel Loading and the Source of SO_4^{2-} on Microbial Respiratory Pathways and the MgO Excess Factor—Effects of Doubling the Time Required for Consumption of All CPR Materials. Adapted from Kanney et al. (2004).

Loading of Panel X and Source of SO_4^{2-}	Denitrification (% of CPR Materials Consumed)	SO_4^{2-} Reduction (% of CPR Materials Consumed)	Methanogenesis (% of CPR Materials Consumed)	MgO Excess Factor
DOE Homogeneous:[a]				
2,000 years	4.75	70.57	24.68	1.37
4,000 years	4.75	95.25	0.00	1.21
DOE Realistic:[b]				
2,000 years	4.48	63.27	32.26	1.40
4,000 years	4.48	86.98	8.54	1.25
DOE Conservative:[c]				
2,000 years	3.00	42.98	54.03	1.13
4,000 years	3.00	59.20	37.81	1.02
EPA Conservative:[d]				
2,000 years	1.03	32.31	66.66	0.94
4,000 years	1.03	44.47	54.51	0.86

[a] Panel X would comprise ~11-12 vol % AMWTP supercompacted waste.
[b] Panel X would comprise 14 vol % AMWTP supercompacted waste.
[c] Panel X would consist of 27 vol % AMWTP supercompacted waste.
[d] Panel X would contain 50 vol % AMWTP supercompacted waste.

Finally, Kanney et al. (2004, Section 4.3, pp. 32-34) predicted the effects of approximately doubling the effective diffusion coefficient for SO_4^{2-}, from 4.48×10^{-12} to 1.00×10^{-11} m^2/s. This change (1) increased the effective diffusion length by 50%, from 1.06 to 1.59 m (3.5 to 5.2 ft); (2) increased the quantity of SO_4^{2-} that diffused into the panel by 49%, from 2.37×10^6 to 3.54×10^6 kg; and (3) increased the total quantity of SO_4^{2-} available by 31%, from $(3.74\text{-}3.77) \times 10^6$ to $(4.91\text{-}4.94) \times 10^6$ kg. Doubling the effective diffusion coefficient for SO_4^{2-} decreased the percentage of CPR materials consumed by methanogenesis by about 15% in the case of the EPA conservative Panel X to 89% for the DOE homogeneous Panel X, and decreased the MgO excess factor for the same panels by about 6-10% (Table MgO-12).

Table MgO-12. Effects of Panel Loading and the Source of SO_4^{2-} on Microbial Respiratory Pathways and the MgO Excess Factor—Effects of Doubling the Effective Diffusion Coefficient for SO_4^{2-}. Adapted from Kanney et al. (2004).

Loading of Panel X and Source of SO_4^{2-}	Denitrification (% of CPR Materials Consumed)	SO_4^{2-} Reduction (% of CPR Materials Consumed)	Methanogenesis (% of CPR Materials Consumed)	MgO Excess Factor
DOE Homogeneous:[a]				
Base Case	4.75	70.57	24.68	1.37
Doubling D_{eff}	4.75	92.48	2.76	1.23
DOE Realistic:[b]				
Base Case	4.48	63.27	32.26	1.40
Doubling D_{eff}	4.48	82.94	12.58	1.27
DOE Conservative:[c]				
Base Case	3.00	42.98	54.03	1.13
Doubling D_{eff}	3.00	56.44	40.57	1.04
EPA Conservative:[d]				
Base Case	1.03	32.31	66.66	0.94
Doubling D_{eff}	1.03	42.40	56.58	0.88

[a] Panel X would comprise ~11-12 vol % AMWTP supercompacted waste.
[b] Panel X would comprise 14 vol % AMWTP supercompacted waste.
[c] Panel X would consist of 27 vol % AMWTP supercompacted waste.
[d] Panel X would contain 50 vol % AMWTP supercompacted waste.

MgO-6.2.3.3 The EPA's Response to the DOE's Analysis of Transport of Naturally Occurring SO_4^{2-} into the WIPP

The EPA concluded that the analysis of Kanney et al. (2004) did not adequately bound the quantity of naturally occurring SO_4^{2-} that could enter WIPP disposal rooms. In its review of the issues associated with the emplacement of AMWTP supercompacted waste in the WIPP, Trinity Engineering Associates (TEA) (2004, pp. 31-33) concluded,

> TEA agrees that advection, dissolution, and diffusion in brine are the major mechanisms for transporting natural [SO_4^{2-}] into the repository. TEA also agrees that basing the quantity of available [SO_4^{2-}] on the maximum available brine volume and ignoring mass transfer limitations in

dissolution and diffusion are conservative. However, TEA questions certain details of the approach that should be resolved before [the DOE's] calculations can be accepted as adequately bounding sulfate availability. These questions primarily concern the questionable basis for the assumed rate of room closure and the associated degree of DRZ healing, a lack of consideration of the anhydrite-rich beds immediately above the repository, and a lack of consideration of the effect of increased [Fe] surface area or the conservatism of the microbial degradation rates in determining an appropriate time scale for the sulfate reduction reaction.

The timing of room closure and the associated degree of DRZ healing cited by Kanney et al. [2004] are related to the accuracy of SANTOS model predictions which are currently being reviewed by the Agency... If the SANTOS model predictions are found to be inaccurate, the conclusions cited by Kanney et al. [2004] may not be supported. In addition, the belief that the vertical DRZ would essentially heal within fewer than 100 years may be inconsistent with the approved conceptual model implemented in the CCA and PAVT [PAs], which incorporate a DRZ that endures for 10,000 years with permeabilities that can be orders of magnitude higher than for intact halite. Even if the vertical DRZ rapidly heals to the extent that additional vertical brine flow is not of concern, [the DOE's] diffusion length of about 1 m is not consistent with the approximately 3 m cited extent of the lateral DRZ. The lateral DRZ includes stress fracturing, provides advective access to Anhydrite B, and will endure significantly longer than the vertical DRZ (Kanney et al. 2004, p. 9).

TEA agrees that pressure-induced fractures are more likely to conduct brine away from the repository rather than toward it, and that brine flow into the repository from the thinner anhydrite layers immediately above the waste rooms is likely to be small compared with the volume of brine inflow assumed in [the DOE's] calculations. However, TEA believes that structural disruptions during room closure, such as a roof collapse that would bring [SO_4^{2-}]-bearing minerals such as anhydrite into direct contact with waste room brines, cannot be ruled out. Additional [SO_4^{2-}] could be derived in this manner from Anhydrite Interbeds A and B, and from the anhydrite-rich halite between these interbeds (Stein 1985). As the [SO_4^{2-}] in the brine is consumed by the reduction reaction, the tendency of the system to maintain chemical equilibrium requires that sulfates present in minerals accessible to repository brines dissolve. These sources of additional natural [SO_4^{2-}] were not considered in [the DOE's] analysis.

The assumption that all [SO_4^{2-}] around the repository within an approximately 1 m diffusion length would be available for reaction was considered by [the DOE] to account for [SO_4^{2-}] that may be dissolved from the Salado as well as [SO_4^{2-}] that may diffuse from the Salado (Kanney et al. 2004, p. 13). The approximately 1 m diffusion length was based in part on the assumption that CPR degradation would be essentially complete within 2,000 years (Kanney et al. 2004, Sections 2.3.1 and 3.2.1). The 2,000-year time scale is used by [the DOE] to establish limits for the volume of brine inflow and diffusion length that need to be considered as sources of [SO_4^{2-}]. However, the assumption that CPR degradation would be essentially complete within 2,000 years does not hold for waste panels with the increased iron surface areas that would be present with supercompacted AMWTF waste. Stein and Zelinski (2003, Figure 2) show that CPR biodegradation endures for over 10,000 years for an increasing number of vectors because of decreased brine saturation as the iron surface area increases. TEA has agreed that the effects of increased iron surface areas can be ignored in [PA] for purposes of gas generation impacts because the prolonged CPR degradation reaction conservatively results in less overall gas generation (see Section 5.2.2 [of TEA, 2004]). However, ignoring a prolonged CPR degradation reaction for purposes of limiting the [SO_4^{2-}]-reduction reaction is not conservative and inappropriate. In addition, the microbial degradation rates used in BRAGFLO are consistent with the higher initial reaction rates observed in microbial degradation experiments. Use of these higher initial rates is conservative from the standpoint of estimating gas generation rates, but use of the lower, long-term rates would be more conservative for the purpose of determining the length of time available for [SO_4^{2-}] diffusion.

> The MgO safety factors calculated by [the DOE] fall below the Agency-approved value of 1.67 (EPA, 2001) for *every* [TEA's italics] waste loading scenario considered in [the DOE's] analysis when natural sulfates are included. [The DOE's] calculated safety factors range from 0.94 for the EPA loading scenario (50 percent supercompacted AMWTF waste and 50 percent standard waste) to 1.40 for the DOE realistic Panel X scenario described in Section 5.2.1.2 [of TEA, 2004] (Kanney et al. 2004, Table 12). TEA believes that uncertainties in the quantities of CPR [materials] present in a waste panel and in the extent to which [SO_4^{2-}] reduction will occur are sufficiently great that the Agency-approved safety factor of 1.67 is the minimum that should be maintained…
>
> TEA concludes that the aforementioned DOE study by Kanney et al. (2004) provides useful information but clearly demonstrates that reductions in the effect of methanogenesis due to the availability of natural [SO_4^{2-}] can have a significant adverse effect on MgO safety factors. TEA also believes that not all potential sources for natural [SO_4^{2-}] to enter the repository were considered in [the DOE's analysis and that an acceptable bounding analysis has therefore not been performed...

Furthermore, U.S. EPA (2004, pp. 7-8) concluded that

> [The] DOE's analysis may be correct but uncertainties remain in the quantities of CPR [materials] present in a waste panel and in the extent to which sulfate reduction will occur. More [SO_4^{2-}] may be present in the waste or waste area environment than currently estimated. More waste with high CPR may be placed in a panel than currently anticipated. Because of these uncertainties, [the] DOE needs to ensure that these uncertainties are accounted for in the calculation of the MgO safety factor, even if it appears that there is enough MgO for [PA] calculations.
>
> Methanogenesis may not occur because of the presence of excess [SO_4^{2-}] in the system, so MgO safety factor calculations need to assume all [C] could be converted to [CO_2] until the Department provides adequate evidence that methanogenesis is the dominant process…

MgO-6.2.4 Changes since the CRA-2004 in the MgO Excess Factor

In March 2004, the EPA approved the DOE's request to dispose of supercompacted waste in the WIPP (Marcinowski 2004; Trinity Engineering Associates 2004; U.S. Environmental Protection Agency 2004). As part of its approval, the EPA specified that the DOE maintain an MgO excess factor of 1.67, calculated assuming that there would be no microbial methanogenesis in the repository. The elimination of methanogenesis from consideration in WIPP PA is discussed in Leigh et al. (2005, Section 2.4) and Cotsworth (2005). In some cases, maintaining an excess factor of 1.67 has, in turn, required that the DOE emplace additional MgO in place of TRU waste (Section MgO-2.1.1). Therefore, the DOE continued to explore various possible approaches to support a PCR for EPA approval of a reduction in the MgO excess factor.

MgO-6.2.4.1 The RSI's Expert Review of the DOE's Use of MgO

In 2005 and 2006, the Institute for Regulatory Science (RSI) of Alexandria, VA, reviewed the DOE's use of MgO in the WIPP, especially the need to emplace additional MgO in rooms with supercompacted waste.

The RSI carries out studies; assesses regulatory actions; conducts peer reviews of studies by other organizations; and provides training and other services to federal, state, and local governments in the biological, chemical, health, and physical sciences, and in all areas of engineering. The RSI was established in 1985 and received nonprofit status in 1986. From 1989

until mid-1995, the RSI operated through the University of Maryland at Baltimore and Temple University in Philadelphia, PA. Since then, the RSI has operated as an independent organization. The RSI has a small in-house staff and utilizes individuals in other organizations, especially for peer reviews (Institute for Regulatory Science [RSI] 2008).

In 2005, the RSI assembled an expert panel chaired by Edward Abbott, Professor of Chemistry at Montana State University in Bozeman, MT. The other members of this panel were Gudmundur S. ("Bo") Bodvarsson, Director of the Earth Sciences Division at Lawrence Berkeley National Laboratory in Berkeley, CA; R. Ian Miller, President of the GoldSim Technology Group, LLC, in Issaquah, WA; Dade W. Moeller, President of Dade Moeller and Associates, Inc., and Professor Emeritus at Harvard University in Cambridge, MA; and Richard Wilson, Mallinckrodt Research Professor of Physics at Harvard University. The GoldSim Technology Group, LLC, develops, maintains, and applies the GoldSim software package for decision analysis and PA calculations for radioactive waste repositories and other environmental studies. Dade Moeller and Associates provides services in the environmental and occupational sciences. A. Alan Moghissi, President of the RSI, oversaw the operation of the expert panel during its review. Sorin R. Straja, Vice President for Science and Technology of the RSI, served as the technical secretary for the expert panel.

The RSI expert panel met for two days in July 2005 in Carlsbad, NM. Several DOE and DOE-contractor personnel made detailed presentations to the panel on

1. The methodology used for WIPP PA
2. The history of engineered barriers in the WIPP disposal system, especially MgO
3. Aspects of WIPP chemistry and geochemistry related to MgO
4. Calculation of the MgO excess factor
5. Preliminary PA calculations pertinent to possible reductions in the amount of excess MgO emplaced in the repository
6. Possible approaches to support a PCR for EPA approval of a reduction in the MgO excess factor

The members of the panel prepared a summary of their initial impressions and identified issues to be addressed at the next meeting (Institute for Regulatory Science [RSI] 2006).

The RSI expert panel met again for two days in September 2005 in Albuquerque, NM. DOE and DOE contractor personnel responded to several issues raised during the first meeting of the panel, including the following:

1. The history of implementing and using MgO in the WIPP disposal system and its description in WIPP regulatory-compliance documents
2. MgO-related assumptions in WIPP PA

3. Issues that arose while scoping PA calculations for possible reductions in the amount of excess MgO

4. Issues pertinent to the availability of naturally occurring SO_4^{2-} in and around the repository

5. Possible approaches to support a PCR for EPA approval of a reduction in the MgO excess factor

The panel also met in a closed session to discuss a possible PCR (Institute for Regulatory Science [RSI] 2006).

Subsequent to the September 2005 meeting, Abbott prepared a set of draft findings and recommendations, which were modified and included in Institute for Regulatory Science (RSI) 2006. At the same time, R. Patterson, D. Mercer, T. W. Thompson, and M. B. Gross assembled brief summaries of the WIPP disposal system and its use of MgO as the engineered barrier from previous WIPP regulatory-compliance documents; these summaries also appeared in Institute for Regulatory Science (RSI) 2006. The report of the expert panel also included excerpts from the EPA's regulations related to natural and engineered barriers in the WIPP (Institute for Regulatory Science [RSI] 2006).

The RSI expert panel reported nine findings. The first three findings dealt with possible generation of CO_2 from microbial consumption of CPR materials in the WIPP.

The first question posed to the panel ("Criterion 1") was, "Is the assumption that *cellulosic* materials [in TRU waste] could be consumed by microbes, under conditions prevailing at WIPP, consistent with scientific and engineering principles, standards, and practices?" (Institute for Regulatory Science [RSI] 2006, p. 19).

In response to this question, the Institute for Regulatory Science (RSI) (2006, p. 19) found

> The assumption that *cellulosic* materials [the RSI's italics] could be consumed by microbes under conditions prevailing at WIPP is consistent with scientific and engineering principles, standards, and practices. Because a small portion of the material will be incorporated into the microbial biomass, biodegradation is unlikely to reach 100%. An extensive review by staff members … led to the conclusion that communities of halophilic, fermentative, and methanogenic are potentially capable of metabolizing cellulosic materials, under expected WIPP conditions.
>
> The biodegradation of cellulosic materials could progress under at least two scenarios:
>
> 1. During the initial phases of emplacement of waste at WIPP when [O_2] is available; and
>
> 2. As a consequence of human intrusion that resulted in brine reaching and interacting with the waste.

However, the RSI expert panel also agreed with two of the conclusions reached by the U.S. National Academy of Sciences' Committee on the Waste Isolation Pilot Plant (National Research Council [NRC] Committee on the Waste Isolation Pilot Plant 1996 and 2001), which RSI (Institute for Regulatory Science [RSI] 2006, p. 19) stated as

> Two committees of the National Research Council (NRC, 1996; 2001) came to the conclusion that

1. The biodegradation of cellulosic materials is expected to be minimal; but

2. For that portion that does undergo biodegradation, the rate is expected to be maximum during the pre-closure period.

Finally, the RSI expert panel stated that they "made no attempt to independently quantify the extent and rate of biodegradation of *cellulosic* materials" (Institute for Regulatory Science [RSI] 2006, p. 10).

The second question posed to the panel ("Criterion 2") was, "Is the assumption that *plastic* materials … in TRU waste could be consumed by microbes, under conditions prevailing at WIPP, consistent with scientific and engineering principles, standards, and practices?" (Institute for Regulatory Science [RSI] 2006, p. 10).

In response, the Institute for Regulatory Science (RSI) (2006, pp. 10–11) found

> The assumption that *plastic* materials [the RSI's italics] will be completely metabolized by microbes under conditions prevailing at WIPP is not consistent with scientific and engineering principles, standards, and practices. However, partial metabolization of such materials is possible, but if it occurs at all, then its rate and extent of reaction is expected to be significantly lower than that for cellulosic materials. Under WIPP conditions, neither thermo-oxidation nor photo-oxidation can occur, and therefore the biodegradation of polymers, such as polyethylene, will be highly unlikely. It is of particular interest to note that, in its regulations [U.S. EPA, 1992a, p. 54,460; U.S. EPA, 1992b, p. 54,461], the EPA … defined the following polymers as nonbiodegradable:
>
> - polyethylene,
> - high density polyethylene (HDPE),
> - polypropylene, polystyrene,
> - polyurethane,
> - polyacrylate,
> - polynorborene,
> - polyisobutylene,
> - ground synthetic rubber,
> - cross-linked allylstyrene,
> - tertiary butyl copolymers.
>
> The EPA regulations, cited above, which were developed as an outgrowth of experience with land disposal facilities, as well as laboratory studies, involved significant public participation.
>
> The rate of biodegradation of a polymer depends on the mechanism of degradation; its structure; and the presence of the required microbial populations and environmental conditions that enhance their growth. Although the understanding of polymer degradation is limited, there is sufficient information indicating that critical parameters include oxygen, temperature, and water.

> In recent years there has been an increasing recognition of a need to develop polymers that would be biodegradable. Through modifications, such as changing the chemical structure of certain plastic materials so as to initiate and accelerate the biodegradation process, this goal has been achieved. In fact, many polymers on the market today, that heretofore were considered not to be subject to biodegradation, are now degradable. However, the polymers likely to be disposed at WIPP are not expected to belong to the new classes of biodegradable polymers. In addition, any biodegradable polymers that may have been present in the initial TRU waste should have been biodegraded by the time it was disposed at WIPP.
>
> On the basis of the information that was provided, the [RSI expert panel] concluded that the fraction of plastics that is expected to be biodegraded under the conditions existing within the WIPP is small. This conclusion is consistent with the assessment of the NRC (2001) and the regulatory decisions of the EPA. However, the [RSI expert panel] made no attempt to independently quantify the extent and the rate of biodegradation of *plastic* materials [the RSI's italics].

The third question ("Criterion 3") was, "Is the assumption that *rubber* materials will be consumed by microbes, under the conditions prevailing at WIPP, consistent with scientific and engineering principles, standards, and practices?" (Institute for Regulatory Science [RSI] 2006, p. 11).

The Institute for Regulatory Science (RSI) (2006, pp. 11–12) found

> The assumption that commercial *rubber* materials [the RSI's italics] will be completely metabolized by microbes, under conditions prevailing at WIPP, is not consistent with scientific and engineering principles, standards, and practices. The extent of biodegradation of rubber materials, if it occurs, is likely to be significantly lower than that for plastic materials, and very much less than that for cellulosic materials.
>
> Raw *natural* rubber [the RSI's italics] obtained from the latex of *Hevea brasiliensis* trees, contains more than 90% poly(cis-1,4-isoprene). The remaining constituents include proteins, lipids, carbohydrates, resins, and inorganic salts. Raw *synthetic* rubber [the RSI's italics] consists essentially of poly(cis-1,4-isoprene) rubber with the addition of antioxidants to prevent ageing. The monomer units of natural rubber contain unsaturated bonds that are susceptible to thermo-oxidative degradation, attack by ozone, or degradation by [ultraviolet]-light. In contrast, the synthetic alternatives to the natural rubber can withstand elevated temperatures for long times even under relatively aggressive conditions. Commercial rubber (natural or synthetic) is usually vulcanized (crosslinked) by heating in the presence of sulfur. The lack of biodegradability of commercial rubber products is the consequence of inhibition of the oxidation process by antioxidants.
>
> On the basis of the information that was provided, the [RSI expert panel] concluded that the fraction of rubber that is expected to be biodegraded under the conditions existing within the WIPP is small. The conclusion is consistent with the assessment of the NRC (2001) and the regulatory decisions of the EPA. However, the level and the rate of biodegradation of *rubber* materials [the RSI's italics], as small as they may be, were not independently quantified by [the RSI expert panel].

The fourth finding of the RSI expert panel dealt with the performance of MgO in the WIPP. The fourth question ("Criterion 4") was, "Under conditions prevailing at WIPP, is the assumption that all the MgO, as presently emplaced, will be available to react with CO_2 consistent with scientific and engineering principles, standards, and practices?" (Institute for Regulatory Science [RSI] 2006, p. 12).

The Institute for Regulatory Science (RSI) (2006, pp. 12-13) found

> Under conditions prevailing at WIPP, [the RSI expert panel] has concluded that the assumption that 100% of the MgO will be available to react with CO_2 is not consistent with scientific and engineering principles, standards, and practices.
>
> The processes that will occur in the emplacement rooms are very complex. They will involve the interplay of multiple processes, including the mechanical creep of the salt formation; the development of a gaseous phase consisting mostly of CO_2; and the gradual inflow of brine from the surrounding saturated salt. These processes will likely result in a very heterogeneous hydrological and chemical environment within the emplacement rooms. Although hydrological and chemical gradients in the gas and liquid phases within the rooms will tend to equilibrate thermodynamic and chemical conditions, local pockets of unreacted MgO are likely to be present for long periods of time. For these reasons, the [RSI expert panel] believes that 100% reaction of the MgO with CO_2 is not likely to occur. Nonetheless, the [RSI expert panel] has concluded that most of the MgO will be active in chemical reactions.

The fifth and sixth findings of the RSI expert panel involved the performance of the WIPP in the hypothetical absence of MgO. (The DOE has never requested that the EPA approve eliminating MgO from the WIPP, only that the EPA approve reducing the amount of excess MgO that the DOE must emplace.)

The fifth question ("Criterion 5") was, "Assuming that only cellulosic materials are consumed by microbes, is it consistent with scientific and engineering principles, standards, and practices to conclude that, in the absence of MgO, the solubility of actinides will be such that releases to the accessible environment will still be below the EPA limits?" (Institute for Regulatory Science [RSI] 2006, p. 13).

The Institute for Regulatory Science (RSI) (2006, p. 13) found

> "On the basis of the information received by the [RSI expert panel], it is likely that releases to the accessible environment will be below the EPA regulatory limits. However, the evidence received by the [RSI expert panel] is not sufficient to definitely support this conclusion.

The sixth question ("Criterion 6") was, "Assuming that all cellulosic, plastic and rubber materials are consumed by microbes, is it consistent with scientific and engineering principles, standards, and practices to conclude that, in the absence of MgO, the solubility of the actinides will be such that releases to the accessible environment will still be below the EPA limits?" (Institute for Regulatory Science [RSI] 2006, p. 13).

The Institute for Regulatory Science (RSI) (2006, pp. 13–14) found

> On the basis of the information received by the [RSI expert panel], it is likely that releases to the accessible environment will be below the EPA regulatory limits. However, the evidence received by the [RSI expert panel] is not sufficient to definitely support this conclusion.

The seventh criterion and finding dealt with the application of "acceptable knowledge" to the characterization of the concentrations of CPR materials in TRU waste, and will not be discussed herein.

The eighth question ("Criterion 8") was, "Is the requirement to emplace a 67% MgO excess consistent with as low as reasonably achievable (ALARA) scientific and engineering principles, standards, and practices? Is the associated increased and real risk to the affected workers and the general public imposed by this requirement offset by the potentially reduced risk to future generations?" (Institute for Regulatory Science [RSI] 2006, p. 15).

The Institute for Regulatory Science (RSI) (2006, p. 15) found

> In reference to Finding 4, the [RSI expert panel] has concluded that most of the MgO will be available for chemical reaction. In reference to Findings 1-3, the [RSI expert panel] has concluded that only a small fraction of the CPR materials is likely to be biodegraded to produce CO_2. In reference to Findings 5-6, the [RSI expert panel] believed that it is likely that the EPA release standards would be met, even if the amount of MgO is less than the quantity required to consume all the CO_2 produced. Therefore, the [RSI expert panel] concludes that 67% MgO excess (i.e., 67% in excess of the stoichiometric quantity required assuming complete biodegradation of CPR materials to CO_2) is not necessary.

The ninth criterion and finding dealt with whether it would be reasonable for the DOE to convene another expert panel to "reach a consensus on the potential extent of consumption of various components of CPR materials" and, if so, if other issues should be considered. The RSI expert panel's response to this criterion is included below in the discussion of its recommendations.

The Institute for Regulatory Science (RSI) (2006, p. 16) made two recommendations:

1. The DOE should consider convening an Expert Elicitation Panel to provide a more realistic and accurate estimate of the potential extent of biodegradation of various components of CPR materials likely to be emplaced in the WIPP.

2. The DOE should consider performing a single-room realistic analysis of the complex processes involved, including gas generation, chemical reactions, biodegradation, and mechanical creep.

In its ninth finding, the RSI expert panel recommended that, in addition to providing "more realistic and accurate estimate[s]" of the fractions of the CPR materials that would be consumed by microbial activity in the WIPP, the expert elicitation panel should also estimate the "fraction of the emplaced MgO [that] is likely to react with the CO_2" and "the performance consequences of a partial or complete shortfall in MgO buffering capacity" (Institute for Regulatory Science [RSI] 2006, p. 16).

The RSI expert panel did not provide any details on how the DOE should perform "a single-room realistic analysis of the complex processes involved" in the WIPP.

MgO-6.2.4.2 The DOE's PCR for EPA Approval of Reducing the MgO Excess Factor from 1.67 to 1.2

In April 2006, the DOE submitted a PCR for EPA approval of reducing the MgO excess factor from 1.67 to 1.2 (Moody 2006). To justify its request, the DOE used reasoned arguments regarding health-related transportation risks to the public, the cost of emplacing MgO, and the

uncertainties inherent in predicting the extent of microbial consumption of CPR materials during the 10,000-year WIPP regulatory period.

The EPA responded by requesting that the "DOE needs to address the uncertainties related to MgO effectiveness, the size of the uncertainties, and the potential impact of the uncertainties on long-term performance" (Gitlin 2006). In particular, the EPA instructed the DOE to identify all of the uncertainties related to the calculation of the MgO excess factor, and quantify these uncertainties, if possible.

MgO-6.2.4.3 The EPA's Review of the Consumption of CPR Materials in the WIPP and Its Effects on the MgO Excess Factor

As the DOE began to address the uncertainties related to the MgO excess factor, S. Cohen and Associates (SCA) carried out a review of the possible consumption of CPR materials in the WIPP for the EPA (S. Cohen and Associates 2006). The objectives of this report were the following:

> [T]o identify specific technical questions that must be answered and uncertainties that must be addressed before EPA can consider changing the amounts of MgO backfill that must be placed in the repository to maintain the effectiveness of the engineered barrier. Therefore, a preliminary review of the available data relevant to a number of issues related to the MgO backfill was carried out. This review included chemistry-related issues such as the potential CO_2-generating microbial degradation reactions that could occur within the repository, the extent to which these reactions could occur, and the reactivity of MgO in the repository environment. These issues were addressed by consulting the available scientific literature, including data generated by the WIPP program and a survey of other relevant information. The possibility of conducting experiments to better define the reaction rates and possible extent of the microbial degradation reactions was also considered. Regulatory requirements related to engineered barriers in the WIPP and ways in which uncertainties must be addressed were evaluated as well, and are summarized in this report [SCA, 2006, pp. 1-1 to 1-2].

In addition, the SCA report (S. Cohen and Associates 2006) responded to the findings and recommendations of the RSI expert panel, and to its assessment of the EPA regulations relevant to MgO.

In its first three findings, the RSI expert panel stated that "[t]he assumption that *cellulosic* materials could be consumed by microbes under conditions prevailing at WIPP is consistent with scientific and engineering principles, standards, and practices" (Institute for Regulatory Science [RSI] 2006, p. 9), but that the fraction of plastic and rubber materials "that is expected to be biodegraded under the conditions existing within the WIPP is small" (Institute for Regulatory Science [RSI] 2006, pp. 11 and 12). With regard to the RSI expert panel's first three findings, SCA (S. Cohen and Associates 2006, p. 4-2) stated

> The rates and extent of CPR degradation during the 10,000-year WIPP regulatory period are likely to be influenced by the following:
>
> - Composition of the CPR materials
> - Microbial population

- Chemical and physical environment, including the quantity and salinity of the repository brines, redox conditions, pH, and temperature
- Radiation dose to the CPR materials and associated brines
- Interactions of different processes.

SCA (S. Cohen and Associates 2006, pp. 4-2 through 4-8) reviewed some of the literature pertaining to these factors. SCA described its review as "preliminary." It then reviewed results obtained by the WIPP project and results in the literature pertaining to the possible microbial consumption of CPR materials (S. Cohen and Associates 2006, pp. 4-8 through 4-18).

With regard to the possible extent of microbial consumption of cellulosic materials in the WIPP, SCA (S. Cohen and Associates 2006, pp. 4-11 through 4-12) stated

> A number of factors contribute to the high likelihood that cellulosics will be completely degraded in the WIPP repository. These factors include the variety of microorganisms that can degrade cellulosic materials, the general adaptability of microbes to their environment and available [C] sources, the abundant [SO_4^{2-}] in the repository, and the long regulatory time period.
>
> Although relatively little data appear to be available regarding the chemical effects of radiation on cellulose, it appears low-level radiation may decrease polymer chain length and alter physical and chemical properties of cellulose. It is expected that radiation-induced degradation of cellulose in the WIPP will occur through direct and indirect interaction with ionizing radiation from radionuclides in the waste. The direct interactions, which are interactions of the ionizing radiation with the solid cellulose, initiate scissions on the backbone of the molecules leading to degradation; however, a very small yield of branching also can occur. The presence of oxygen in the repository environment is not required for these scission reactions. Indirect interactions will occur through the radiolysis of water. As mentioned above in Section 4.1.4, the radiolysis of water produces hydroxyl radicals ($^{\bullet}OH$). Hydroxyl radicals can cause hydrolytic cleavage of glycoside linkages in cellulose, which would be expected to facilitate microbial degradation.
>
> Although some radiation-induced effects could act to limit cellulose biodegradation, on balance, the overall effects of radiation on cellulose appear to increase the likelihood of microbial degradation of cellulose through cleavage of the polymer backbone and decreased molecular weight. The available literature appears to indicate that microbial and radiation-induced degradation of cellulosics may proceed virtually to completion over 10,000 years if water is present in the WIPP repository.

With regard to the possible extent of microbial consumption of plastic materials, SCA (S. Cohen and Associates 2006, p. 4-15) stated

> Literature data are available regarding both microbial degradation and radiation-induced degradation of plastics such as polyethylene and [polyvinylchloride]. Microbial degradation of plastics generally is less extensive in the short term than microbial degradation of cellulosic materials, based on the data identified in the literature. Radiolytic processes may degrade plastics directly, and also may indirectly contribute to the long-term biodegradability of plastics by altering their chemical and physical properties. The likelihood of significant radiolytic effects on plastics degradation would depend on the dose. The dose to WIPP waste can be calculated from the DOE's inventory projections (Leigh and Trone 2005). The presence of oxygen in the repository before closure and for a period of time after closure could affect both radiolytic and microbial processes. This preliminary evaluation of the data indicates that plastic degradation may occur over 10,000 years in the WIPP repository.

SCA (S. Cohen and Associates 2006, pp. 3-4 through 3-6) also responded to the RSI expert panel's statement in its second finding (Institute for Regulatory Science [RSI] 2006, pp. 10–11) that the EPA had defined polymers such as polyethylene, HDPE, and polypropylene as nonbiodegradable:

> RSI (2006) cited EPA's RCRA [Resource Conservation and Recovery Act] regulations at 40 CFR 264.314 and 40 CFR 265.314 to support the contention that 'the fraction of plastics that is expected to be biodegraded under conditions existing within the WIPP is small' (Finding 2). For example, 40 CFR 264.314 lists a number of high molecular weight polymers, such as polyethylene, polypropylene, and ground synthetic rubber, as non-biodegradable sorbents to sequester free liquids prior to disposal in surface hazardous landfills. EPA has listed in its *Federal Register* notice 'Final Rule Regarding Liquids in Hazardous Waste Landfills' [U.S. EPA, 1992a; 1992b] on November 18, 1992, of certain high-density polymers as non-biodegradable sorbents in RCRA landfills. The *Federal Register* notice did not, however, provide any background information supporting the contention that such high molecular weight polymers were non-biodegradable. The Agency merely stated that such materials 'have proved to be highly resistant to biodegradation.' In an earlier *Federal Register* notice of June 1987, when EPA first proposed the use of high-molecular weight polymers as nonbiodegradable sorbents, the notice stated the following [U.S. EPA, 1987, p. 23,696]:
>
> > *[T]he Agency now believes that a different criterion should be used to determine if an organic polymer is biodegradable. The Agency proposes to determine this alternative criterion by using tests which involve incubating the absorbent materials with prepared stock cultures of various microorganisms under ideal conditions for their growth. This incubation demonstrates the fungal resistance of polymers and is used by the American Society for … Testing [and] Materials laboratory test ASTM Method G21-70… [SCA's italics].*
>
> The relevance of the fact that certain plastics and rubbers are defined as non-biodegradable for use as sorbents in RCRA surface landfills to the assumption that such materials are nonbiodegradable in the context of the WIPP environment is questionable based on the following considerations:
>
> - Under 40 CFR 264.117, post-closure monitoring is limited to 30 years unless extended by the EPA Regional Administrator, while at the WIPP, regulatory compliance must be demonstrated through PA for 10,000 years.
>
> - Under 40 CFR 264.314, EPA offers three tests to demonstrate that materials not specifically listed as non-biodegradable sorbents in §264.314(e)(1)(i) and (ii) can be used as non-biodegradable sorbents. Two of the tests are American Society for Testing and Materials (ASTM) procedures and one is an Organisation for Economic Co-operation and Development (OECD) procedure. In 1995, EPA decided to add the OECD test to §264.314(e)(2) as described in its *Federal Register* notice [U.S. EPA, 1995]. In the *Federal Register* notice, EPA noted that:
>
> > *[T]he OECD [T]est 301B is a test for biodegradability in an aerobic environment, as are the two ASTM tests that were promulgated in the November 18, 1992 rule. The Agency also recognizes that the actual environment in which the sorbents will be used, i.e., in a container in a landfill, will be anaerobic. The Agency does not know, however, of any published widely accepted tests for the biodegradability of materials in anaerobic conditions that would be practical for purposes of this rule. The Agency believes, however, that OECD 301B is an acceptable surrogate for determining if a sorbent will biodegrade in containerized liquids in a hazardous waste landfill [SCA's italics].*

> The environment in the WIPP will become anaerobic shortly after closure and will remain so throughout the regulatory period. Therefore, the assumption that high molecular weight polymers will not biodegrade may not be valid at WIPP.
>
> - While materials may be judged functionally as non-biodegradable sorbents in RCRA surface landfills, they can achieve that functionality even if limited biodegradation actually occurs. In the WIPP, on the other hand, at least one mol of MgO backfill must be provided for each mol of CO_2 generated from CPR decomposition. This places a greater burden on defining quantitatively the extent to which biodegradation occurs at the WIPP.

The Resource Conservation and Recovery Act (RCRA) definition of some plastic sorbents as nonbiodegradable is based mainly on observations over relatively short time frames and testing in aerobic environments. These conditions do not appear relevant to the long-term WIPP environment or regulatory period of performance. Therefore, the RCRA definition of some plastic sorbents as nonbiodegradable appears to have essentially no relevance to the determination of whether plastic and rubber materials are likely to be substantially biodegraded in the WIPP repository.

With respect to the possible extent of microbial consumption of rubber materials, SCA (S. Cohen and Associates 2006, p. 4-18) stated

> Available WIPP and literature data indicate that rubber materials likely to be present in the WIPP repository will be partially degraded by microbes. Radiation appears to affect both the physical and chemical properties of rubber, and in WIPP experiments appeared to enhance microbial degradation. The presence of oxygen in the repository before closure and immediately after closure could affect the physical and chemical properties of the rubber. This preliminary evaluation of the data indicates that rubber degradation may occur over 10,000 years in the WIPP repository.

The RSI expert panel's fourth finding was that, "100% reaction of the MgO with CO_2 is not likely to occur. Nonetheless … most of the MgO will be active in chemical reactions" (Institute for Regulatory Science [RSI] 2006, p. 13). SCA (S. Cohen and Associates 2006, p. 5-1) agreed with this finding:

> Review of the available information related to MgO reactivity indicates that MgO is likely to react in the repository to control CO_2 concentrations in the brine. However, it is possible that a small fraction of the MgO could become unavailable for reaction because of physical segregation. This relatively small source of uncertainty has been adequately accounted for by using an MgO safety factor greater than one.

With regard to the RSI expert panel's fourth finding, SCA (S. Cohen and Associates 2006, p. 6-1) also stated

> [T]he MgO backfill is likely to perform as designed and control brine pH and CO_2 concentrations in the repository. Incomplete reaction of the MgO with brine and CO_2 is unlikely to occur unless the MgO is physically segregated from the brine or CO_2; if such physical segregation should occur, the effective MgO safety factor would be decreased by a commensurate amount. The recent changes in MgO placement methods, with a constant safety factor calculated for each disposal room, limit the potential effects of inhomogeneous distribution of CPR in the waste, and are likely to minimize the uncertainties associated with possible physical segregation of the MgO from brine and CO_2. However, the small remaining uncertainty related to physical segregation should be addressed by the MgO safety factor.

The RSI expert panel's fifth and sixth findings, which responded to the question, "Assuming that only cellulosic materials [or all of the CPR materials] are consumed by microbes, is it consistent with scientific and engineering principles, standards, and practices to conclude that, in the absence of MgO, the solubility of actinides will be such that releases to the accessible environment will still be below the EPA limits?" (Institute for Regulatory Science [RSI] 2006, p. 13), were that: "On the basis of the information received by the [RSI expert panel], it is likely that releases to the accessible environment will be below the EPA regulatory limits. However, the evidence received by the [RSI expert panel] is not sufficient to definitely support this conclusion" (Institute for Regulatory Science [RSI] 2006, pp. 13–14).

SCA did not specifically address whether, in the absence of MgO, the WIPP would continue to meet the EPA's containment requirements, given microbial consumption of cellulosic materials, or microbial consumption of all of the CPR materials. However, SCA (S. Cohen and Associates 2006, p. 3-4) stated

> The use of at least one engineered barrier at WIPP is required by 40 CFR 194.44 to 'prevent or substantially delay the movement of water or radionuclides toward the accessible environment.' For the CCA, DOE identified and EPA approved MgO backfill in the disposal rooms as the only WIPP engineered barrier (DOE 1996[b]). MgO backfill was designed to maintain alkaline pH and mitigate the effects of CO_2 generation in the disposal rooms, thereby controlling actinide solubilities in intruding brines ([U.S.] EPA 1997). The inclusion of MgO backfill as an engineered barrier remained unchanged for the CRA, although the required safety factor and backfill emplacement strategy have changed since the CCA….

Furthermore, in response to a recommendation by the NRC (2001) that "The committee recommends that the net benefit of MgO used as backfill be reevaluated. The option to discontinue emplacement of MgO should be considered," SCA (S. Cohen and Associates 2006, p. 3-1) stated that

> Removing the MgO backfill from the repository design will likely affect predictions of gas generation and actinide solubilities. Additional information would be necessary before EPA could consider elimination of, or significant modifications to, the MgO backfill. EPA regulations require assurance requirements (40 CFR 191.14), including an engineered barrier, to compensate for uncertainties in the prediction of future repository performance and provide increased confidence in the disposal system. The MgO backfill is the only engineered barrier in the WIPP repository and an engineered barrier is required by regulation….

The RSI expert panel's seventh finding, which dealt with the application of "acceptable knowledge" to the characterization of the concentrations of CPR materials in TRU waste, and SCA's response to this finding are not discussed herein.

In its eighth finding, the RSI expert panel stated that "[a] 67% MgO … is not necessary" (Institute for Regulatory Science [RSI] 2006, p. 15). SCA (S. Cohen and Associates 2006, p. 5-1) responded by stating that

> In the original certification review (EPA 1997), EPA accepted MgO as the only engineered barrier (40 CFR 194.44). This acceptance was predicated on the assumption that MgO was necessary to control chemical conditions in disposal rooms. [U.S.] EPA (1997) also stated that excess MgO, i.e., the MgO safety factor, was a conservative measure, an assurance requirement, necessary to overcome the uncertainty associated with predicting the expected future(s) of the WIPP disposal system. The engineered barrier is of critical importance because of a number of uncertainties

> associated with repository performance over the long regulatory time period. Assuming that all CPR [C] could be converted to CO_2 was a conservative assumption associated with the engineered barrier's performance. If this conservative assumption is no longer included in the determination of the MgO safety factor, the potential significance of other uncertainties would increase, such as those related to CPR inventory, CPR degradation rates and extents, and the possible physical segregation of small amounts of MgO. The MgO safety factor must account for these uncertainties in the absence of conservative assumptions regarding the extent of CPR degradation to form CO_2. Because of the importance of the MgO backfill, an understanding of the potential effects of a shortfall would be necessary before the technical feasibility of significantly reducing the MgO safety factor could be assessed.

In its summary and conclusions, SCA listed "a number of potential technical issues … related to whether the amount of MgO placed in the repository can be reduced without affecting repository safety" (S. Cohen and Associates 2006, p. 6-1). These included (1) the availability of MgO, which could be reduced by the possible physical segregation of small quantities of MgO from brine; (2) uncertainties in the quantities of CPR materials in the inventory; and (3) the extent of microbial consumption of CPR materials during the 10,000-year regulatory period.

SCA (S. Cohen and Associates 2006, pp. 6-1 to 6-2) also identified several issues that could affect the possible extent of microbial consumption of CPR materials. These included the following:

1. The adaptability of microbes to different substrates and environments

2. The short-term effects of microbial consumption of CPR materials by aerobic bacteria and fungi

3. The short-term effects of α radiolysis of CPR materials (i.e., radiolysis under oxic conditions) on the biodegradability of these materials

4. The length of time that molecular oxygen (O_2) will be present

5. The long-term effects of α radiolysis of CPR materials (i.e., radiolysis under anoxic conditions) on the biodegradability of these materials

6. The long-term, integrated radiation dose to CPR materials

7. Uncertainties associated with the predicted availability of brine in the repository

In its ninth finding and its first recommendation, the RSI expert panel stated that (1) "[t]he DOE should consider convening an Expert Elicitation Panel to provide a more realistic and accurate estimate of the potential extent of biodegradation of various components of CPR materials likely to be emplaced in the WIPP"; (2) the Expert Elicitation Panel should estimate the "fraction of the emplaced MgO [that] is likely to react with the CO_2"; and (3) that the Expert Elicitation Panel should estimate "the performance consequences of a partial or complete shortfall in MgO buffering capacity" (Institute for Regulatory Science [RSI] 2006, p. 16). SCA (S. Cohen and Associates 2006, p. 3-4), responded

Requirements related to the elicitation of expert judgment for use in compliance applications are provided in 40 CFR 194.26. With regard to the circumstances under which expert judgment can be used for compliance applications, the regulation states [40 CFR 194.26(a)]:

> *Expert judgment, by an individual expert or panel of experts, may be used to support any compliance application, provided that expert judgment does not substitute for information that could reasonably be obtained through data collection or experimentation* [SCA's italics].

In its summary and conclusions, SCA (S. Cohen and Associates 2006, pp. 6-2 through 6-3) went on to describe the "information that could reasonably be obtained through data collection or experimentation" with regard to the possible extent of microbial consumption of CPR materials:

> The results of the preliminary review described in this report indicate that cellulosics may be completely degraded in the repository environment over the 10,000-year regulatory period. The preliminary review of information regarding the possible extent of plastics and rubber degradation in the repository is less conclusive; therefore, additional literature review and experimental investigations may be necessary to determine the likely extent of radiolytic and microbial degradation of plastics and rubber during the 10,000-year regulatory period. Processes likely to affect waste during use, storage, transport, and the early disposal period include degradation by aerobic bacteria and fungi, and radiolysis in the presence of $[O_2]$. Estimation of the length of time $[O_2]$ will persist in the repository and the radiation doses to waste could be used to determine the likely effects of these processes. Although these processes may not significantly affect short-term rates and extents of degradation of CPR, their effects could influence mechanisms, rates, and extents of CPR degradation over the long WIPP regulatory time period. The available literature should be reviewed to determine whether these early degradation processes and long-term radiolysis under anaerobic conditions are likely to make CPR more susceptible to microbial degradation in the longer-term anaerobic WIPP environment.
>
> Any assessment of the extents of degradation of CPR should include an estimation of associated uncertainties, which should be incorporated in the MgO safety factor. These estimated uncertainties should reflect all possible physical and chemical processes that might occur over 10,000 years including:
>
> - The adaptability of microbes to different substrates and environments
> - Potential physical segregation of small quantities of MgO from brine
> - CPR inventory uncertainties
> - Effects of short-term aerobic radiolysis and biodegradation reactions on long-term microbial degradation of CPR
> - Effects of long-term anaerobic radiolytic processes on CPR biodegradation
> - Uncertainties associated with the predicted availability of brine in the repository
>
> EPA regulations require that expert judgment should not be substituted for available experimental data or data that could be obtained from a reasonable set of experiments (40 CFR 194.26). The results of this review have indicated that literature describing experimental data is available that might be used to reduce the uncertainties associated with the extent of CPR degradation in the WIPP repository and improve understanding of WIPP's future performance. Consequently, use of expert judgment to assess the likely extents of CPR degradation in the WIPP repository may not be justified at this time and would require adequate justification by DOE. If the use of expert judgment is justified, this judgment should include not only the likely extents of CPR degradation, but also the associated uncertainties, taking into account the factors listed above.

> A more extensive evaluation of the available WIPP and non-WIPP literature should be carried out to determine whether the data are sufficient for estimating the likely extent of CPR degradation during the 10,000-year regulatory period, or whether experiments might be designed to determine the probable extents of degradation of the various materials over this long regulatory time period. The goal of the literature review and experimental studies would be to adequately quantify or capture system uncertainties, including both the uncertainties associated with the quantities of CPR in the repository and the chemical uncertainties related to the CPR degradation reactions and reactions of the MgO backfill. Sufficient excess MgO (an adequate safety factor) needs to be emplaced in each disposal room to compensate for the range of uncertainties related to CPR degradation and the effective performance of the MgO engineered barrier, thereby ensuring WIPP's expected safe performance in the future.

Finally, SCA noted that the RSI expert panel recommended that "[t]he DOE should consider performing a single-room realistic analysis of the complex processes involved, including gas generation, chemical reactions, biodegradation, and mechanical creep" (Institute for Regulatory Science [RSI] 2006, p. 16). However, SCA did not comment on this recommendation.

MgO-6.2.4.4 The DOE's Assessment of the Uncertainties Related to the MgO Excess Factor

The DOE carried out an analysis (Vugrin, Nemer, and Wagner 2006) and several supporting analyses (Brush and Roselle 2006; Brush et al. 2006; Clayton and Nemer 2006; Deng et al. 2006; Kanney and Vugrin 2006; Kirchner and Vugrin 2006) to respond to the EPA's request for additional information on "the uncertainties related to MgO effectiveness, the size of the uncertainties, and the potential impact of the uncertainties on long-term performance" (Gitlin 2006).

Vugrin, Nemer, and Wagner (2006, p. 2) defined the MgO effective excess factor as "a quantity that incorporates uncertainties into the current definition of the MgO excess factor." The results of the supporting analyses cited above were used to quantify these uncertainties whenever possible and incorporate them in the effective excess factor.

Vugrin, Nemer, and Wagner (2006, p. 8) recognized four categories of uncertainties that could affect the MgO effective excess factor:

1. Uncertainties in the quantities of CPR materials that will be consumed during the 10,000-year WIPP regulatory period

2. Uncertainties in the number of moles of CO_2 produced per mole of organic C in CPR materials (i.e., the CO_2 yield)

3. Uncertainties in the quantity of MgO that will be available to consume CO_2

4. Uncertainties in the number of moles of CO_2 consumed per mole of available MgO

Although Vugrin, Nemer, and Wagner (2006, Appendix A) reviewed previous discussions of the uncertainties inherent in predicting the extent of microbial consumption of CPR materials in 10,000 years (Brush 1995; Gillow and Francis 2003; Brush 2004; the CRA-2004, Appendix BARRIERS), they did not attempt to incorporate them in the MgO effective excess factor.

Therefore, they used the conservative assumption that microbes will consume 100% of the CPR materials to calculate the MgO effective excess factor.

MgO-6.2.4.4.1 Uncertainties in the CO_2 Yield From Microbial Consumption of CPR Materials

Vugrin, Nemer, and Wagner (2006, Section 4) included two sources of the uncertainties inherent in predicting the CO_2 yield per mole of organic C in CPR materials: (1) uncertainty in the quantities of CPR materials emplaced in WIPP disposal rooms, and (2) uncertainty as to the microbial respiratory pathways involved in consumption of the CPR materials (see Section MgO-6.1).

Kirchner and Vugrin (2006) quantified the uncertainties in the estimates of the quantities of CPR materials emplaced in WIPP disposal rooms. Their analysis was based on the differences between the masses of CPR materials measured by real-time radiography (RTR) and visual examination (VE), paired by waste container. They assumed that the VE measurements were the more accurate values and, because they observed no significant bias in the RTR measurements, that the sum of the RTR measurements best estimate the true value of the CPR material quantity in a room. Kirchner and Vugrin (2006) then used Monte Carlo methods "to simulate potential errors in the RTR measurements and to construct a distribution representing the uncertainty in the … CPR [materials] in a room" and concluded "that the uncertainty [standard deviation] on the total mass of CPR [materials] in a room would be less than 0.3%." See Kirchner and Vugrin (2006) for a detailed explanation of this analysis, and Vugrin, Nemer, and Wagner (2006) for an explanation of how the results were incorporated in the MgO effective excess factor.

Vugrin, Nemer, and Wagner (2006) reviewed previous discussions on the effects of microbial respiratory pathways on the CO_2 yield per mole of organic C in CPR materials (Wang and Brush 1996a; Snider 2003d; and Section MgO-6.1). However, Vugrin, Nemer, and Wagner (2006) did not include the effects of possible methanogenesis on the CO_2 yield, because the EPA concluded that Kanney et al. (2004) did not adequately bound the quantity of naturally occurring SO_4^{2-} that could enter WIPP disposal rooms (TEA 2004, pp. 31-33; U.S. EPA 2004, pp. 7-8) and specified that methanogenesis not be included in PA. Therefore, Vugrin, Nemer, and Wagner (2006) included only denitrification and SO_4^{2-} reduction in their analysis. They calculated that microbes would consume 4.89 mol % of the organic C in the CPR materials in the CRA-2004 PABC inventory via denitrification and 0.84 mol % via SO_4^{2-} reduction using SO_4^{2-} in the waste (Vugrin, Nemer, and Wagner 2006, p. 11). The remainder of the organic C, 94.27 mol %, would be consumed via SO_4^{2-} reduction using naturally occurring SO_4^{2-}.

Vugrin, Nemer, and Wagner (2006) quantified the effects of the source of SO_4^{2-} on the MgO effective excess factor. There are three potential sources of SO_4^{2-} for microbial consumption of CPR materials via SO_4^{2-} reduction: (1) SO_4^{2-} in the waste; (2) SO_4^{2-} dissolved in Salado or Castile brines; and (3) SO_4^{2-} contained in DRZ minerals such as anhydrite, gypsum, or polyhalite. Microbes would consume 0.84 mol % of the organic C in the CPR materials in the CRA-2004 PABC inventory via SO_4^{2-} reduction using SO_4^{2-} in the waste, and produce CO_2 with a yield of 1 mol per mol of organic C consumed. The CO_2 yield from the SO_4^{2-} dissolved in WIPP brines would be 1 mol per mol of organic C consumed (see below), but the amount of organic C in the CPR materials that would be consumed via SO_4^{2-} reduction using SO_4^{2-} in brines

had never been calculated. Furthermore, neither the amount of organic C in the CPR materials that would be consumed via SO_4^{2-} reduction using SO_4^{2-} in DRZ minerals nor the CO_2 yield from this process had previously been calculated.

Therefore, Clayton and Nemer (2006) calculated the quantities of dissolved SO_4^{2-} that could enter the repository in brine, and Brush et al. (2006) calculated the CO_2 yield from microbial consumption of CPR materials via SO_4^{2-} reduction using DRZ minerals. The analysis of Clayton and Nemer will be described first because Vugrin, Nemer, and Wagner (2006) assumed that microbes would use SO_4^{2-} from the waste and brine before using the SO_4^{2-} from DRZ minerals. This assumption was conservative because SO_4^{2-} reduction with SO_4^{2-} from the waste and brine would have a higher CO_2 yield than SO_4^{2-} reduction using SO_4^{2-} from DRZ minerals (see below).

Clayton and Nemer (2006) determined at the outset of their analysis that it was conservative to assume that Salado brine will not be a significant source of SO_4^{2-} for microbial consumption of CPR materials. Microbial SO_4^{2-} reduction produces 2 mol of CO_2 per mol of SO_4^{2-} consumed (see Equation MgO.14 in Section MgO-6.1). For every mol of SO_4^{2-} dissolved in GWB, there are about 5.76 mol of dissolved Mg before equilibration with the solids in WIPP disposal rooms (Section MgO-5.1) and 2.54 mol of dissolved Mg after equilibration with these solids (Table MgO-6). Therefore, GWB will always contain enough dissolved Mg to consume all of the CO_2 that would be produced via SO_4^{2-} reduction using the SO_4^{2-} dissolved in this brine.

Clayton and Nemer (2006) then established a probability distribution for the quantities of SO_4^{2-} dissolved in Castile brines that could enter a panel during the 10,000-year regulatory period. They used a Monte Carlo simulation to generate 1,000 possible human-intrusion (drilling) futures. Each of these futures consisted of possible intrusion sequences into all 10 panels of the repository. For each future, they identified the "worst-case" panel: the panel with the most boreholes that intersected a Castile brine reservoir and hence the largest volume of Castile brine in that future. Clayton and Nemer (2006) then used the results from the BRAGFLO calculations for the CRA-2004 PABC (Nemer and Stein 2005) to calculate a probability distribution of the quantities of SO_4^{2-} that could enter a panel from a single intrusion that penetrated a Castile brine reservoir. Finally, Clayton and Nemer (2006) combined the uncertainties in the drilling futures with those in the quantities of Castile-brine SO_4^{2-} from a single intrusion to create a probability distribution of the quantities of SO_4^{2-} that could enter the worst-case panel in 10,000 years. Clayton and Nemer (2006, Figure 1) obtained a complementary cumulative distribution function (CCDF) for the quantities of Castile SO_4^{2-} that could enter a panel in 10,000 years. The mean value of this CCDF was consumption of 2.4 mol % of the organic C in CPR materials via SO_4^{2-} reduction using Castile-brine SO_4^{2-}, with a standard deviation of 5.1 mol %. The mean value was small because almost 30% of the drilling futures did not have intrusions that penetrated a brine reservoir and thus did not have any Castile-brine SO_4^{2-}. Vugrin, Nemer, and Wagner (2006) incorporated these values into the MgO effective excess factor.

Brush et al. (2006) calculated the CO_2 yield from microbial consumption of CPR materials via SO_4^{2-} reduction using DRZ minerals. If microbes consume all the SO_4^{2-} in the waste and in brines that enter WIPP disposal rooms, the resulting concentration gradient from the intergranular brines in the DRZ to the brine(s) in the repository would drive diffusive transport of SO_4^{2-} from the DRZ through saturated voids to the waste. This would in turn decrease the SO_4^{2-} concentration in the brines in the DRZ, which would lead to the dissolution of SO_4^{2-}-

bearing minerals such as anhydrite, gypsum, and polyhalite present in both the marker beds and the nearly pure halites in the Salado (Stein 1985). Because all of these SO_4^{2-}-bearing minerals also contain Ca, dissolution of these minerals would release Ca^{2+} to these intergranular brines and (after transport) to the repository. This Ca^{2+} would remove CO_2 from both the aqueous and gaseous phases by precipitating it as minerals such as calcite ($CaCO_3$); metastable polymorphs of calcite like aragonite, vaterite, or ikaite; monohydrocalcite ($CaCO_3 \cdot H_2O$), amorphous $CaCO_3$ ($CaCO_3$(amorphous [am])), or pirssonite ($Na_2Ca(CO_3)_2 \cdot 2H_2O$). Consumption of CO_2 by precipitation of $CaCO_3$-bearing minerals would reduce the amount of MgO that must be emplaced, thus impacting the calculation of the MgO effective excess factor.

Brush et al. (2006) used the reaction-path code EQ6 (Wolery and Daveler 1992), part of the EQ3/6 geochemical software package (Daveler and Wolery 1992; Wolery 1992a and 1992b), to simulate the precipitation of $CaCO_3$-bearing minerals via the process described above. Brush et al. (2006) quantified the sensitivity of the CO_2 yield to factors such as

1. The initial brine composition and the brine volume
2. Whether carbonation of brucite produces hydromagnesite (5424) or magnesite
3. The effects of organic ligands
4. The effects of precipitation of $CaCO_3$(am) instead of calcite

They assumed that microbes will consume all of the CPR materials in WIPP disposal rooms, and calculated that microbes would consume 4.89 mol % of the organic C in the CPR materials in the CRA-2004 PABC inventory via denitrification using NO_3^- in the waste and produce CO_2 with a yield of 1 mol per mol of organic C consumed; 0.84 mol % of the organic C via SO_4^{2-} reduction using SO_4^{2-} in the waste with a yield of 1 mol of CO_2 per mol of organic C; and 94.27 mol % of the organic C via SO_4^{2-} reduction using SO_4^{2-} from DRZ minerals. Brush et al. (2006) did not include any SO_4^{2-} reduction using Castile-brine SO_4^{2-} because this was an uncertain parameter, the effects of which were incorporated later by Vugrin, Nemer, and Wagner (2006).

Brush et al. (2006) calculated that the effective CO_2 yield from SO_4^{2-} reduction using SO_4^{2-} from DRZ minerals would be 0.54-0.60 mol per mol of organic C in the CPR materials consumed. The overall CO_2 yield, which included denitrification and SO_4^{2-} reduction using SO_4^{2-} from the waste, but not Castile-brine SO_4^{2-}, would be 0.57-0.62 mol per mol of organic C.

A potential concern evaluated by Brush et al. (2006) is that certain elements or compounds in WIPP disposal rooms could inhibit or even prevent calcite precipitation. Dissolved Mg, for example, could inhibit or prevent the precipitation of calcite, depending on its concentration. However, the literature reviewed for this analysis suggested that if an element or compound inhibits or prevents the precipitation of one $CaCO_3$-bearing mineral, another, less-stable $CaCO_3$-bearing mineral precipitates instead. Thus, if dissolved Mg inhibits or prevents the formation of calcite, aragonite would precipitate (Fernández-Diáz et al. 1996), possibly with coprecipitation of as much as 20% $MgCO_3$ in addition to $CaCO_3$ (Morse 1983). The most important point, however, is that if precipitation of $CaCO_3$-bearing minerals were prevented, microbial SO_4^{2-} reduction would cease after the consumption of 4.89 mol % of the organic C in the CPR materials in the CRA-2004 PABC inventory via denitrification, 0.84 mol % via SO_4^{2-} reduction

using SO_4^{2-} in the waste, and 2.4 mol % via SO_4^{2-} reduction using Castile-brine SO_4^{2-}. Any additional consumption of CPR materials could only occur via methanogenesis, which has a CO_2 yield of 0.5 mol per mol of organic C consumed. This is because failure of $CaCO_3$ to precipitate would prevent additional dissolution of SO_4^{2-}-bearing minerals and result in rapid microbial depletion of SO_4^{2-}.

Vugrin, Nemer, and Wagner (2006) accounted for the possibility of magnesian calcite formation in the WIPP by conservatively assuming that any CO_2 not consumed by hydromagnesite (5424) or magnesite in the simulations of Brush et al. (2006) would be incorporated in a solid solution or two-phase mixture with the composition $Mg_{0.22}Ca_{0.78}CO_3$, rather than a polymorph of $CaCO_3$ or pirssonite as predicted by EQ6. Magnesian calcite with the composition $Mg_{0.22}Ca_{0.78}CO_3$ (Meldrum and Hyde 2001) was the most Mg-rich calcite that Brush et al. (2006) found, if dissolved SO_4^{2-} were present, in their literature review of elements or compounds that could inhibit $CaCO_3$ precipitation. Vugrin, Nemer, and Wagner (2006) implemented this assumption by adjusting the effective CO_2 yield from SO_4^{2-} reduction using SO_4^{2-} from DRZ minerals from 0.54-0.60 mol per mol of organic C consumed (Brush et al. 2006) to 0.62-0.69 mol per mol of organic C. They added additional conservatism by using only the upper end of this range, or 0.69 mol of CO_2 per mol of organic C in their calculation of the MgO effective excess factor.

Finally, Vugrin, Nemer, and Wagner (2006, Section 5.2.3, pp. 51-52) combined the yields for each step of the possible microbial consumption of CPR materials as follows:

1. Consumption of 4.89% of the organic C in the CPR materials via denitrification using NO_3^- in the waste, with a yield of 1 mol of CO_2 per mol of organic C

2. Consumption of 0.84% of the organic C via SO_4^- reduction using SO_4^{2-} in the waste, with a yield of 1 mol of CO_2 per mol of organic C

3. Consumption of 2.4 mol % of the organic C via SO_4^{2-} reduction using Castile-brine SO_4^{2-}, with a yield of 1 mol of CO_2 per mol of organic C

4. Consumption of the remaining 91.87 mol % of the organic C via SO_4^{2-} reduction using SO_4^{2-} from DRZ minerals, with a yield of 0.69 mol of CO_2 per mol of organic C

The overall yield for this combination of microbial respiratory pathways and these sources of electron acceptors is 0.715 mol of CO_2 per mol of organic C, with a standard deviation of 0.016 mol of CO_2 per mol of organic C.

MgO-6.2.4.4.2 Uncertainties in the Quantity of MgO that will be Available to Consume CO_2

Vugrin, Nemer, and Wagner (2006, Section 5.0, p. 19) divided these uncertainties into two categories: (1) uncertainties related to the characteristics and performance of MgO, and (2) those related to the characteristics and performance of the WIPP.

Vugrin, Nemer, and Wagner (2006, Section 5.1, p. 20) identified three uncertainties related to MgO: (1) the concentration of reactive constituents in MgO, (2) the extent to which these

reactive constituents react with atmospheric CO_2 prior to emplacement in the repository, and (3) the extent to which they react with CO_2 after emplacement.

Vugrin, Nemer, and Wagner (2006, Section 5.1.1) incorporated the results of Deng et al. (2006a) and Deng, Xiong, and Nemer (2007b) in the MgO effective excess factor because these were the first results obtained directly for Martin Marietta WTS-60, the MgO currently being emplaced in the WIPP. Deng et al. (2006) and Deng, Xiong, and Nemer (2007b) reported that WTS-60 contains 96 ± 5 mol % periclase and lime (see Section MgO-3.3.2). Vugrin et al. (2006, Section 5.1.1) selected these results based on the review by Brush and Roselle (2006, Section 2) of the characterization of the MgO that has been emplaced in the WIPP since it opened in March 1999 (see also Section MgO-3.0).

Vugrin, Nemer, and Wagner (2006, Section 5.1.2, p. 21) assumed that "due to carbonation of periclase prior to emplacement, 0.1% of the emplaced MgO will be unavailable to sequester CO_2 after closure of the repository." This assumption is based on a DOE analysis carried out during the EPA's review of the CCA demonstrating that less than 0.1% of the MgO would be carbonated in 30 years by CO_2 that penetrates the bag over 30 years, and the WTS specification for MgO that states, "The super sack shall function as a barrier to atmospheric moisture and CO_2, which is equivalent to or better than that provided by a standard commercial cement bag" (Washington TRU Solutions 2005, Section 3.3.2 E.).

Vugrin, Nemer, and Wagner (2006, Section 5.1.3, p. 22) also assumed "that all of the periclase will be available to react and will continue to react until all of the CO_2 [in the repository] is consumed." This assumption is based on the conclusion by Brush and Roselle (2006, Section 3.2, p. 8):

> Because all results to date imply that the periclase and lime present in MgO will be available to react – and will continue to react – until all CO_2 in the repository has been consumed, the MgO effective excess factor need not be reduced to account for incomplete reaction. This is consistent with multiplication of the excess factor by 1.

However, Vugrin, Nemer, and Wagner (2006, Section 5.1.3, p. 22) also stated that they did not include uncertainty in the MgO effective excess factor because they could not quantify it.

Vugrin, Nemer, and Wagner (2006, Section 5.2, p. 22) identified five uncertainties in the quantity of MgO that will be available to consume CO_2 related to the characteristics and performance of the WIPP:

1. The probability that the supersacks will rupture and expose MgO to the repository environment (i.e., aqueous and gaseous CO_2)
2. The loss of dissolved MgO from the repository via brine outflow
3. The mass of MgO in individual supersacks
4. The probability that CO_2 will be transported to MgO via brine-mixing processes
5. The probability of physical segregation of MgO from CO_2

Vugrin, Nemer, and Wagner (2006, Section 5.2.1, p. 23) assumed "that all MgO supersacks will rupture due to either microbial degradation or lithostatic loading, making the MgO available for consumption of CO_2."

Clayton and Nemer (2006) established a probability distribution for the fraction of MgO that could be lost via brine outflow during the 10,000-year regulatory period. They used methods similar to those for calculating the probability distribution for the quantities of SO_4^{2-} dissolved in Castile brines that could enter a panel in 10,000 years. Clayton and Nemer (2006) used a Monte Carlo simulation to generate 1,000 possible drilling futures, the brine-outflow results from the BRAGFLO calculations for the CRA-2004 PABC (Nemer and Stein 2005), and an MgO excess factor of 1.2 to calculate a CCDF for the quantities of MgO that could be lost in 10,000 years. The mean of this CCDF was 0.8% of the quantity of MgO initially emplaced, with a standard deviation of 1.9%. The mean value was small because almost 30% of the drilling futures did not have intrusions that penetrated a brine reservoir, and thus did not have any Castile-brine SO_4^{2-}. Vugrin, Nemer, and Wagner (2006, Section 5.2.2, p. 23) incorporated these results into the MgO effective excess factor.

Kanney and Vugrin (2006) updated the analysis of Wang (2000b), which demonstrated that, in the absence of minisacks, molecular diffusion in WIPP brines would be fast enough for MgO to control chemical conditions in the repository (see Section MgO-2.1.2). Kanney and Vugrin (2006) updated Wang's (2000b) work by modifying it to be consistent with the CRA-2004 PABC, and applying it in a modified form to the results of analysis of the effects of supercompacted waste on the long-term performance of the WIPP (Hansen et al. 2004). Neither of these modifications changed the conclusion reached by Wang (2000b), that diffusive transport alone is sufficient to mix CO_2 in the aqueous phase over length scales corresponding to the postclosure height of WIPP disposal rooms and time scales appropriate to that of maximum average brine flows. Both analyses (Wang 2000b; Kanney and Vugrin 2006) conservatively omitted advective and dispersive mixing in the aqueous phase, which would be more effective than diffusion; and diffusive transport of CO_2 in the gaseous phase, which would be very fast relative to that in brine. Therefore, Vugrin, Nemer, and Wagner (2006, Section 5.2.3, p. 25) "assume[d] that the mixing processes expected in the repository will be sufficient to maintain a well-mixed brine."

Vugrin, Nemer, and Wagner (2006, Section 5.2.4, p. 25) assumed that none of the MgO emplaced in WIPP disposal rooms would become physically segregated from the repository environment. The report stated

> Physical segregation of a quantity of MgO from brine or CO_2 due to roof collapse could potentially impact the quantity of MgO available to sequester CO_2; however, the probability of this segregation and the potential impact is negligible. It is probable that any roof failure will occur by lowering of a roof beam onto the waste/MgO stack so that the failed material will not intrude into the stack. Secondly, any failed roof which might occur in smaller blocks will be fractured and will maintain a fairly high permeability to brine and gas for a significant amount of time. Finally, any small scale spalling of the roof into the interstices of the stacks will also probably maintain a high permeability either because grains will not re-cement easily, or if they do, they will form a coherent mass with brine, MgO, and gas outside of them.
>
> Furthermore, the current method that DOE uses to emplace the MgO and calculation of the MgO excess factor on a room basis likely minimizes the possible physical segregation of MgO from

> brine and CO_2. Operational controls guarantee one MgO supersack is emplaced on each stack of waste. If this quantity is not sufficient to meet the required MgO [excess factor] for a room, additional MgO is emplaced. These EPA audited operations are detailed in WIPP technical procedures (WTS, 2006).

Vugrin, Nemer, and Wagner (2006, Section 5.2.4, p. 25) also stated that "The uncertainty with this assumption cannot presently be quantified, so the uncertainty will not be included in [the] calculations of the MgO effective excess factor."

Vugrin, Nemer, and Wagner (2006, Section 5.2.5, pp. 25-26) carried out a statistical analysis of the uncertainty in the mass of MgO in the supersacks and concluded that they could use a mean value of 4200 lbs, the value specified by WTS (Washington TRU Solutions 2005, Section 3.4.1, p. 3) for the mass of MgO in a supersack, and a standard deviation of 0.037%.

MgO-6.2.4.4.3 Uncertainties in the Number of Moles of CO_2 Consumed per Mole of Available MgO

Vugrin, Nemer, and Wagner (2006) recognized four uncertainties that could affect the number of moles of CO_2 that would be consumed per mole of available MgO:

1. The extent to which consumption of CO_2 by brucite produces hydromagnesite (5424) or magnesite in WIPP disposal rooms
2. Possible consumption of CO_2 by materials other than MgO
3. Dissolution of CO_2 in WIPP brines
4. Incorporation of CO_2 in biomass

The extent to which carbonation of brucite produces hydromagnesite (5424) or magnesite will affect the MgO effective excess factor (Brush and Roselle 2006, Section 4; Vugrin, Nemer, and Wagner 2006, Section 6.1). The brucite-hydromagnesite (5424) carbonation reaction consumes 0.8 mol of CO_2 per mol of MgO consumed; the brucite-magnesite reaction consumes 1 mol of CO_2 per mol of MgO (compare Reactions [MgO.7] and [MgO.8] in Section MgO-5.1). Brush and Roselle (2006, Section 4.1, Section 5.2, and Section 5.3) reviewed the results of laboratory and natural-analog studies of brucite carbonation. Based on their review, Brush and Roselle (2006, Section 4.1, p. 12) concluded

> Any hydromagnesite formed prior to 9,000 years after the WIPP is filled and sealed would convert completely to magnesite, which – along with the initially formed hydromagnesite – would consume 1 mol of CO_2 per mol of periclase. Furthermore, much of the hydromagnesite formed after 9,000 years would react to form magnesite.

Brush and Roselle (2006, Section 4.2, pp. 12-13) also concluded

> Incorporation of the ratio of the number of moles of CO_2 consumed per mol of periclase in MgO into the effective excess factor necessitates multiplication of this factor by a value close to 1. The number of moles of CO_2 consumed per mol of periclase will be close to 1 because: (1) magnesite will be the dominant Mg carbonate throughout most of the 10,000-year regulatory period; and (2) formation of magnesite from brucite (or periclase), and formation of hydromagnesite followed by

> conversion of hydromagnesite to magnesite would both consume 1 mol of CO_2 per mol of periclase. The exact ratio of CO_2 consumed per mol of periclase will depend on how much CO_2 is produced by microbial activity prior to 9,000 years. Therefore, this ratio might have to be computed on a vector-by-vector basis.

The laboratory and some of the natural-analog studies on which these conclusions are based are also reviewed in Section MgO-4.2.2 (see above).

Vugrin, Nemer, and Wagner (2006, Section 6.1, p. 29) carried out an analysis that demonstrated that "as long as the half life for the conversion of hydromagnesite [5424] to magnesite is less than 3,000 years, uncarbonated Mg[O] will remain." Their analysis was based on the results of Zhang et al. (1999), but introduced additional conservatisms that are not required to apply these results to the formation of magnesite in the WIPP (see Section MgO-4.2.2). Vugrin, Nemer, and Wagner (2006, Table 5, p. 35) also assumed that carbonation of brucite will consume 1 mol of CO_2 per mol of MgO, consistent with conversion of all of the hydromagnesite (5424) in WIPP disposal rooms to magnesite (Reaction [MgO.9] in Section MgO-4.2.2).

Brush and Roselle (2006, Section 6) reviewed the results of studies relevant to the possible consumption of CO_2 by materials other than MgO in the WIPP. Brush and Roselle (2006, Section 6.6, p. 25) concluded

> Inclusion of the effects of consumption of CO_2 by Fe-base metals and their corrosion products, lead (Pb)-base metals and their corrosion products, and CaO and $Ca(OH)_2$ in Portland cement would be difficult at present because of the uncertainties associated with these processes in the WIPP ... However, these materials could consume 36.1, 1.36, and 0.177% of the CO_2 that would be produced by complete microbial consumption of all CPR materials in the repository.

Therefore, Vugrin, Nemer, and Wagner (2006, Section 6.2, p. 31) decided

> Because of these uncertainties, this analysis will use the conservative assumption that CO_2 will not be consumed by Fe-base metals or their corrosion products, Pb-base metals or their corrosion products, or lime and portlandite in portland cements. However, if it were possible to quantify the expected quantities of CO_2 that would be consumed by these materials and the associated uncertainty in calculation of the [MgO effective excess factor], it would increase the mean [MgO effective excess factor] and possibly the … uncertainty. The magnitude of these increases is not known.

Brush and Roselle (2006, Section 6.4, p. 24) demonstrated

> Dissolution of CO_2 in WIPP brines cannot consume significant quantities of CO_2 relative to the quantity that would be produced by microbial consumption of all CPR materials in the repository. This is because the solubility of CO_2 in brines is too low, and the volumes of brines that could flow through the repository are too low to dissolve significant amounts of CO_2. The CO_2 solubility is too low because the brucite-magnesite or brucite-hydromagnesite carbonation reactions will buffer f_{CO_2} at values of [1.26×10^{-7} or 3.16×10^{-6} atm], respectively.

For example, Brush and Roselle (2006, Section 6.4, p. 24) calculated that "the amounts of CO_2 dissolved in 10,011 m^3 of GWB, 100,000 m^3 of ERDA-6 brine, or 1,000,000 m^3 of ERDA-6 brine are just 0.000318%, 0.00389%, and 0.0389%, respectively, of the total quantity of CO_2 that would be produced by microbial consumption of all [of the] CPR materials in the repository." Therefore, Vugrin, Nemer, and Wagner (2006, Section 6.3, p. 32) "assume[d] that no CO_2 is consumed by dissolution in brine."

Brush et al. (2006, Section 6.5, p. 24) stated

> Some of the organic C in CPR materials would be sequestered in biomass (cellular material) instead of being oxidized to CO_2 if significant microbial consumption of these materials occurs in the WIPP. However, it would be difficult to predict defensibly how much C would be sequestered in biomass.

Therefore, Vugrin, Nemer, and Wagner (2006, Section 6.4, p. 32) concluded

> Because the uncertainty in the quantity of organic [C] that might be sequestered in biomass cannot presently be quantified, this analysis will conservatively assume that no organic [C] in CPR materials will be incorporated into biomass. If it [were] possible to quantify this uncertainty and the uncertainty was included in calculation of the [MgO effective excess factor], it would have the impact of increasing the mean [MgO effective excess factor] and increasing the standard deviation. The magnitudes of these changes are not known.

MgO-6.2.4.4.4 Conclusions Regarding the Uncertainties Related to the MgO Excess Factor

Vugrin, Nemer, and Wagner (2006, Section 7) used the mean values and standard deviations of the uncertainties that could be quantified (see above) to calculate an MgO effective excess factor for an MgO excess factor of 1.2. They summarized the values of these parameters for the uncertainties in the number of moles of CO_2 produced per mole of organic C in CPR materials, the uncertainties in the quantity of MgO that will be available to consume CO_2, and the uncertainties in the number of moles of CO_2 consumed per mole of available MgO in their Table 3, Table 4, and Table 5. Vugrin, Nemer, and Wagner (2006) summarized their calculation of the MgO effective excess factor in their Equation 7-1 and provided details on their calculations of the means and uncertainties (standard deviations) for their random variables and the MgO effective excess factor in Appendix C of their report.

Vugrin, Nemer, and Wagner (2006, Section 7.1, pp. 35-36) calculated that, for an MgO excess factor of 1.2, the MgO effective excess factor has a mean value of 1.60 and that the uncertainty (standard deviation) is 0.0819. Based on the assumption that the distribution of the effective excess factor is lognormal, Vugrin, Nemer, and Wagner (2006, Section 7.1, p. 36) calculated

> [T]here is a 3×10^{-5} probability that the [MgO effective excess factor] will be less than 1.30 (Table 7), which is 30% higher than the minimum [MgO effective excess factor] required to maintain chemical conditions assumed in PA. Furthermore, there is only a 10^{-19} probability that the [MgO effective excess factor] will be less than 1.01.

As long as the MgO effective excess factor is greater than or equal to 1.00, there would be enough MgO present in WIPP disposal rooms to consume all the CO_2 produced by complete consumption of all of the CPR materials in the repository.

MgO-6.2.4.5 Revision of the DOE's Assessment of the Uncertainties Related to the MgO Excess Factor

Vugrin, Nemer, and Wagner (2007) revised the uncertainties used by Vugrin, Nemer, and Wagner (2006) because of EPA-mandated changes to the PA technical baseline for the CRA-2004 PABC. Vugrin, Nemer, and Wagner (2007) (1) changed the overall yield for microbial

consumption of all of the CPR materials in the repository from 0.715 mol of CO_2 per mol of organic C, with a standard deviation of 0.0158 mol of CO_2 per mol of organic C, to a constant value of 1 mol of CO_2 per mol of organic C; and (2) changed the assumption that carbonation of brucite will consume 1 mol of CO_2 per mol of MgO, consistent with conversion of all of the hydromagnesite (5424) in WIPP disposal rooms to magnesite, and introduced a random variable with a uniform distribution between 0.8 and 1 mol of CO_2 per mol of MgO, consistent with an equal likelihood of forming hydromagnesite (5424) or magnesite.

Vugrin, Nemer, and Wagner (2006, Section 5.2.3, pp. 51-52) combined the yields for each step of the possible microbial consumption of CPR materials in the repository and obtained an overall yield of 0.715 mol of CO_2 per mol of organic C, with a standard deviation of 0.016 mol of CO_2 per mol of organic C (see the discussion above of the uncertainties in the number of moles of CO_2 produced per mole of organic C in CPR materials). Vugrin et al. (2007, Section 4.2.3, p. 13) changed the overall yield from 0.715 mol of CO_2 per mol of organic C, with a standard deviation of 0.016 mol of CO_2 per mol of organic C, to a constant value of 1 because

> [T]he current PA technical baseline (established by the CRA-2004 PABC) includes only denitrification and [SO_4^{2-}] reduction as microbial [respiratory] pathways for the consumption of organic [C]. Methanogenesis was not included in the CRA-2004 PABC. The current baseline also does not include consumption of CO_2 by [Mg] in Salado brines or by precipitation of $CaCO_3$-bearing minerals. Consequently, the effective CO_2 yield corresponding to the baseline assumptions is 1 mol of CO_2 per mol of consumed organic [C]. This value represents the maximum yield that could occur.
>
> Because of the complexity involved with quantifying the uncertainty in the effective CO_2 yield, this analysis will model the yield in a conservative manner consistent with the CRA 2004 PABC. That is, it will be assumed that:
>
> (1) Denitrification and [SO_4^{2-}] reduction [would be] the only microbial [respiratory] pathways or the consumption of organic [C].
>
> (2) Methanogenesis [would not] occur.
>
> (3) No CO_2 [would be] consumed by precipitation of $CaCO_3$-bearing minerals.
>
> (4) No CO_2 [would be] consumed by [Mg] in Salado brines.
>
> Consequently, this analysis will assume that the effective CO_2 yield is 1 mol of CO_2 per mol of consumed organic [C]. This value represents the maximum effective yield that could occur, so modeling the yield in this manner is conservative. The variable y_{yield} represents the effective CO_2 yield in this analysis, and it will be assigned a constant value of 1 mol of CO_2 per mol of consumed organic [C]. If it [were] possible to quantify this uncertainty and the uncertainty [were] included in [the] calculation of the [MgO effective excess factor], it would have the impact of increasing the mean [effective excess factor] and increasing the standard deviation.

Vugrin, Nemer, and Wagner (2006, Table 5, p. 35) also assumed that carbonation of brucite will consume 1 mol of CO_2 per mol of MgO, consistent with conversion of all of the hydromagnesite (5424) in WIPP disposal rooms to magnesite (Reaction MgO.9 in Section MgO-4.2.2). They based this assumption on the review by Brush and Roselle (2006, Section 4.1, Section 5.2, and Section 5.3) of laboratory studies carried out for the WIPP project, laboratory studies carried out for other applications, and studies of anthropogenic and natural analogs. However, Vugrin,

Nemer, and Wagner (2007, Section 6.1, p. 22) abandoned this assumption and introduced a random variable:

> As noted above, there is some uncertainty in the length of time required for hydromagnesite to convert to magnesite. Thus, this analysis includes an approach that does not require the rate of magnesite formation to model the uncertainty in the moles of CO_2 consumed per mol of MgO. Two bounding scenarios are considered for modeling purposes:
>
> > **Scenario 1**. No hydromagnesite converts to magnesite. In this scenario, each mol of MgO can consume 0.8 mol of CO_2, and this value represents the lower bound for the moles of CO_2 sequestered per mol of MgO.
> >
> > **Scenario 2**: All hydromagnesite converts to magnesite. In this scenario, each mol of MgO can consume 1 mol of CO_2, and this value represents the upper bound for the moles of CO_2 sequestered per mol of MgO.
>
> For the [MgO effective excess factor] calculation, the moles of CO_2 sequestered per mol of MgO are modeled as a random variable with a uniform distribution on [0.8,1]. Representing the quantity in this manner incorporates the lower and upper bounds associated with Scenarios 1 and 2 and maximizes the uncertainty since the distribution is not weighted towards any particular value on [0.8,1].

Vugrin, Nemer, and Wagner (2007, Section 7) used the mean values and standard deviations of the uncertainties that could be quantified to recalculate an MgO effective excess factor for an MgO excess factor of 1.2. They summarized the values of these parameters for the uncertainties in the number of moles of CO_2 produced per mole of organic C in CPR materials, the uncertainties in the quantity of MgO that will be available to consume CO_2, and the uncertainties in the number of moles of CO_2 consumed per mole of available MgO in their Table 2, Table 3, and Table 4. Vugrin, Nemer, and Wagner (2007) summarized their calculation of the MgO effective excess factor in their Equation 7-1 and provided details on their calculations of the means and uncertainties (standard deviations) for their random variables and the MgO effective excess factor in their Appendix B.

Vugrin, Nemer, and Wagner (2007, Section 7.1, pp. 27-28) calculated that, for an MgO excess factor of 1.2, the MgO effective excess factor has a mean value of 1.03 and the uncertainty (standard deviation) is 0.072.

Because the MgO effective excess factor is greater than 1.00, there would be enough MgO present in WIPP disposal rooms to consume all of the CO_2 produced by complete consumption of all of the CPR materials in the repository.

MgO-6.2.4.6 The EPA's Approval of the DOE's Planned Change Request to Reduce the MgO Excess Factor from 1.67 to 1.2

The EPA approved the reduction of the MgO excess factor to 1.2 in February 2008 (Reyes 2008). However, the EPA imposed two conditions in its approval letter (Reyes 2008, p. 1):

> First, [the] DOE must continue to calculate and track both the [C] disposed and the required MgO needed on a room-by-room basis. Second, [the] DOE must annually verify the reactivity of MgO and ensure that it is maintained at 96 [mol] % as assumed in [the] DOE's supporting documentation. These conditions ensure that the WIPP will continue to meet the assurance requirements in our radioactive waste disposal regulations.

The EPA's approval (Reyes 2008, p. 1) went on to state

> As a result of this evaluation, it is our opinion that further reductions in the MgO safety factor are not warranted given the current state of knowledge. We believe that reducing the safety factor below 1.2, based on our current understanding of the disposal system, would not be sufficient to comply with the assurance requirement that MgO is intended to address.

The EPA (U.S. Environmental Protection Agency 2008) summarized its review of the DOE's PCR for a reduction in the MgO excess factor from 1.67 to 1.2. SCA (2008) carried out a detailed review of the uncertainties related to the use of MgO as the engineered barrier in the WIPP. Langmuir (2007) reviewed the results of the analysis published by SCA (2008), and SCA (2007) responded to this review. Finally, PECOS Management Services, Inc. reviewed the use of MgO as an engineered barrier, and concluded that reducing the MgO excess factor from 1.67 to 1.2 would be appropriate and that the excess factor could be reduced even more (PMS 2007). Langmuir (2007), PMS (PECOS Management Services, Inc. 2007), SCA (S. Cohen and Associates 2007), SCA (S. Cohen and Associates 2008), and U.S. Environmental Protection Agency (2008) were all included in Reyes (2008) as attachments.

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Title 40 CFR Part 191
Subparts B and C
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for the
Waste Isolation Pilot Plant

Appendix MON-2009
WIPP Monitoring Programs

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix MON-2009
WIPP Monitoring Programs

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Acronyms and Abbreviations

CARD	Compliance Application Review Document
CBFO	Carlsbad Field Office
CCA	Compliance Certification Application
cm	centimeter
CMP	Compliance Monitoring Program
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
EPA	U.S. Environmental Protection Agency
FEP	feature, event, or process
ft	feet
GMP	Groundwater Monitoring Program
GWMPP	Groundwater Monitoring Program Plan
kg	kilogram
km	kilometer
m	meter
M&OC	Management and Operating Contractor
mi	mile
PA	performance assessment
QA	quality assurance
QAPD	Quality Assurance Program Document
SMP	Subsidence Monitoring Program
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program
WWIS	WIPP Waste Information System

Elements and Chemical Compounds

Am	americium
Pu	plutonium
U	uranium

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MON-1.0 Introduction

This appendix to the 2009 Compliance Recertification Application (CRA-2009) describes a specific monitoring program that was developed to meet commitments contained in the U.S. Department of Energy's (DOE's) application to the U.S. Environmental Protection Agency (EPA), which demonstrated compliance with radioactive waste disposal regulations 40 CFR Part 191 Subparts B and C and the certification criteria in 40 CFR Part 194. This appendix does not address monitoring activities intended to demonstrate compliance with 40 CFR Part 191 Subpart A.

The monitoring activities described are performed as assurance measures to detect substantial and detrimental deviations from expected disposal system performance. This program consists of a preclosure and postclosure monitoring program using monitoring techniques that do not jeopardize the isolation of the waste. The program must be conducted until the DOE and EPA agree there are no significant concerns to be addressed by further monitoring. The long-term performance expectations for the disposal system are derived from conceptual models, scenarios, and assumptions developed for the Waste Isolation Pilot Plant (WIPP) performance assessment (PA).

On January 3, 2002, the DOE Carlsbad Field Office (CBFO) submitted a letter to the EPA (Triay 2002). This letter requested Appendix MON be rewritten to incorporate the portions of Appendices EMP, GWMP, GTMP, SMP, and DMP required to demonstrate compliance with 40 CFR § 191.14(b) (U.S. Environmental Protection Agency 1993) in accordance with the criteria established by 40 CFR § 194.42 (U.S. Environmental Protection Agency 1996). The EPA approved the request in a letter to CBFO on March 15, 2002 (Marcinowski 2002).

The activities performed for the overall monitoring programs at WIPP comprehensively address the range of regulatory requirements at departmental, state, and federal levels. This appendix addresses activities relevant to monitoring the disposal system. This document provides an overview of the Compliance Monitoring Program (CMP) and specifically describes how

- The 10 compliance monitoring parameters are derived from the data.
- Information and data are extracted from the various WIPP monitoring and sampling programs.
- The assessments are made against repository performance expectations.
- The results are reported to the EPA.

The descriptions provided in this appendix are specific to the CMP and, thus, the requirements of section 191.14(b) and section 194.42.

MON-1.1 Compliance Monitoring Program

This appendix describes the CMP for the WIPP. Compliance monitoring concentrates on the following areas:

- The Geotechnical Engineering Program
- The Groundwater Monitoring Program (GMP)
- The Delaware Basin Drilling Surveillance Program (DBDSP)
- The Subsidence Monitoring Program (SMP)
- WIPP Waste Tracking and Control

The data and information collected since the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004a) for the above-listed programs are recorded or referenced in Appendix DATA-2009.

MON-1.2 Preclosure and Postclosure Monitoring

The requirements of 40 CFR § 191.14, section 194.42, the initial EPA certification (U.S. Environmental Protection Agency 1998a), and the CRA-2004 serve as the regulatory basis for preclosure and postclosure monitoring. These requirements specify that disposal systems must be monitored to detect substantial and detrimental deviation from expected disposal system performance.

MON-1.3 Monitoring Assessment

The DOE was required by 40 CFR § 194.42(a) to perform an analysis that would determine the effects of various parameters on the performance of the disposal system, and to use the results in preclosure and postclosure monitoring plans. The disposal system performance identified 10 monitoring parameters, listed in Section MON-2.1, to be monitored and assessed within the CMP. The discussion of preclosure monitoring activities for these 10 parameters includes the following:

- Identifying activities required to comply with the monitoring requirements of the EPA's certification and recertification of compliance with Part 191 Subparts B and C during the preclosure phase of the project
- Identifying organizations that generate the monitoring data, organizations that convert the data to monitoring parameters and assess the results against expected results, and the organization that reports the results of the assessments to the EPA
- Identifying the compliance monitoring schedule
- Providing an overview of quality assurance (QA) requirements applicable to the CMP

MON-1.4 Appendix Summary

Section MON-2.0 identifies the monitoring requirements of Part 191 Subparts B and C in keeping with the criteria of Part 194. Section MON-3.0 describes the preclosure monitoring

program associated with each monitoring parameter, the monitoring schedules, and program outputs. Section MON-4.0 describes the planned postclosure monitoring. Section MON-5.0 describes the QA requirements applicable to the CMP. Section MON-6.0 describes the process of communicating and reporting CMP results and evaluations.

MON-2.0 Compliance Monitoring Program Requirements

The DOE's preclosure and postclosure CMP assesses the performance of specific aspects of the disposal system. The relevant monitoring requirements are identified in

- Section 191.14(b)
- Section 194.42
- The May 18, 1998, 40 CFR Part 194 Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision, Section VIII.D.4 Monitoring (U.S. Environmental Protection Agency 1998a)
- The CRA-2004, Chapter 7.0, Section 7.2

MON-2.1 Compliance Certification/Recertification

The original approach used to develop the CMP was based on the results of the parameter analysis documented in the CCA, Chapter 7.0, and Appendix MON, Attachment MONPAR. The EPA documented its approval of the DOE monitoring approach in the compliance certification decision (U.S. Environmental Protection Agency 1998a) and Compliance Application Review Document (CARD) 42 (U.S. Environmental Protection Agency 1998b). In the CRA-2004, Appendix MON 2004 was rewritten to incorporate portions of Appendices EMP, GWMP, GTMP, SMP, and DMP that were not revised from the CRA-2004. The DOE reassessed the CCA, Appendix MON, Attachment MONPAR, for the CRA-2004 and determined the original conclusions and monitoring parameters identified in MONPAR remain valid and unchanged (Kirkes and Wagner 2003). For the CRA-2009, the DOE once again assessed the original MONPAR analysis used to determine which monitoring parameters should be included in the CMP. Based on the review of operational activities, conditions, monitoring data, PA, and experimental programs that occurred since the CRA-2004, the reassessment states, "the conclusions of the MONPAR analysis remain valid and its conclusions continue to be adequate for inclusion in the CRA-2009*"* (Wagner 2008). The EPA-approved monitoring approach recognizes that the DOE will monitor 10 parameters. These parameters are

1. Creep closure and stresses
2. Extent of brittle deformation
3. Initiation of brittle deformation
4. Displacement of deformation features
5. The Culebra Dolomite Member of the Rustler Formation (hereafter referred to as Culebra) groundwater composition
6. Change in Culebra groundwater flow
7. Drilling rate

8. Probability of encountering a Castile brine reservoir
9. Subsidence
10. Waste activity

All of the above parameters are being monitored during the preclosure period.

The CRA-2004, Appendix MON 2004, Attachment A, describes DOE's plans for postclosure monitoring. The DOE will revisit this plan for postclosure monitoring before the end of facility operations.

The monitoring parameters that have related PA parameters include

- Drilling rate
- Probability of encountering Castile brine
- Change in Culebra groundwater flow
- Culebra groundwater composition
- Waste activity

The other monitoring parameters are related to screening decisions for repository features, events, or processes (FEPs). Table MON-1 describes the related PA parameters and the major FEPs screening decisions.

The data used to determine the 10 monitoring parameters of the CMP are generated by 5 separate monitoring programs (described in Section MON-3.1, Section MON-3.2, Section MON-3.3, Section MON-3.4, and Section MON-3.5). Each monitoring program focuses on the collection of direct field measurements. The programs that generate or evaluate the data are described in Section MON-6.0. Results from each monitoring program are documented individually in annual reports (see Appendix DATA-2009), while the assessment results of the 10 parameters are documented and reported in a compliance monitoring parameter assessment report (Sandia National Laboratories 2004, 2005a, 2005b, 2006, and 2008).

As stated earlier, if any of the data, parameters, or observations are not consistent with expectations as defined in Section MON-6.1.1, the CMP process requires addressing concerns and developing recommendations identified by unexpected results. Results from monitoring programs will be generated on an ongoing basis throughout the operational period of the repository. Compliance monitoring data are provided to the cognizant individuals and organizations within the project and evaluated for their significance, and the evaluation results and data summaries are reported to the EPA. Section MON-6.0 describes the process of communicating and reporting CMP results and evaluations.

Table MON-1. Monitoring Parameters

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related PA Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Creep Closure and Stresses	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. May provide a short-term (operational) observation of the geomechanical response of repository excavation. Can provide confidence in the creep closure model.	Salt creep, excavation-induced stress changes, changes in stress field, pressurization. Consolidation of waste/backfill.	Data from this monitoring program are evaluated annually and during recertification.
Extent of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. Can provide confidence in the long-term behavior of the disturbed rock zone (DRZ), as modeled. Intrinsic shaft DRZ permeability and effective shaft seal permeability is calculated from this parameter.	DRZ, roof falls, consolidation of seals.	Data are evaluated annually and during recertification.
Initiation of Brittle Deformation	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. Can provide confidence in the anhydrite fracture model implemented in the BRAGFLO code. May provide related repository observation data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Disruption due to gas effects.	Data are evaluated annually and during recertification.
Displacement of Deformation Features	Geotechnical Monitoring Program	Various data calls from weekly to monthly based on repository conditions, instrumentation, and data collection system. Data are reported annually.	Not directly related to a PA parameter. Provides related repository operational data on initiation or displacement of major brittle deformation features in the roof or surrounding rock.	Stability of open panel.	Data are evaluated annually and during recertification.

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Table MON-1. Monitoring Parameters (Continued)

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related PA Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Culebra Groundwater Composition	GMP	Data are collected semiannually and reported annually.	Average Culebra brines composition and matrix distribution coefficient for uranium (U) (IV, VI), plutonium (Pu) (III, IV), thorium (Th) (IV), americium (Am) (III). Matrix distribution coefficient is not a sensitive PA parameter.	Groundwater geochemistry, actinide sorption.	Data are evaluated annually and during recertification.
Change in Culebra Groundwater Flow	GMP	Data are collected monthly and reported annually.	Culebra transmissivity, fracture and matrix porosity, fracture spacing, dispersivity, and climate index. Changes in Culebra groundwater flow are moderately significant to performance and incorporated into the PA.	Groundwater flow and recharge/ discharge. Infiltration. Precipitation.	Data are evaluated annually and during recertification.
Drilling Rate	DBDSP	As well records are received (weekly and monthly basis). Data are reported annually.	Drilling rate per unit area. The number of holes is used to calculate a frequency of potential future intrusions into the repository.	Drilling.	Data are evaluated annually and during recertification.
Probability of Encountering a Castile Brine Reservoir	DBDSP	As drilling records are received. Data are reported annually.	Probability of encountering a Castile brine reservoir, reservoir pressure, and volume. These parameters are significant to long-term repository performance.	Drilling fluid flow, drilling fluid loss, blowouts, brine reservoirs.	Data are evaluated annually and during recertification.
Subsidence	SMP	Data are reported annually or as determined necessary by the DOE.	Not directly related to a PA parameter. Can provide spatial information on surface subsidence (if any) over the influence area of the underground openings during operations.	Changes to groundwater flow due to mining effects; subsidence baseline.	Data are evaluated annually or as determined necessary by the DOE.

Table MON-1. Monitoring Parameters (Continued)

Monitoring Parameter	Monitoring Program	Frequency of Data Collection and Reporting	Related PA Parameter	Related FEPs Evaluation Cycle	Evaluation of Data
Waste Activity	WIPP Waste Tracking and Control	Continually updated as waste is approved for shipment to WIPP. Data are reported annually.	Radionuclide inventory. Material parameter weights. These parameters are important to PA.	Waste radiological characteristics.	Data are evaluated annually and during recertification.

The 10 parameters above are called *compliance monitoring parameters*. As discussed previously, the EPA determined during the WIPP certification and the 2004 recertification that these parameters met the regulatory monitoring requirements.

MON-3.0 Preclosure Compliance Monitoring

This section describes the preclosure CMP and the resulting data. The 10 parameters, associated monitoring program for each, frequency of data collection and reporting, related PA parameters, and related screening decisions used to support the PA are listed in Table MON-1.

MON-3.1 Geotechnical Engineering Program Plan

The WIPP Geotechnical Engineering Program Plan (Waste Isolation Pilot Plant 2006) defines the field programs and investigations carried out by the Geotechnical Engineering group within the Management and Operating Contractor (M&OC). The geotechnical engineering activities provide geologic information related to geotechnical characteristics and assess the stability and performance of the underground facility. The activities defined in the WIPP Geotechnical Engineering Program Plan that collects data related to PA parameters and make up the Geotechnical Monitoring Program described in Table MON-1 are the Geomechanical Monitoring Activities and Geosciences Activities.

MON-3.1.1 Geomechanical Monitoring Activities

Geomechanical monitoring activities provide data to validate design, track short-term and long-term geotechnical performance of underground openings, and support routine safety and stability evaluations of the excavations. Geomechanical monitoring generates data related to the following four parameters:

1. Creep closure and stresses
2. Extent of brittle deformation
3. Initiation of brittle deformation
4. Displacement of deformation features

MON-3.1.1.1 Scope

The geomechanical monitoring activities provide data on the WIPP design for evaluating the safety and stability of excavations and the behavior of underground openings. From an operational point of view, data related to identifying areas of potential instability allow corrective action to be taken in a timely manner. For underground opening behavior, in situ data are used to model long-term disposal system performance.

MON-3.1.1.2 Instrumentation

Geomechanical instruments installed in the shafts and along drifts within the WIPP facility monitor the geotechnical parameters. Instrumentation in the shafts and the underground repository presently include tape extensometer stations, convergence meters, borehole extensometers, piezometers, embedment strain gauges, stress gauges, inclinometers, load cells,

and crack meters. Instruments in the underground repository are either monitored remotely by a surface data logger or read manually.

MON-3.1.1.3 Data Acquisition

Geomechanical data are acquired either remotely by the geomechanical data logging system or manually by geotechnical engineering technicians. Manually acquired data are collected on a quarterly basis and remotely acquired data are collected on a monthly basis, at a minimum.

MON-3.1.1.4 Data Analysis and Dissemination

Data analysis is performed on an annual basis and published. The results of the analyses are published annually in the Geotechnical Analysis Report (U.S. Department of Energy 2004b, 2005a, 2006a, 2007a, and 2008).

An assessment of convergence measurements and geotechnical observations is made after each round of data collection. The results of each assessment are distributed to affected underground repository operations, engineering, and safety managers.

MON-3.1.2 Geosciences Activities

Geosciences activities document existing geologic conditions and characteristics and monitor for changes resulting from the excavations. These activities generate data related to the following four parameters:

1. Creep closure and stresses
2. Extent of brittle deformation
3. Initiation of brittle deformation
4. Displacement of deformation features

MON-3.1.2.1 Scope

Changes resulting from excavations are monitored by routine inspections of selected borehole arrays to detect and quantify the occurrences of discontinuities such as fractures and bed separations. The data collected from these inspections further the understanding of fracture development within the Salado Formation that occurs around the excavations. Geosciences activities also provide geologic and fracture mapping, geologic sampling, and seismic monitoring.

MON-3.1.3 Schedule

The following activities are performed on the indicated schedule:

- Geomechanical Monitoring. This program uses instrumentation located in the shafts and drifts, including tape extensometer stations, convergence meters, borehole extensometers,

piezometers, embedment strain gauges, stress gauges, inclinometers, load cells, and crack meters. Instruments are read as designated in Table MON-1.

- Seismic Monitoring. Regional seismic monitoring and evaluation are conducted by the New Mexico Institute of Mining and Technology. The network is operated continuously and monitoring results are reported quarterly.

- Geologic Mapping. Geologic mapping is conducted in newly excavated areas and in other areas when deemed necessary by the cognizant engineer or Geotechnical Engineering Manager.

- At a minimum, a complete analysis of geotechnical data is performed annually. The geotechnical activities will continue throughout the operational period.

MON-3.2 GMP

The purpose of the GMP is to collect groundwater data from numerous wells located at and near the facility. Groundwater monitoring at the WIPP is carried out under the WIPP Groundwater Monitoring Program Plan (GWMPP) (Washington Regulatory Environmental Services 2007).

The Culebra remains the focus of the GMP. It has been extensively studied during past hydrologic characterization programs, and was found to be the most likely hydrologic pathway to the accessible environment or compliance point for any potential human-intrusion-caused release scenario.

Data obtained through the GMP are used to generate the Culebra groundwater composition and the Culebra groundwater flow parameters. Details on how the program is implemented are provided in the GWMPP (Washington Regulatory Environmental Services 2007).

MON-3.2.1 Scope

The GWMPP addresses requirements for sample collection, groundwater surface elevation monitoring, groundwater flow direction, data management, and reporting of groundwater monitoring data. It also identifies analytical parameters selected to assess groundwater quality.

Seven wells were drilled as part of the WIPP GMP: six Water Quality Sampling Program (WQSP) wells (WQSP-1 through WQSP-6), completed to the Culebra, and WQSP-6a, completed to the Dewey Lake Formation. Water samples are collected from these wells and analyzed for certain chemical and physical parameters. This activity generates data in support of the Culebra Groundwater Composition parameter. This parameter calls for analyzing the following ions:

Cations: Ca^{2+}, K^{+}, Na^{+}, Mg^{2+}

Anions: Cl^{-}, HCO_3^{-}, SO_4^{2-}

Water level data are collected to assess changes in Culebra groundwater flow. Water level measurements are tracked over time using WQSP wells and other wells that are widely

distributed across the WIPP area to monitor the area's potentiometric surface and groundwater flow directions. If changes in water level(s) occur, the cause is investigated, and any potential impact on the long-term performance of the repository is assessed.

MON-3.2.1.1 Sampling and Reporting for Water Quality

Sampling for water quality is performed at seven groundwater monitoring wells. The Culebra is monitored using wells WQSP-1 through WQSP-6, and the Dewey Lake is monitored using well WQSP-6a. Two types of water samples are collected: serial samples and final samples.

Serial samples are taken at regular intervals and analyzed for various physical and chemical parameters (called field indicator parameters) in a mobile field laboratory positioned at the wellhead. The serial sample data are used to determine when a representative sample of the formation water can be taken. The field indicator parameters are chloride, divalent cations, alkalinity, total iron, pH, Eh, temperature, specific conductance, and specific gravity. Interpretation of the serial sampling data determines when conditions representative of undisturbed groundwater are attained in the pumped groundwater.

When the field indicator parameters have stabilized, indicating that the sample is representative of formation groundwater, final samples are collected in the appropriate type of container for the specific analysis to meet state and federal groundwater requirements. The final samples are submitted to laboratories for chemical analysis. Section MON-3.2.1 lists the analytes needed to support the PA parameter.

The sample tracking system at WIPP uses uniquely numbered Chain of Custody forms and Request for Analysis forms. For storage or transportation, the primary consideration is that samples must be analyzed within the prescribed holding times for the parameters of interest.

MON-3.2.1.2 Sampling and Reporting for Water Level Fluctuations

Water level measurements are taken in the six groundwater monitoring wells (WQSP-1 through WQSP-6) and other available WIPP wells in the monitoring network (Appendix HYDRO-2009, Figure HYDRO-1. Location of WIPP Wells). The water level monitoring will identify water level fluctuations.

In addition to the water level measurements, density is determined in the wells. This density is used to convert the water level measurements to equivalent freshwater heads for developing potentiometric surface maps.

MON-3.2.2 Schedule

Background water quality in both the upgradient and downgradient monitoring wells has been established for the WIPP. The seven WQSP monitoring wells constructed for the GMP are sampled on a semiannual basis to compare to the baseline water quality.

The groundwater level is measured by monitoring the wells at least on a monthly basis. Groundwater level measurements are monitored and collected for other WIPP wells, as well as for the WQSP wells. The water levels are determined in at least one accessible, completed

interval at each available well pad, and quarterly in redundant wells at well pads where two or more wells are completed in the same interval. Groundwater level measurements primarily examine changes in groundwater flow rate and direction to identify any changes pertinent to compliance. These groundwater data supplement the area water level database.

The characteristics of the GMP, such as the frequency of sampling and the location of the sampled wells, will be reevaluated if significant changes are observed in the groundwater flow direction or gradient. Reporting frequencies are listed in Table MON-2.

Table MON-2. WIPP GMP Sample Collection and Water Level Reporting Frequency

Type of Well	Frequency
Water Quality Sampling	
WQSP wells (seven)	Semiannually
Water Level Monitoring	
WQSP wells (seven)	Monthly and before sampling events
Other available WIPP wells	Monthly/quarterly

MON-3.2.3 Program Outputs

The groundwater samples are analyzed to quantify Culebra Groundwater Composition parameters and water quality parameters listed in Section MON-3.2.1.

The GMP also generates Culebra water level data. The data and results of the GMP are summarized and published on an annual basis in the WIPP Annual Site Environmental Report (U.S. Department of Energy 2003a, 2004c, 2005b, 2006b, and 2007b).

MON-3.3 Delaware Basin Drilling Surveillance Program

The DBDSP is described in the Delaware Basin Drilling Surveillance Plan (Waste Isolation Pilot Plant 2004). This plan provides for the surveillance of drilling activities within the Delaware Basin, with specific emphasis on the nine-township area surrounding the WIPP site. The DBDSP collects information related to the following two parameters:

1. Probability of encountering a Castile brine reservoir
2. Drilling rate

In addition to the parameters listed above, the DBDSP collects information on the following activities:

- Borehole plugging
- Enhanced recovery
- Natural gas storage

- Solution mining
- Potash mining
- Seismic events

The WIPP PA includes the impacts of drilling on the performance of the repository. The number of deep boreholes drilled per square kilometer is a parameter used in PA calculations for WIPP inadvertent intrusion scenarios. This parameter is based on actual drilling rates within the Delaware Basin over the last 100 years, as required by 40 CFR § 194.33 (U.S. Environmental Protection Agency 1996).

The results of the DBDSP continue to expand the existing database. This program updates these data to detect any substantial deviations from the assumptions used in the previous PA (see Section MON-3.3.1, Table MON-3). Collecting additional information about resource exploration and exploitation activities and practices in the Delaware Basin provides information to determine whether the drilling scenarios, assumptions, and probabilities used in the PA will continue to be valid for each five-year recertification of the WIPP.

Drilling information for the study area is obtained through commercially available electronic databases and the records of government agencies. The electronic database is updated and reviewed weekly to reflect drilling activities in the Delaware Basin. Records of government agencies are updated as they become available.

MON-3.3.1 Schedule

Table MON-3 shows the frequency of DBDSP data collection.

Table MON-3. DBDSP Data Collection Schedule

Information Collected	Frequency
Borehole plugging	Weekly
Enhanced recovery	Monthly
Gas storage	Annually
Solution mining	Annually
Potash mining	Annually
Seismic events	Quarterly
Drilling-related	Weekly
Probability of encountering a Castile brine reservoir	Weekly
Drilling rate calculations	Quarterly

MON-3.3.2 Program Outputs

The DBDSP updates and maintains a database of drilling activities and related practices in the Delaware Basin. For the nine-township area surrounding the WIPP, the DBDSP updates and maintains a database containing the following information:

- Plugging and abandonment activities, including descriptions of plugging configurations
- The fraction of plugged and abandoned boreholes that are sealed
- Well conversion activities (injection, disposal, water)
- Injection well operations (disposal and secondary recovery)
- Drilling activities, including borehole depths, diameters, and type and amount of drilling fluid
- Ownership of all state and federal minerals and hydrocarbon leases within the area
- Occurrences of pressurized brine within the Castile

Data collected and recorded by the DBDSP are reported annually in the Delaware Basin Monitoring Annual Program Report (U.S. Department of Energy 2003b, 2004d, 2005c, 2006c, and 2007c).

MON-3.4 SMP

The SMP is described in detail in the WIPP Underground and Surface Surveying Program (Waste Isolation Pilot Plant 2009). Subsidence monitoring measures vertical movement of the land surface relative to a reference location using state-of-the-art leveling equipment. The technique used to monitor subsidence measures the vertical height difference between two or more markers placed on a surface a known distance away from each other using a leveling survey. A reference benchmark is used as the standard and the relative movement of the other benchmark(s) is measured to detect vertical movement over time. Subsidence measurements are relative because the reference is fixed only with respect to the subsidence marker(s).

The activities associated with the SMP are designed to

- Provide time-related spatial information on surface subsidence within 152.4 meters (m) (500 feet (ft)) surrounding the waste shaft during the operational phase of the repository
- Provide time-related spatial information on surface subsidence over the influence area of the underground openings for comparison with subsidence predictions
- Maintain a database of subsidence data

With current technology, vertical elevation can be measured at a precision of 0.0305 centimeters (cm) (0.001 ft). Subsidence monitoring was chosen by the DOE as a long-term monitoring tool

because it effectively meets the requirements in section 191.14(b) for long-term monitoring. Subsidence monitoring is conducted to detect substantial and detrimental deviations from expected repository performance by comparing actual subsidence to predicted subsidence.

Subsidence data currently being compiled will be compared to subsidence predictions. In addition, subsidence monitoring during the operational phase generates data to establish a baseline against which long-term subsidence data and information may be evaluated.

MON-3.4.1 Schedule

Subsidence surveys are performed annually throughout the operations period. After closure of the repository, subsidence surveys will be performed at 10-year intervals for at least 100 years or until no further useful information may be obtained through continued monitoring.

MON-3.4.2 Program Outputs

The SMP generates annual surface subsidence data for 24.14 kilometers (km) (15 miles (mi)) of leveling loops through approximately 50 monuments. Results are reported annually in the WIPP Subsidence Monument Leveling Survey (U.S. Department of Energy 2003c, 2004e, 2005d, 2006d, and 2007d).

MON-3.5 WIPP Waste Information System

Information on the waste activity parameter is measured or estimated by generator sites through waste characterization activities. Sites are required to report certain information in the WIPP Waste Information System (WWIS). Reports are generated to tabulate key waste parameters. The waste activity parameter includes tracking the total material parameter weights and curie content of 10 radionuclides listed in Section MON-3.5.2.

MON-3.5.1 Schedule

Radionuclide inventory data and material parameter weights for every container of waste placed in the WIPP underground repository are submitted to the WWIS database at the time waste is certified for shipment to WIPP. A current collection of radionuclide inventory data and material parameter weights for the WIPP is maintained within the WWIS.

MON-3.5.2 Program Outputs

The data collected for the waste activity parameter is tracked by the WWIS. The WWIS annually generates a Waste Emplacement Summary Report that is submitted each November to the EPA in the annual 40 CFR § 194.4(b)(4) report (Triay 2003 and U.S. Department of Energy 2004f, 2005e, 2006e, and 2007e). The waste activity parameters being tracked and reported include radiological activity (in curies) that were emplaced during the 40 CFR § 194.4(b)(4) (U.S. Environmental Protection Agency 1996) reporting period and the cumulative activity since waste was first emplaced in the repository. The radionuclides being tracked (in curies) include

- ^{241}Am

- ^{238}Pu
- ^{239}Pu
- ^{240}Pu
- ^{242}Pu
- ^{233}U
- ^{234}U
- ^{238}U
- ^{90}Sr
- ^{137}Cs

The WWIS tracks other waste-related components that are annually reported in the section 194.4(b)(4) report. These waste components include

- Emplaced magnesium oxide (kg per room and per panel)
- Emplaced cellulose, plastic and rubber materials (kg per room and per panel)
- Emplaced container volume (m^3)
- Emplaced ferrous metals (kg)
- Emplaced non ferrous metals (kg)

MON-4.0 Postclosure (Long-Term) Monitoring

The final Postclosure Monitoring Plan will be developed prior to final facility closure (sealing of the shafts), but will not be implemented until after facility closure. This plan will include a review of the CRA-2004, Appendix MON 2004, Attachment A. When the final Postclosure Monitoring Plan is written, any proposed changes to the commitments made in Attachment A must be approved by the appropriate regulatory authorities.

MON-5.0 Monitoring Programs Quality Assurance Requirements

The quality of the work performed under the DOE CMP is accomplished per the criteria of 40 CFR § 194.22(a)(2)(ii) (U.S. Environmental Protection Agency 1996) and controlled by the application of the CBFO Quality Assurance Program Document (QAPD) (U.S. Department of Energy 2007f). Waste information is controlled by implementing the QAPD at generator sites.

In addition to the management requirements, such as document and record control established in the QAPD, requirements related to sampling and monitoring activities are specified. In particular, the following two sections of the QAPD are directly related to the performance of monitoring work and the control of samples:

- Section 2.4 – Inspection and Testing
  - Qualification of personnel
  - Inspection
  - Test requirements
  - Monitoring, measuring, testing, and data collection
  - Use and control of measuring and test equipment
  - Calibration
- Section 4.0 – Sample Control Requirements
  - Sample control
  - Sample identification
  - Handling, storing, and shipping samples
  - Disposition of nonconforming samples

WIPP monitoring programs are subject to EPA inspections in accordance with 40 CFR § 194.21 (U.S. Environmental Protection Agency 1996).

The CMP relies on the individual monitoring plan's QA program to ensure compliance with DOE WIPP requirements for data quality assessments, objectives, and analyses. Each sampling and monitoring program is implemented through individual implementation plans, which include the QA descriptions, objectives, and references to the applicable governing QA documents.

MON-6.0 Reporting And Assessment

Information flow is controlled to ensure important monitoring results are communicated to the appropriate individuals and groups.

MON-6.1 Monitoring Data Reporting

The monitoring programs that generate data used in the CMP are implemented by the M&OC. Reporting the data for the 10 compliance monitoring parameters is coordinated through the M&OC.

MON-6.1.1 CMP Assessment Report

The results of the CMP are reported in the compliance assessment report (Sandia National Laboratories 2004, 2005a, 2005b, 2006, and 2008).

The CMP results may indicate two general cases: normal or expected conditions, in which results are generally consistent with existing data, parameter values, and conceptual models; and anomalous conditions, in which results are inconsistent with existing data, parameter values, or conceptual models. DOE determines whether these results are consistent with expected conditions modeled in the PA or screening decisions used to support the compliance determination. The report also recommends if the CMP should be modified based on results of the monitoring programs.

This report is sent to the EPA as part of the annual reporting requirement of 40 CFR § 194.4(b)(4).

MON-6.1.2 External Reporting

The DOE reviews the recommendations of the M&OC and the scientific advisor to evaluate their significance. Significance is determined based on consideration of the following criteria:

- Containment requirements established pursuant to 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993) are, or are expected to be, exceeded.

- Releases from previously emplaced waste that lead to committed effective doses that are, or are expected to be, in excess of those established pursuant to 40 CFR § 191.15 (U.S. Environmental Protection Agency 1993) (not including emissions from operations covered pursuant to Part 191 Subpart A).

- Releases that have caused, or are expected to cause, concentrations of radionuclides (or estimated doses due to radionuclides in underground sources of drinking water in the accessible environment) to exceed the limits established pursuant to Part 191 Subpart C.

If monitoring results meet any of these criteria, the results are considered significant. Significant monitoring results are promptly reported to the EPA. The report is accompanied by a recommended course of action, including the appropriate external reporting. If the monitoring

results exceed or possibly exceed containment requirements or release limits as specified in 40 CFR § 194.4(b)(3)(ii), the CBFO will immediately cease emplacement of waste in the WIPP and notify the EPA within 24 hours.

If the DOE discovers a condition or activity that differs significantly from what is indicated in the most recent compliance application, but does not involve conditions or activities listed in section 194.4(b)(3)(ii), then the difference shall be reported in writing to the EPA within 10 calendar days of discovery.

For normal conditions where monitoring results are within expectations, the CMP assessment documents this condition (Sandia National Laboratories 2004, 2005a, 2005b, 2006, and 2008). As stated previously, this report is sent to the EPA as part of the annual reporting requirement of section 194.4(b)(4).

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for the
Waste Isolation Pilot Plant

Appendix PA-2009
Performance Assessment

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix PA-2009
Performance Assessment

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Acronyms and Abbreviations

%	percent
AIC	active institutional control
An	actinide
BRAGFLO	BRine And Gas FLOw computer code
C	Celsius
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic
Ci	curies
CL	Confidence Limit
CPR	cellulosic, plastic, and rubber
CRA	Compliance Recertification Application
DBR	direct brine release
DDZ	drilling damaged zone
DOE	U.S. Department of Energy
DP	disturbed repository performance
DRZ	disturbed rock zone
E	deep drilling scenario
EPA	U.S. Environmental Protection Agency
ERDA	U.S. Energy Research and Development Administration
FEP	feature, event, and process
FMT	Fracture-Matrix Transport
FVW	fraction of excavated repository volume occupied by waste
gal	gallon
GWB	Generic Weep Brine
in	inch
J	Joule
K	Kelvin
K_d	distribution coefficient

kg	kilogram
km	kilometer
km^2	square kilometers
L	liter
LHS	Latin hypercube sampling
LWB	land withdrawal boundary
M	mining scenario
m	meter
m^2	square meters
m^3	cubic meters
MB	marker bed
ME	mining and drilling scenario
mi	miles
mol	mole
MPa	megapascal
MTHM	metric tons of heavy metal
MWd	megawatt-days
N	Newton
Pa	Pascal
PA	performance assessment
PABC	performance assessment baseline calculation
PAVT	Performance Assessment Verification Test
PCC	partial correlation coefficient
PCS	panel closure system
PDE	partial differential equation
PDF	probability distribution function
PIC	passive institutional control
PRCC	partial rank correlation coefficient
RH-TRU	remote-handled transuranic
RKS	Redlich-Kwong-Soave
RoR	Rest of Repository
s	second

s^2	seconds squared
SCF/d	standard cubic feet per day
SMC	Salado Mass Concrete
SNL	Sandia National Laboratories
SRC	standardized regression coefficient
T field	transmissivity field
TRU	transuranic
TVD	Total Variation Diminishing
UP	undisturbed repository performance
WIPP	Waste Isolation Pilot Plant
yr	year

Elements and Chemical Compounds

Al	aluminum
Am	americium
C	carbon
$C_6H_{10}O_5$	generic formula for CPR
Ca	calcium
CH_4	methane
Cm	curium
CO_2	carbon dioxide
Cr	chromium
Cs	cesium
Fe	iron
H_2	hydrogen gas
H_2O	water
H_2S	hydrogen sulfide
I	iodine
Mg	magnesium
$Mg(OH)_2$	brucite
$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	hydromagnesite (5424)

MgO	magnesium oxide, or periclase
Mn	manganese
Ni	nickel
NO_3^-	nitrate
Np	neptunium
Pb	lead
Pm	promethium
Pu	plutonium
Ra	radium
Sn	tin
SO_4	sulfate
SO_4^{2-}	sulfate ion
Sr	strontium
Tc	technetium
Th	thorium
U	uranium
V	vanadium

PA-1.0 Introduction

This appendix presents the mathematical models used to evaluate performance of the Waste Isolation Pilot Plant (WIPP) disposal system and the results of these models for the 2009 Compliance Recertification Application (CRA-2009) Performance Assessment (PA). The term PA signifies an analysis that (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events (40 CFR § 191.12 [U.S. Environmental Protection Agency 1993]). PA is designed to address three primary questions about the WIPP:

Q1: What processes and events that might affect the disposal system could take place at the WIPP site over the next 10,000 years?

Q2: How likely are the various processes and events that might affect the disposal system to take place at the WIPP site over the next 10,000 years?

Q3: What are the consequences of the various processes and events that might affect the disposal system that could take place at the WIPP site over the next 10,000 years?

In addition, accounting for uncertainty in the parameters of the PA models leads to a further question:

Q4: How much confidence should be placed in answers to the first three questions?

These questions give rise to a methodology for quantifying the probability distribution of possible radionuclide releases from the WIPP repository over the next 10,000 years and characterizing the uncertainty in that distribution due to imperfect knowledge about the parameters contained in the models used to predict releases. The containment requirements of 40 CFR § 191.13 require this probabilistic methodology.

This appendix is organized as follows: Section PA-2.0 gives an overview and describes the overall conceptual structure of the CRA-2009 PA. The WIPP PA is designed to address the requirements of section 191.13, and thus involves three basic entities: (1) a probabilistic characterization of different futures that could occur at the WIPP site over the next 10,000 years, (2) models for both the physical processes that take place at the WIPP site and the estimation of potential radionuclide releases that may be associated with these processes, and (3) a probabilistic characterization of the uncertainty in the models and parameters that underlies the WIPP PA. Section PA-2.0 is supplemented by Appendix SCR-2009, which documents the results of the screening process for features, events, and processes (FEPs) that are retained in the conceptual models of repository performance.

Section PA-3.0 describes the probabilistic characterization of different futures. This characterization plays an important role in the construction of the complementary cumulative distribution function (CCDF) specified in section 191.13. Regulatory guidance and extensive review of the WIPP site identified exploratory drilling for natural resources and the mining of

potash as the only significant disruptions at the WIPP site with the potential to affect radionuclide releases to the accessible environment. Section PA-3.0 summarizes the stochastic variables that represent future drilling and mining events in the PA. The results of the PA for CRA-2009, as documented in Section PA-7.0, Section PA-8.0, and Section PA-9.0 of this appendix, confirm that direct releases from drilling intrusions are the major contributors to radionuclide releases to the accessible environment.

Section PA-4.0 presents the mathematical models for both the physical processes that take place at the WIPP and the estimation of potential radionuclide releases. The mathematical models implement the conceptual models as prescribed in 40 CFR § 194.23 (2004), and permit the construction of the CCDF specified in section 191.13. Models presented in Section PA-4.0 include two-phase (i.e., gas and brine) flow in the vicinity of the repository; radionuclide transport in the Salado Formation (hereafter referred to as the Salado); releases to the surface at the time of a drilling intrusion due to cuttings, cavings, spallings, and direct brine releases (DBRs); brine flow in the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra); and radionuclide transport in the Culebra. Section PA-4.0 is supplemented by Appendices MASS-2009, TFIELD-2009, and PORSURF-2009. Appendix MASS-2009 discusses the modeling assumptions used in the WIPP PA. Appendix TFIELD-2009 discusses the generation of the transmissivity fields (T fields) used to model groundwater flow in the Culebra. Appendix PORSURF-2009 presents results from modeling the effects of excavated region closure, waste consolidation, and gas generation in the repository.

Section PA-5.0 discusses the probabilistic characterization of parameter uncertainty, and summarizes the uncertain variables incorporated into the CRA-2009 PA, the distributions assigned to these variables, and the correlations between variables. Section PA-5.0 is supplemented by Fox (2008) and Appendix SOTERM-2009. Fox (2008) catalogs the full set of parameters used in the CRA-2009 PA, previously referred to as the CCA Appendix PAR and the CRA-2004, Appendix PA, Attachment PAR. Appendix SOTERM-2009 describes the actinide (An) source term for the WIPP performance calculations, including the mobile concentrations of actinides that may be released from the repository in brine.

Section PA-6.0 summarizes the computational procedures used in the CRA-2009 PA, including sampling techniques (i.e., random and Latin hypercube sampling (LHS)); sample size, statistical confidence for mean CCDF, generation of sample, generation of individual futures, construction of CCDFs, calculations performed with the models discussed in Section PA-4.0, construction of releases for each future, and the sensitivity analysis techniques in use.

Section PA-7.0 presents the results of the PA for an undisturbed repository. Releases from the undisturbed repository are determined by radionuclide transport in brine flowing from the repository to the land withdrawal boundary (LWB) through the marker beds (MBs) or shafts. Releases in the undisturbed scenario are used to demonstrate compliance with the individual and groundwater protection requirements in 40 CFR Part 191 (40 CFR § 194.51 and 40 CFR § 194.52).

Section PA-8.0 presents PA results for a disturbed repository. As will be discussed in Section PA-2.3.1, the only future events and processes in the analysis of disturbed repository performance are those associated with mining and deep drilling. Release mechanisms include

direct releases at the time of the intrusion via cuttings, cavings, spallings, and DBR, and long-term releases via radionuclide transport up abandoned boreholes to the Culebra and thence to the LWB.

Section PA-9.0 presents the set of CCDFs resulting from the CRA-2009 PA. This material supplements 40 CFR § 194.34, which demonstrates compliance with the containment requirements of section 191.13. Section PA-9.0 presents the most significant output variables from the PA models, accompanied by sensitivity analyses to determine which subjectively uncertain parameters are most influential in the uncertainty of PA results.

The overall structure of the CRA-2009 PA does not differ from that presented in the first WIPP Compliance Certification Application (CCA) (U.S. Department of Energy 1996), the CRA-2004 (U.S. Department of Energy 2004) or the CRA-2004 Performance Assessment Baseline Calculation (PABC) (Leigh et al. 2005). This recertification application appendix follows the approach used by Helton et al. (1998) to document the mathematical models used in the CCA PA and the results of that analysis. Much of the content of this appendix derives from Helton et al. (1998); these authors' contributions are gratefully acknowledged.

PA-2.0 Overview and Conceptual Structure of the PA

Because of the amount and complexity of the material presented in Appendix PA-2009, an introductory summary is provided below, followed by detailed discussions of the topics in the remainder of this section, which is organized as follows:

Section PA-2.1 – Overview of PA and the results

Section PA-2.2 – The conceptual structure of the PA used to evaluate compliance with the containment requirements

Section PA-2.3 – The overall methodology used to develop FEPs, the screening methodology applied to the FEPs, the results of the screening process, and the development of the scenarios considered in the system-level consequence analysis

The U.S. Department of Energy (DOE) continues to use the same PA methodology as in the CCA and CRA-2004 because changes that have been made since the U.S. Environmental Protection Agency (EPA) certified WIPP do not impact PA methodology. A corresponding detailed presentation for the CRA-2004 PA methodology is provided in the CRA-2004, Chapter 6.0, Section 6.1, and a detailed presentation for the CRA-2004 PABC implementation is provided in Leigh et al. (2005). A corresponding detailed presentation for the CCA PA methodology is provided in Helton et al. (1998, Section 2).

PA-2.1 Overview of Performance Assessment

A demonstration of future repository performance was required by the disposal standards in Part 191. The EPA required a PA to demonstrate that potential cumulative releases of radionuclides to the accessible environment over a 10,000-year period after disposal are less than specified limits based on the nature of the materials disposed (section 191.13). The PA is to determine the effects of all significant processes and events that may affect the disposal system, consider the associated uncertainties of the processes and events, and estimate the probable cumulative releases of radionuclides.

A PA was included in the CCA. This was the first demonstration of compliance by the DOE with the EPA's disposal standards. The EPA required a verification PA based on the CCA PA that included revised parameters and distributions. This PA was termed the CCA Performance Assessment Verification Test (PAVT) (Trovoto 1997). The EPA based the original certification of the WIPP on the information in the CCA and the results of the CCA PAVT (U.S. Environmental Protection Agency 1998a). The CCA PAVT is documented in Sandia National Laboratories (SNL) 1997 and U.S. Department of Energy 1997.

The WIPP is required to be recertified every five years after first waste receipt (Public Law 02-579). A revised PA was included in the first recertification application in 2004. This PA is termed the CRA-2004 PA, and is documented in the CRA-2004, Chapter 6.0. The EPA again required a verification PA using revised modeling assumptions and parameters (Cotsworth 2005). This PA was termed the CRA-2004 PABC and was documented in Leigh et al. (2005).

As part of the five-year recertification cycle, a PA is included in the CRA-2009. The CRA-2009 PA is a culmination of the previous PAs and is not significantly different from the CRA-2004 PABC, as the methodologies, conceptual models, and assumptions have not changed. Updates to parameters and improvements to computer codes are incorporated in the CRA-2009.

PA-2.1.1 Changes in the CRA-2009 PA

A list of changes to PA since the CRA-2004 and citations for where they are discussed is shown in Table PA-1. In addition to the changes discussed in Table PA-1, the terminology used to describe uncertainty has been updated to reflect the usage now prevalent in the risk assessment literature. Previously, uncertainty in model parameters was referred to as "subjective uncertainty," and that due to stochastic processes was referred to as "stochastic uncertainty." In the years since these terms were first employed, these concepts have matured, and the term "epistemic uncertainty" is now used to describe uncertainty from lack of knowledge, while the term "aleatory uncertainty" now describes uncertainty due to natural variability, e.g. uncertainty arising from future events whose occurrence can be defined in terms of probabilities. In this text, the terms epistemic uncertainty and aleatory uncertainty are used in place of the terms subjective uncertainty and stochastic uncertainty, respectively.

Table PA-1. WIPP Project Changes and Cross References

WIPP Project Change	Cross Reference
CRA-2004 to CRA-2004 PABC Changes[a]	
Inventory Information	Leigh, Trone, and Fox 2005
An Solubility Values	Garner and Leigh 2005
An Solubility Uncertainty Ranges	Garner and Leigh 2005
Microbial Gas Generation Model	Nemer and Stein 2005
Culebra T Fields Mining Modification	Lowry and Kanney 2005
Anhydrite Material Parameters	Vugrin et al. 2005
SPALL Model Parameters	Vugrin 2005
CRA-2004 PABC to CRA-2009 Changes[b]	
DBR Maximum Duration Parameter	Kirkes 2007
Conditional Relationship Between Humid and Inundated Cellulosic, Plastic, or Rubber (CPR) Degradation Rates	Kirchner 2008a
BRAGFLO Code Improvements	Nemer and Clayton 2008
Capillary Pressure and Relative Permeability Model	Nemer and Clayton 2008
Drilling Rate	Clayton 2008a
Parameter Error Corrections • Emplaced CPR • Halite/Disturbed Rock Zone (DRZ) Parameter • Fraction of Repository Occupied by Waste • NUTS and DBR Calculation Input Files	Nemer 2007a, Ismail 2007a, Dunagan 2007, Ismail 2007b, Clayton 2007

[a] See Leigh et al. 2005 for additional discussion of these changes and their implementation in the CRA-2004 PABC.
[b] See Clayton et al. 2008 for additional discussions of these changes and their implementation in the CRA-2009 PA.

From this assessment, the DOE has demonstrated that the WIPP continues to comply with the containment requirements of section 191.13. The containment requirements are stringent and state that the DOE must demonstrate a reasonable expectation that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and consider uncertainties caused by all significant processes and events that may affect the disposal system, including future inadvertent human intrusion into the repository. A quantitative PA is conducted using a series of loosely coupled computer models in which epistemic parameter uncertainties are addressed by a stratified Monte Carlo sampling procedure on selected input parameters, and uncertainties related to future intrusion events are addressed using simple random sampling.

As required by regulation, results of the PA are displayed as CCDFs showing the probability that cumulative radionuclide releases from the disposal system will exceed the values calculated for scenarios considered in the analysis. These CCDFs are calculated using reasonable and, in some cases, conservative conceptual models based on the scientific understanding of the disposal system's behavior. Parameters used in these models are derived from experimental data, field observations, and relevant technical literature. Changes to the CCA and CRA-2004 parameters and models since the original certification have been incorporated into the CRA-2009 PA (Clayton 2008a). The overall mean CCDF continues to lie entirely below the specified limits, and the WIPP therefore continues to be in compliance with the containment requirements of 40 CFR Part 191 Subpart B (see Section PA-2.1.6). Sensitivity analysis of results shows that the location of the mean CCDF is dominated by radionuclide releases that could occur on the surface during an inadvertent penetration of the repository by a future drilling operation (Section PA-9.0). Releases of radionuclides to the accessible environment from transport in groundwater through the shaft seal systems and the subsurface geology are negligible, with or without human intrusion, and do not significantly contribute to the mean CCDF. No releases are predicted to occur at the ground surface in the absence of human intrusion. The natural and engineered barrier systems of the WIPP provide robust and effective containment of transuranic (TRU) waste, even if the repository is penetrated by multiple boreholes.

PA-2.1.2 Conceptual Basis for PA

The foundations of PA are a thorough understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. The DOE's confidence in the results of PA is based in part on the strength of the original research done during site characterization, experimental results used to develop and confirm parameters and models, and robustness of the facility design.

The progression of compliance applications document these aspects of PA leading up to the CRA-2009 PA (i.e., the CCA, the CCA PAVT [Sandia National Laboratories 1997 and U.S. Department of Energy 1997], the CRA-2004 PA, and the CRA-2004 PABC [Leigh et al. 2005]).

The interactions of the repository and waste with the geologic system, and the response of the disposal system to possible future inadvertent human intrusion, are described in Section PA-2.1.4.

PA-2.1.3 Undisturbed Repository Performance

An evaluation of undisturbed repository performance, which is defined to exclude human intrusion and unlikely disruptive natural events, is required by regulation (see 40 CFR § 191.15 and 40 CFR § 191.24). Evaluations of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years (see the CCA, Appendix SCR, Section SCR.1). Disposal system behavior is dominated by the coupled processes of rock deformation surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which they occur is affected by the others.

Rock deformation immediately around the repository begins as soon as excavation creates a disturbance in the stress field. Stress relief results in some degree of brittle fracturing and the formation of a DRZ, which surrounds excavations in all deep mines including the WIPP repository. For the WIPP, the DRZ is characterized by an increase in permeability and porosity, and it may ultimately extend a few meters (m) from the excavated region. Salt will also deform by creep processes resulting from deviatoric stress, causing the salt to move inward and fill voids. Salt creep will continue until deviatoric stress is dissipated and the system is once again at stress equilibrium (see the CRA-2004, Chapter 6.0, Section 6.4.3.1).

The ability of salt to creep, thereby healing fractures and filling porosity, is one of its fundamental advantages as a medium for geologic disposal of radioactive waste, and one reason it was recommended by the National Academy of Sciences (see the CCA, Chapter 1.0, Section 1.3). Salt creep provides the mechanism for crushed salt compaction in the shaft seal system, yielding properties approaching those of intact salt within 200 years (see the CCA, Appendix SEAL, Appendix D, Section D5.2). Salt creep will also cause the DRZ surrounding the shaft to heal rapidly around the concrete components of the seal system. In the absence of elevated gas pressure in the repository, salt creep would also substantially compact the waste and heal the DRZ around the disposal region. Fluid pressures can become large enough through the combined effect of salt creep reducing pore volumes, and gas generation from waste degradation processes, to maintain significant porosity (greater than 20%) within the disposal room throughout the performance period (see also the CRA-2004, Chapter 6.0, Section 6.4.3).

Characterization of the Salado indicates that fluid flow from the far field does not occur on time scales of interest in the absence of an artificially imposed hydraulic gradient (see the CRA-2004, Chapter 2.0, Section 2.1.3.4 for a description of Salado investigations). This lack of fluid flow is the second fundamental reason for choosing salt as a medium for geologic disposal of radioactive waste. Lack of fluid flow is a result of the extremely low permeability of evaporite rocks that make up the Salado. Excavating the repository has disturbed the natural hydraulic gradient and rock properties, resulting in fluid flow. Small quantities of interstitial brine present in the Salado move toward regions of low hydraulic potential, and brine seeps are observed in the underground repository. The slow flow of brine from halite into more permeable anhydrite MBs, and then through the DRZ into the repository, is expected to continue as long as the hydraulic potential within the repository is below that of the far field. The repository environment will also include gas, so the fluid flow must be modeled as a two-phase process. Initially, the gaseous phase will consist primarily of air trapped at the time of closure, although other gases may form from waste degradation. In the PA, the gaseous phase pressure will rise due to creep closure, gas generation,

and brine inflow, creating the potential for flow from the excavated region (see also the CRA-2004, Chapter 6.0, Section 6.4.3.2).

An understanding of waste degradation processes indicates that the gaseous phase in fluid flow and the repository's pressure history will be far more important than if the initial air were the only gas present. Waste degradation can generate significant additional gas by two processes (see also the CRA-2004, Chapter 6.0, Section 6.4.3.3 for historical perspective, and Leigh et al. 2005, Section 2.3 and Section 2.4 for changes):

1. The generation of hydrogen (H_2) gas by anoxic corrosion of steels, other iron (Fe)-based alloys, and aluminum (Al) and Al-based alloys

2. The generation of carbon dioxide (CO_2), hydrogen sulfide (H_2S), and methane (CH_4) by anaerobic microbial consumption of waste containing CPR materials

Coupling these gas-generation reactions to fluid-flow and salt-creep processes is complex. Gas generation will increase fluid pressure in the repository, thereby decreasing the hydraulic gradient and deviatoric stress between the far field and the excavated region and inhibiting the processes of brine inflow and salt creep. Anoxic corrosion will also consume brine as it breaks down water to oxidize steels and other Fe-based alloys and release H_2. Thus, corrosion has the potential to be a self-limiting process, in that as it consumes all water in contact with steels and other Fe-based alloys, it will cease. Microbial reactions also require water, either in brine or the gaseous phase. It is assumed that microbial reactions will result in neither the consumption nor production of water.

The total volume of gas generated by corrosion and microbial consumption may be sufficient to result in repository pressures that approach lithostatic. Sustained pressures above lithostatic are not physically reasonable within the disposal system, because the more brittle anhydrite layers are expected to fracture if sufficient gas is present. The conceptual model implemented in the PA causes anhydrite MB permeability and porosity to increase rapidly as pore pressure approaches and exceeds lithostatic. This conceptual model for pressure-dependent fracturing approximates the hydraulic effect of pressure-induced fracturing and allows gas and brine to move more freely within the MBs at higher pressures (see the CRA-2004, Chapter 6.0, Section 6.4.5.2).

Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components and permanently sealed the shafts. Around the shafts, the DRZ in halite layers will heal rapidly because the presence of the solid material within the shafts will provide rigid resistance to creep. The DRZ around the shaft, therefore, will not provide a continuous pathway for fluid flow (see the CRA-2004, Chapter 6.0, Section 6.4.4). Similarly, the panel closure will rigidly resist creep, leading to a build-up of compressive stress which in turn will cause a rapid elimination of the DRZ locally. In PA, it is conservatively assumed that the DRZ does not heal around either the disposal region or the operations and experimental regions, and pathways for fluid flow may exist indefinitely to the overlying and underlying anhydrite layers (e.g., MB 139 and Anhydrites

A and B). Some quantity of brine will be present in the repository under most conditions and may contain actinides mobilized as both dissolved and colloidal species. Gas generation by corrosion and microbial degradation is expected to occur, and will result in elevated pressures within the repository. These pressures will not significantly exceed lithostatic because the more brittle anhydrite layers will fracture and provide a pathway for gas to leave the repository. Fracturing due to high gas pressures may enhance gas and brine migration from the repository, but gas transport will not contribute to the release of actinides from the disposal system. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species. However, the quantity of actinides that may reach the accessible environment boundary through the interbeds during undisturbed repository performance is insignificant and has no effect on the compliance determination. No migration of radionuclides is expected to occur vertically through the Salado (see Section PA-7.0, and Ismail and Garner 2008).

PA-2.1.4 Disturbed Repository Performance

The WIPP PA is required by the performance standards to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. The probability of these intrusions is based on a future drilling rate. This rate was calculated using the method outlined in Section 33, which analyzes the past record of drilling events in the Delaware Basin. Active institutional controls (AICs) are assumed to prevent intrusion during the first 100 years after closure (40 CFR § 194.41). Passive institutional controls (PICs) were assumed in the CCA to effectively reduce the drilling rate by two orders of magnitude for the 600-year period following 100 years of active control. However, in certifying the WIPP, the EPA denied credit for the effectiveness of passive controls for 600 years (U.S. Environmental Protection Agency 1998a). Although the CRA-2009 PA does not include a reduced drilling intrusion rate to account for PICs, future PAs may do so. Future drilling practices are assumed to be the same as current practice, also consistent with regulatory criteria. These practices include the type and rate of drilling, emplacement of casing in boreholes, and the procedures implemented when boreholes are plugged and abandoned (see 40 CFR § 194.33).

Human intrusion by drilling may cause releases from the disposal system through five mechanisms:

1. Cuttings, which include material intersected by the rotary drilling bit
2. Cavings, which include material eroded from the borehole wall during drilling
3. Spallings, which include solid material carried into the borehole during rapid depressurization of the waste disposal region
4. DBRs, which include contaminated brine that may flow to the surface during drilling
5. Long-term brine releases, which include the contaminated brine that may flow through a borehole after it is abandoned

The first four mechanisms immediately follow an intrusion event and are collectively referred to as direct releases. The accessible environment boundary for these releases is the ground surface. The fifth mechanism, An transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. The accessible environment boundary for these releases is the lateral subsurface limit of the controlled area (CRA-2004, Chapter 6.0, Section 6.0.2.3).

Repository conditions prior to intrusion will be the same as those for undisturbed repository performance, and all processes active in undisturbed repository performance will continue to occur following intrusion. Because an intrusion provides a pathway for radionuclides to reach the ground surface and enter the geological units above the Salado, additional processes will occur that don't in the undisturbed repository performance. These processes include the mobilization of radionuclides as dissolved and colloidal species in repository brine and groundwater flow, and subsequent An transport in the overlying units. Flow and transport in the Culebra are of particular interest because it is the most transmissive unit above the repository. Thus, the Culebra is a potential pathway for lateral migration of contaminated brine in the event of a drilling intrusion accompanied by significant flow up the intrusion borehole (see the CRA-2004, Chapter 6.0, Section 6.4.6.2).

PA-2.1.4.1 Cuttings and Cavings

In a rotary drilling operation, the volume of material brought to the surface as cuttings is calculated as the cylinder defined by the thickness of the unit and the diameter of the drill bit. The quantity of radionuclides released as cuttings is therefore a function of the activity of the intersected waste and the diameter of the intruding drill bit. The DOE uses a constant value of 0.31115 m (12.25 inches [in]), consistent with bits currently used at the WIPP depth in the Delaware Basin (see the CRA-2004, Chapter 6.0, Section 6.4.12.5). The intersected waste activity may vary depending on the type of waste intersected. The DOE considers random penetrations into remote-handled (RH) transuranic (TRU) (RH-TRU) waste and each of the 690 different waste streams (Leigh, Trone, and Fox 2005, Section 4.4) identified for contact-handled (CH) transuranic (TRU) (CH-TRU) waste (569 and 693 waste streams were used in the CCA and the CRA-2004, respectively; see the CRA-2004, Chapter 6.0, Section 6.0.2.3.1).

The volume of particulate material eroded from the borehole wall by the drilling fluids and brought to the surface as cavings may be affected by the drill bit diameter, effective shear resistance of the intruded material, speed of the drill bit, viscosity of the drilling fluid and rate at which it is circulated in the borehole, and other properties related to the drilling process. The most important of these parameters, after drill bit diameter, is the effective shear resistance of the intruded material (Leigh et al. 2005, Section 7.2). In the absence of data describing the reasonable and realistic future properties of degraded waste and magnesium oxide (MgO) backfill, the DOE used conservative parameter values based on the properties of fine-grained sediment. Other properties are assigned fixed values consistent with current practice. The quantity of radionuclides released as cavings depends on the volume of eroded material and its activity, which is treated in the same manner as the activity of cuttings (see also Section PA-4.5 and Section PA-6.8.2.1).

PA-2.1.4.2 Spallings

Unlike releases from cuttings and cavings, which occur with every modeled borehole intrusion, spalling releases will occur only if pressure in the waste-disposal region exceeds the hydrostatic pressure in the borehole. At lower pressures, below about 8 megapascals (MPa), fluid in the waste-disposal region will not flow toward the borehole. At higher pressures, gas flow toward the borehole may be sufficiently rapid to cause additional solid material to enter the borehole. If spalling occurs, the volume of spalled material will be affected by the physical properties of the waste, such as its tensile strength and particle diameter. The DOE based the parameter values used in the PA on reasonable and conservative assumptions. Since the CCA, a revised conceptual model for the spallings phenomena has been developed (see the CRA-2004, Appendix PA, Section PA-4.6 and Appendix PA, Attachment MASS, Section MASS-16.1.3). Model development, execution, and sensitivity studies necessitated implementing parameter values pertaining to waste characteristics, drilling practices, and physics of the process. The parameter range for particle size was derived by expert elicitation (Carlsbad Area Office Technical Assistance Contractor [CTAC] 1997).

The quantity of radionuclides released as spalled material depends on the volume of spalled waste and its activity. Because spalling may occur at a greater distance from the borehole than cuttings and cavings, spalled waste is assumed to have the volume-averaged activity of CH-TRU waste, rather than the sampled activities of individual waste streams. The low permeability of the region surrounding the RH-TRU waste means it is isolated from the spallings process and does not contribute to the volume or activity of spalled material (see also Section PA-4.6 and Section PA-6.8.2.2 for more description of the spallings model).

PA-2.1.4.3 Direct Brine Flow

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. The quantity of radionuclides released by direct brine flow depends on the volume of brine reaching the ground surface and the concentration of radionuclides contained in the brine. As with spallings, DBRs will not occur if repository pressure is below the hydrostatic pressure in the borehole. At higher repository pressures, mobile brine present in the repository will flow toward the borehole. If the volume of brine flowing from the repository into the borehole is small, it will not affect the drilling operation, and flow may continue until the driller reaches the base of the evaporite section and installs casing in the borehole (see also Section PA-4.7 and Section PA-6.8.2.3).

PA-2.1.4.4 Mobilization of Actinides in Repository Brine

Actinides may be mobilized in repository brine in two principal ways:

1. As dissolved species

2. As colloidal species

The solubilities of actinides depend on their oxidation states, with the more reduced forms (for example, III and IV oxidation states) being less soluble than the oxidized forms (V and VI).

Conditions within the repository will be strongly reducing because of large quantities of metallic Fe in the steel containers and the waste, and—in the case of plutonium (Pu)—only the lower-solubility oxidation states (Pu(III) and Pu(IV)) will persist. Microbial activity will also help create reducing conditions. Solubilities also vary with pH. The DOE is therefore emplacing MgO in the waste-disposal region to ensure conditions that reduce uncertainty and establish low An solubilities. MgO consumes CO_2 and buffers pH, lowering An solubilities in WIPP brines (see Appendix SOTERM-2009 and Appendix MgO-2009). Solubilities in the PA are based on the chemistry of brines that might be present in the waste-disposal region, reactions of these brines with the MgO engineered barrier, and strongly reducing conditions produced by anoxic corrosion of steels and other Fe-based alloys.

The waste contains organic ligands that could increase An solubilities by forming complexes with dissolved An species. However, these organic ligands also form complexes with other dissolved metals, such as magnesium (Mg), calcium (Ca), Fe, lead (Pb), vanadium (V), chromium (Cr), manganese (Mn), and nickel (Ni), that will be present in repository brines due to corrosion of steels and other Fe-based alloys. The CRA-2009 PA speciation and solubility calculations include the effect of organic ligands but not the beneficial effect of competition with Fe, Pb, V, Cr, Mn, and Ni. (Appendix SOTERM-2009, Section SOTERM-2.3.6 and Section SOTERM-4.6, and Brush and Xiong 2005).

Colloidal transport of actinides has been examined, and four types of colloids have been determined to represent the possible behavior at the WIPP. These include microbial colloids, humic substances, An intrinsic colloids, and mineral fragments. Concentrations of An mobilized as these colloidal forms are included in the estimates of total An concentrations used in PA (Appendix SOTERM-2009, Section SOTERM-3.8.1 and Section SOTERM-4.7, and Garner and Leigh 2005).

PA-2.1.4.5 Long-Term Brine Flow up an Intrusion Borehole

Long-term releases to the ground surface or groundwater in the Rustler Formation (hereafter referred to as the Rustler) or overlying units may occur after the borehole has been plugged and abandoned. In keeping with regulatory criteria, borehole plugs are assumed to have properties consistent with current practice in the basin. Thus, boreholes are assumed to have concrete plugs emplaced at various locations. Initially, concrete plugs effectively limit fluid flow in the borehole. However, under most circumstances, these plugs cannot be expected to remain fully effective indefinitely. For the purposes of PA, discontinuous borehole plugs above the repository are assumed to degrade 200 years after emplacement. From then on, the borehole is assumed to fill with a silty-sand-like material containing degraded concrete, corrosion products from degraded casing, and material that sloughs into the hole from the walls. Of six possible plugged borehole configurations in the Delaware Basin, three are considered either likely or adequately representative of other possible configurations; one configuration (a two-plug configuration) is explicitly modeled in the flow and transport model (see Section PA-3.7 and Appendix MASS-2009, Section MASS-16.3).

If sufficient brine is available in the repository, and if pressure in the repository is higher than in the overlying units, brine may flow up the borehole following plug degradation. In principle, this brine could flow into any permeable unit or to the ground surface if repository pressure were

high enough. For modeling purposes, brine is allowed to flow only into the higher-permeability units and to the surface. Lower-permeability anhydrite and mudstone layers in the Rustler are treated as if they were impermeable to simplify the analysis while maximizing the amount of flow into units where it could potentially contribute to disposal system releases. Model results indicate that essentially all flow occurs into the Culebra, which has been recognized since the early stages of site characterization as the most transmissive unit above the repository and the most likely pathway for subsurface transport (see also the CRA-2004, Chapter 2.0, Section 2.2.1.4.1.2).

PA-2.1.4.6 Groundwater Flow in the Culebra

Site characterization activities in the units above the Salado have focused on the Culebra. These activities have shown that the direction of groundwater flow in the Culebra varies somewhat regionally, but in the area that overlies the repository, flow is southward. These characterization and modeling activities conducted in the units above the Salado confirm that the Culebra is the most transmissive unit above the Salado. The Culebra is the unit into which actinides are likely to be introduced from long-term flow up an abandoned borehole. Regional variation in the Culebra's groundwater flow direction is influenced by the transmissivity observed, as well as the lateral (facies) changes in the lithology of the Culebra in the groundwater basin where the WIPP is located. Site characterization activities have provided no evidence of karst groundwater systems in the controlled area, although groundwater flow in the Culebra is affected by the presence of fractures, fracture fillings, and vuggy pore features (see Appendix HYDRO-2009 and the CRA-2004, Chapter 2.0, Section 2.1.3.5). Other laboratory and field activities have focused on the behavior of dissolved and colloidal actinides in the Culebra.

Basin-scale regional modeling of three-dimensional groundwater flow in the units above the Salado demonstrates that it is appropriate, for the purposes of estimating radionuclide transport, to conceptualize the Culebra as a two-dimensional confined aquifer (see the CRA-2004, Chapter 2.0, Section 2.2.1.1). Uncertainty in the flow field is incorporated by using 100 different geostatistically based T fields, each of which is consistent with available head and transmissivity data (Appendix PA-2009, Appendix TFIELD-2009).

Groundwater flow in the Culebra is modeled as a steady-state process, but two mechanisms considered in the PA could affect flow in the future. Potash mining in the McNutt Potash Zone (hereafter referred to as the McNutt) of the Salado, which occurs now in the Delaware Basin outside the controlled area and may continue in the future, could affect flow in the Culebra if subsidence over mined areas causes fracturing or other changes in rock properties (see the CRA-2004, Chapter 6.0, Section 6.3.2.3). Climatic changes during the next 10,000 years may also affect groundwater flow by altering recharge to the Culebra (see the CRA-2004, Chapter 6.0, Section 6.4.9 and the CCA, Appendix CLI).

Consistent with regulatory criteria of 40 CFR § 194.32, mining outside the controlled area is assumed to occur in the near future, and mining within the controlled area is assumed to occur with a probability of 1 in 100 per century (adjusted for the effectiveness of AICs during the first 100 years after closure). Consistent with regulatory guidance, the effects of mine subsidence are incorporated in PA by increasing the transmissivity of the Culebra over the areas identified as mineable by a factor sampled from a uniform distribution between 1 and 1000 (U.S.

Environmental Protection Agency 1996a, p. 5229). T fields used in PA are therefore adjusted and steady-state flow fields calculated accordingly; once for mining that occurs only outside the controlled area, and once for mining that occurs both inside and outside the controlled area (Appendix TFIELD-2009, Section 9.0). Mining outside the controlled area is considered in both undisturbed and disturbed repository performance.

The extent to which the climate will change during the next 10,000 years and how such a change will affect groundwater flow in the Culebra are uncertain. Regional three-dimensional modeling of groundwater flow in the units above the Salado indicates that flow velocities in the Culebra may increase by a factor of 1 to 2.25 for reasonably possible future climates (see the CCA, Appendix CLI). This uncertainty is incorporated in PA by scaling the calculated steady-state specific discharge within the Culebra by a sampled parameter within this range.

PA-2.1.4.7 Actinide Transport in the Culebra

Field tests have shown that the Culebra is best characterized as a double-porosity medium for estimating contaminant transport in groundwater (see the CRA-2004, Chapter 2.0, Section 2.2.1.4.1.2 and Appendix HYDRO-2009). Groundwater flow and advective transport of dissolved or colloidal species and particles occurs primarily in a small fraction of the rock's total porosity and corresponds to the porosity of open and interconnected fractures and vugs. Diffusion and slower advective flow occur in the remainder of the porosity, which is associated with the low-permeability dolomite matrix. Transported species, including actinides (if present), will diffuse into this porosity.

Diffusion from the advective porosity into the dolomite matrix will retard An transport through two mechanisms. Physical retardation occurs simply because actinides that diffuse into the matrix are no longer transported with the flowing groundwater. Transport is interrupted until they diffuse back into the advective porosity. In situ tracer tests have demonstrated this phenomenon. Chemical retardation also occurs within the matrix as actinides are sorbed onto dolomite grains. The relationship between sorbed and liquid concentrations is assumed to be linear and reversible. The distribution coefficients (K_ds) that characterize the extent to which actinides will sorb on dolomite were based on experimental data (see the CRA-2004, Chapter 6.0, Section 6.4.6.2).

PA-2.1.4.8 Intrusion Scenarios

Human intrusion scenarios evaluated in the PA include both single intrusion events and combinations of multiple boreholes. Two different types of boreholes are considered: those that penetrate a pressurized brine reservoir in the underlying Castile Formation (hereafter referred to as the Castile), and those that do not.

The presence of a brine reservoir under the repository is speculative, but on the basis of current information cannot be ruled out. A pressurized brine reservoir was encountered at the WIPP-12 borehole within the controlled area to the north of the disposal region, and other pressurized brine reservoirs associated with regions of deformation in the Castile have been encountered elsewhere in the Delaware Basin (see the CRA-2004, Chapter 2.0, Section 2.2.1.2.2). Based on a geostatistical analysis of the geophysical data of brine encounters in the region, the DOE

estimates that there is a 0.08 probability that a random borehole penetrating waste in the WIPP will also penetrate an underlying brine reservoir (see the CCA, Appendix MASS, Attachment 18-6). Upon their review of the CCA, the EPA determined that the DOE should treat this probability as uncertain, ranging from 0.01 to 0.60 in the CCA PAVT. The EPA also required the DOE to modify the assumptions concerning Castile properties to increase the brine reservoir volumes (U.S. Environmental Protection Agency 1998b; *Technical Support Document for 194.23: Parameter Justification Report*, Section 5). The EPA determined that changing the rock compressibility and porosity of the Castile effectively modified the sampled brine reservoir volume to include the possibility of larger brine reservoir volumes like those encountered by the WIPP-12 borehole.

The primary consequence of penetrating a pressurized reservoir is to provide an additional source of brine beyond that which might flow into the repository from the Salado. Direct releases at the ground surface resulting from the first repository intrusion would be unaffected by additional Castile brine, even if it flowed to the surface, because brine moving straight up a borehole will not significantly mix with waste. However, the presence of Castile brine could significantly increase radionuclide releases in two ways. First, the volume of contaminated brine that could flow to the surface may be greater for a second or subsequent intrusion into a repository that has already been connected by a previous borehole to a Castile reservoir. Second, the volume of contaminated brine that may flow up an abandoned borehole after plug degradation may be greater for combinations of two or more boreholes that intrude the same panel if one of the boreholes penetrates a pressurized reservoir. Both processes are modeled in PA.

PA-2.1.5 Compliance Demonstration Method

The DOE's approach to demonstrating continued compliance is the PA, which is based on the criteria indicated in section 194.34. The PA process comprehensively considers the FEPs relevant to disposal system performance (see Appendix SCR-2009). Those FEPs shown by screening analyses to potentially affect performance are included in quantitative calculations using a system of loosely coupled computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. Uncertainty in parameter values is incorporated in the analysis by a Monte Carlo approach, in which multiple simulations (or realizations) are completed using sampled values for the imprecisely known input parameters (see the CRA-2004, Chapter 6.0, Section 6.1.5). Distribution functions characterize the state of knowledge for these parameters, and each realization of the modeling system uses a different set of sampled input values. A sample size of 300 results in 300 different values of each parameter. Thus, there are 300 different sets (vectors) of input parameter values. These 300 vectors were divided among 3 replicates. Quality assurance activities demonstrate that the parameters, software, and analysis used in PA were the result of a rigorous process conducted under controlled conditions (40 CFR § 194.22).

Of the FEPs considered, exploratory drilling for natural resources was identified as the only disruption with sufficient likelihood and consequence of impacting releases from the repository. For each vector of parameters values, 10,000 possible futures (realizations) are simulated, where a single future is defined as a series of intrusion events that occur randomly in space and time (Section PA-2.2). Each of these futures is assumed to have an equal probability of occurring;

hence a probability of 0.0001. Cumulative radionuclide releases from the disposal system are calculated for each future, and CCDFs are constructed by sorting the releases from smallest to largest and then summing the probabilities across the future. Mean CCDFs were then computed for the three replicates of sampled parameters (Section PA-2.2).

PA-2.1.6 Results of the PA

This section summarizes the results of the CRA-2009 PA and demonstrates that the WIPP continues to comply with the quantitative containment requirements in 40 CFR § 191.13(a). The CRA-2009 PA is different than the original certification PA in the CCA and the PA in the CRA-2004 PABC because it includes additional information, changes, and new data required by 40 CFR § 194.15 recertification application requirements. Table PA-1 details the changes and new information included in this PA.

The results of the CRA-2009 PA demonstrate that the repository continues to comply with the disposal standards. The key metric for regulatory compliance is the mean CCDF. Figure PA-1, which compares the overall mean CCDF for the CRA-2009 PA to the overall mean CCDF for the CRA-2004 PABC, demonstrates two key points. First, the overall mean CCDF lies entirely below the limits specified in section 191.13(a). Thus, the WIPP is in compliance with the containment requirements of Part 191. Second, for any probability, the expected releases in the CRA-2009 PA are only slightly higher than those in the CRA-2004 PABC, primarily because of the increased drilling rate.

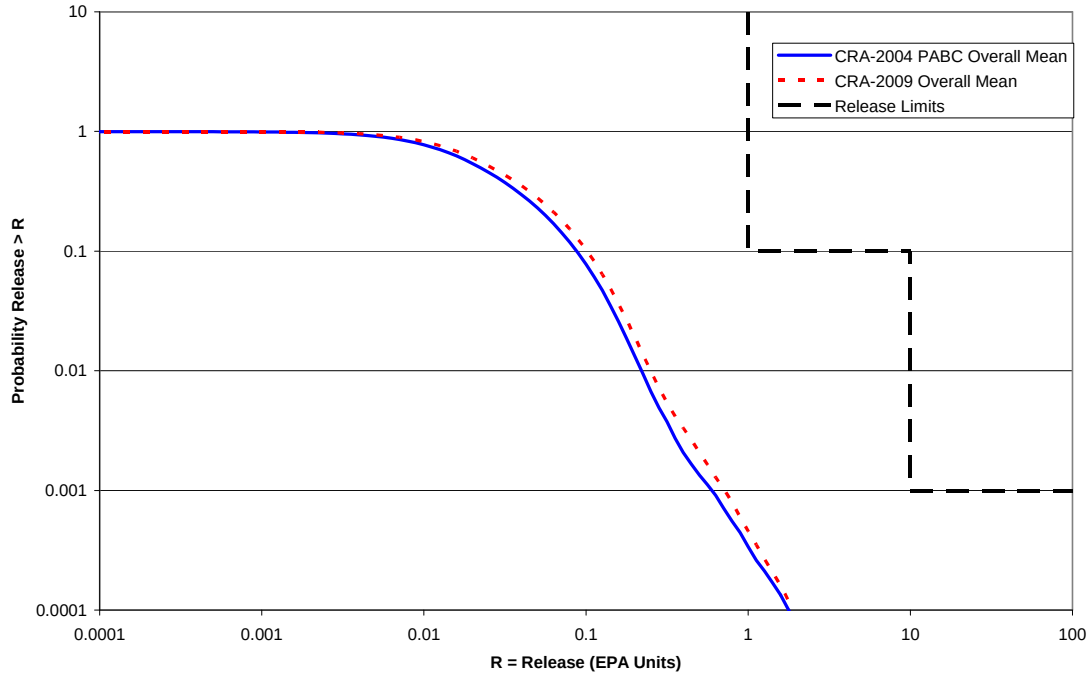


Figure PA-1. Overall Mean CCDFs for Total Normalized Releases: CRA-2009 PA and CRA-2004 PABC

Detailed results of the CRA-2009 PA are contained in Section PA-9.0, which describes sensitivity analyses conducted as the final step in the Monte Carlo analysis. These sensitivity

analyses indicate the relative importance of each sampled parameter in terms of its contribution to uncertainty in estimating disposal system performance. Analyses also examine the sensitivity of intermediate performance measures to the sampled parameters. Examples of such intermediate performance measures include the quantity of radionuclides released to the accessible environment by any one mechanism (for example, cuttings or DBRs), and other model results that describe conditions of interest, such as disposal region pressure.

Section PA-9.0 presents CCDF distributions for each replication of the analysis, mean CCDFs, and an overall mean CCDF with the 95% confidence interval estimated from the 3 independent mean distributions. All 300 individual CCDFs, as well as the overall mean CCDF determined from the 3 replicates, lie entirely below and to the left of the limits specified in section 191.13(a) (see Figure PA-79). Thus, the WIPP continues to comply with the containment requirements of Part 191. Comparing the results of the 3 replicates indicates that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes (see Figure PA-80). Within the region of regulatory interest (that is, at probabilities greater than $10^{-3}/10^{4}$ year [yr]), the mean CCDFs from each replicate are essentially indistinguishable from the overall mean.

As discussed in Section PA-9.1, Section PA-9.2, and Section PA-9.3, examining the normalized releases from cuttings and cavings, spallings, and DBRs provides insight into the relative importance of each release mode's contribution to the mean CCDF's location and the compliance determination. Releases from cuttings and cavings dominate the mean CCDF at high probabilities, while DBRs dominate the mean CCDF at low probabilities. Spallings are less important and have very little effect on the location of the mean. Subsurface releases from groundwater transport are less than 10^{-6} EPA units and make no contribution to the mean CCDF's location.

Uncertainties characterized in the natural system and the interaction of waste with the disposal system environment show little variation between the location of the mean CCDFs of the three replicates, providing additional confidence in the compliance determination. The natural and engineered barrier systems of the WIPP provide robust and effective containment of TRU waste even if the repository is penetrated by multiple borehole intrusions.

PA-2.2 Conceptual Structure of the PA

This section outlines the conceptual structure of the WIPP PA. First, a discussion of the regulatory requirements is given. The requirements of section 191.13 and section 194.34 (summarized in Section PA-2.2.1) lead to the identification of three main PA components:

1. A probabilistic characterization of the likelihood for different futures to occur at the WIPP site over the next 10,000 years

2. A procedure for estimating the radionuclide releases to the accessible environment associated with each possible future that could occur at the WIPP site over the next 10,000 years

3. A probabilistic characterization of the uncertainty in the parameters used to estimate potential releases

The probabilistic methods employed in WIPP PA give rise to the CCDF specified in section 191.13(a) and the distributions specified by 40 CFR § 194.34(b).

PA-2.2.1 Regulatory Requirements

The methodology employed in PA derives from the EPA's standard for the geologic disposal of radioactive waste, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (Part 191) (U.S. Environmental Protection Agency 1993), which is divided into three subparts. 40 CFR Part 191 Subpart A applies to a disposal facility prior to decommissioning and establishes standards for the annual radiation doses to members of the public from waste management and storage operations. Part 191 Subpart B applies after decommissioning and sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years (section 191.13) and assurance requirements to provide confidence that section 191.13 will be met (40 CFR § 191.14). Part 191 Subpart B also sets limits on radiation doses to members of the public in the accessible environment for 10,000 years of undisturbed repository performance (section 191.15). 40 CFR Part 191 Subpart C limits radioactive contamination of groundwater for 10,000 years after disposal (section 191.24). In this recertification application, the DOE must demonstrate a reasonable expectation that the WIPP will continue to comply with the requirements of Part 191 Subparts B and C.

The following is the central requirement in Part 191 Subpart B, and the primary determinant of the PA methodology (U.S. Environmental Protection Agency 1985, p. 38086).

> § 191.13 Containment Requirements:
>
> (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
>
> (b) Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13(a) will be achieved.

Section 191.13(a) refers to "quantities calculated according to Table 1 (Appendix A)," which means a normalized radionuclide release to the accessible environment based on the type of waste being disposed, the initial waste inventory, and the size of release that may occur (U.S. Environmental Protection Agency 1985, Appendix A). Table 1 of Appendix A specifies allowable releases (i.e., release limits) for individual radionuclides and is reproduced as Table

PA-2. The WIPP is a repository for TRU waste, which is defined as "waste containing more than 100 nanocuries of alpha-emitting TRU isotopes, with half-lives greater than twenty years, per gram of waste" (U.S. Environmental Protection Agency 1985, p. 38084). The normalized release R for TRU waste is defined by

$$R = \sum_i \left(\frac{Q_i}{L_i} \right) \left(\frac{1 \times 10^6 \text{ Ci}}{C} \right) \quad \text{(PA.1)}$$

where Q_i is the cumulative release of radionuclide i to the accessible environment during the 10,000-year period following closure of the repository (curies [Ci]), L_i is the release limit for radionuclide i given in Table PA-2 (Ci), and C is the amount of TRU waste emplaced in the repository (Ci). In the CRA-2009 PA, $C = 2.32 \times 10^6$ Ci (Leigh and Trone 2005, Section 3). Further, "accessible environment" means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere beyond the controlled area. "Controlled area" means (1) a surface location, to be identified by PICs, that encompasses no more than 100 square kilometers (km^2) and extends horizontally no more than 5 kilometers (km) in any direction from the outer boundary of the original radioactive waste's location in a disposal system, and (2) the subsurface underlying such a location (section 191.12).

PAs are the basis for addressing the containment requirements. To help clarify the intent of Part 191, the EPA promulgated 40 CFR Part 194 (2004), Criteria for the Certification and

Table PA-2. Release Limits for the Containment Requirements (U.S. Environmental Protection Agency 1985, Appendix A, Table 1)

Radionuclide	Release Limit L_i per 1000 MTHM[a] or Other Unit of Waste[b]
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Pu-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium (Th) -230 or -232	10
Tin-126	1,000
Uranium (U) -233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

a Metric tons of heavy metal (MTHM) exposed to a burnup between 25,000 megawatt-days (MWd) per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

b An amount of TRU wastes containing one million Ci of alpha-emitting TRU radionuclides with half-lives greater than 20 years.

Recertification of the Waste Isolation Pilot Plant's Compliance with the Part 191 Disposal Regulations. There, an elaboration on the intent of section 191.13 is prescribed.

> § 194.34 Results of performance assessments.
>
> (a) The results of performance assessments shall be assembled into "complementary, cumulative distributions functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.
>
> (b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application.
>
> (c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application.
>
> (d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability.
>
> (e) Any compliance application shall display the full range of CCDFs generated.
>
> (f) Any compliance application shall provide information which demonstrates that there is at least a 95% level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

The DOE's methodology for PA uses information about the disposal system and waste to evaluate performance over the 10,000-year regulatory time period. To accomplish this task, the FEPs with potential to affect the future of the WIPP are first defined (Section PA-2.3.1). Next, scenarios that describe potential future conditions in the WIPP are formed from logical groupings of retained FEPs (Section PA-2.3.2). The scenario development process results in a probabilistic characterization for the likelihood of different futures that could occur at the WIPP (Section PA-2.2.2). Using the retained FEPs, models are developed to estimate the radionuclide releases from the repository (Section PA-2.2.3). Finally, uncertainty in model parameters is characterized probabilistically (Section PA-2.2.4).

PA-2.2.2 Probabilistic Characterization of Different Futures

As discussed in Section PA-2.3.1, the CCA PA scenario development process for the WIPP identified exploratory drilling for natural resources as the only disruption with sufficient likelihood and consequence of impacting releases from the repository (see the CCA, Appendix SCR). In addition, Part 194 specifies that the occurrence of mining within the LWB must be included in the PA. This has not changed for the CRA-2009 PA. As a result, the projection of releases over the 10,000 years following closure of the WIPP is driven by the nature and timing of intrusion events.

The collection of all possible futures $\boldsymbol{x}_{st}$ forms the basis for the probability space $(\mathcal{S}_{st}, \mathbb{S}_{st}, p_{st})$ characterizing aleatory uncertainty, where $\mathcal{S}_{st} = \{\boldsymbol{x}_{st} : \boldsymbol{x}_{st}$ is a possible future of the WIPP$\}$, $\mathbb{S}_{st}$ is a suitably restricted collection of sets of futures, called "scenarios" (Section PA-3.10), and p_{st} is

a probability measure for the elements of $\mathcal{S}_{st}$. A possible future, $\mathbf{x}_{st,i}$, is thus characterized by the collection of intrusion events that occur in that future:

$$\mathbf{x}_{st,i} = [\underbrace{(t_1, e_1, l_1, b_1, p_1, \mathbf{a}_1)}_{1^{st}\text{ intrusion}}, \underbrace{(t_2, e_2, l_2, b_2, p_2, \mathbf{a}_2)}_{2^{nd}\text{ intrusion}}, \ldots, \underbrace{(t_n, e_n, l_n, b_n, p_n, \mathbf{a}_n)}_{n^{th}\text{ intrusion}}, t_{\min}] \quad \text{(PA.2)}$$

where

- n is the number of drilling intrusions
- t_j is the time (year) of the j^{th} intrusion
- l_j designates the location of the j^{th} intrusion
- e_j designates the penetration of an excavated or nonexcavated area by the j^{th} intrusion
- b_j designates whether or not the j^{th} intrusion penetrates pressurized brine in the Castile Formation
- p_j designates the plugging procedure used with the j^{th} intrusion (i.e., continuous plug, two discrete plugs, three discrete plugs)
- $\mathbf{a}_j$ designates the type of waste penetrated by the j^{th} intrusion (i.e., no waste, CH-TRU waste, RH-TRU waste, and, for CH-TRU waste, the waste streams encountered)
- t_{min} is the time at which potash mining occurs within the LWB

The subscript *st* indicates that aleatory (i.e., stochastic) uncertainty is being considered; the letters *st* are retained for historical context. The subscript *i* indicates that the future $\mathbf{x}_{st}$ is one of many sample elements from $\mathcal{S}_{st}$.

The probabilistic characterization of n, t_j, l_j, and e_j is based on the assumption that drilling intrusions will occur randomly in time and space at a constant average rate (i.e., follow a Poisson process); the probabilistic characterization of b_j derives from assessed properties of brine pockets; the probabilistic characterization of $\mathbf{a}_j$ derives from the volumes of waste emplaced in the WIPP in relation to the volume of the repository; and the probabilistic characterization of p_j derives from current drilling practices in the sedimentary basin (i.e., the Delaware Basin) in which the WIPP is located. A vector notation is used for $\mathbf{a}_j$ because it is possible for a given drilling intrusion to miss the waste or to penetrate different waste types (CH-TRU and RH-TRU) as well as to encounter different waste streams in the CH-TRU waste. Further, the probabilistic characterization for t_{min} follows from the criteria in Part 194 that the occurrence of potash mining within the LWB should be assumed to occur randomly in time (i.e., follow a Poisson process with a rate constant of $\lambda_m = 10^{-4}$ yr^{-1}), with all commercially viable potash reserves within the LWB extracted at time t_{min}. In practice, the probability measure p_{st} is defined by specifying probability distributions for each component of $\mathbf{x}_{st}$, as discussed further in Section PA-3.0.

PA-2.2.3 Estimation of Releases

Based on the retained FEPs (Section PA-2.3.1), release mechanisms include direct transport of material to the surface at the time of a drilling intrusion (i.e., cuttings, spallings, and brine flow) and release subsequent to a drilling intrusion due to brine flow up a borehole with a degraded

plug (i.e., groundwater transport). The quantities of releases are determined by the state of the repository through time, which is determined by the type, timing, and sequence of prior intrusion events. For example, pressure in the repository is an important determinant of spallings, and the amount of pressure depends on whether the drilling events that have occurred penetrated brine pockets and how long prior to the current drilling event the repository was inundated.

Computational models for estimating releases were developed using the retained FEPs; these models are summarized in Figure PA-2. These computational models implement the conceptual models representing the repository system as described in section 194.23 and the mathematical models for physical processes presented in Section PA-4.0. Most of the computational models involve the numerical solution of partial differential equations (PDEs) used to represent processes such as material deformation, fluid flow, and radionuclide transport.

The collection of computation models can be represented abstractly as a function $f(\mathbf{x}_{st}|\mathbf{v}_{su})$, which quantifies the release that could result from the occurrence of a specific future $\mathbf{x}_{st}$ and a specific set of values for model parameters $\mathbf{v}_{su}$. Because the future of the WIPP is unknown, the values of $f(\mathbf{x}_{st}|\mathbf{v}_{su})$ are uncertain. Thus, the probability space $(\mathcal{S}_{st}, \mathbb{S}_{st}, p_{st})$, together with the function $f(\mathbf{x}_{st}|\mathbf{v}_{su})$, give rise to the CCDF specified in section 191.13(a), as illustrated in Figure PA-3. The CCDF represents the probability that a release from the repository greater than R will be observed, where R is a point on the abscissa (x-axis) of the graph (Figure PA-3).

Formally, the CCDF depicted in Figure PA-3 results from an integration over the probability space $(\mathcal{S}_{st}, \mathbb{S}_{st}, p_{st})$:

$$prob\left(rel > R\middle|\mathbf{v}_{su}\right) = \int_{\mathcal{S}_{st}} \delta_R\left(f\left(\mathbf{x}_{st}\middle|\mathbf{v}_{su}\right)\right) d_{st}\left(\mathbf{x}_{st}\middle|\mathbf{v}_{su}\right) dV_{st} \tag{PA.3}$$

where $\delta_R(f(\mathbf{x}_{st}|\mathbf{v}_{su})) = 1$ if $f(\mathbf{x}_{st}|\mathbf{v}_{su}) > R$, $\delta_R(f(\mathbf{x}_{st}|\mathbf{v}_{su})) = 0$ if $f(\mathbf{x}_{st}|\mathbf{v}_{su}) \le R$, and $d_{st}(\mathbf{x}_{st}|\mathbf{v}_{su})$ is the probability density function associated with the probability space $(\mathcal{S}_{st}, \mathbb{S}_{st}, p_{st})$. In practice, the integral in Equation (PA.3) is evaluated by a Monte Carlo technique, where a random sample $\mathbf{x}_{st,i}$, $i = 1, nR$, is generated from $\mathcal{S}_{st}$ consistent with the probability distribution p_{st}. Using this random sample, Equation (PA.3) is numerically evaluated as

$$\begin{aligned} prob\left(rel > R\middle|\mathbf{v}_{su}\right) &= \int_{\mathcal{S}_{st}} \delta_R\left(f\left(\mathbf{x}_{st}\middle|\mathbf{v}_{su}\right)\right) d_{st}\left(\mathbf{x}_{st}\middle|\mathbf{v}_{su}\right) dV_{st} \\ &\cong \sum_{j=1}^{nR} \delta_R\left(f\left(\mathbf{x}_{st,j}\middle|\mathbf{v}_{su}\right)\right) \Big/ nR \end{aligned} \tag{PA.4}$$

The models in Figure PA-2 are too complex to permit a closed-form evaluation of the integral in Equation (PA.4) that defines the CCDF specified in Part 191. In WIPP PA, these probability distribution functions (PDFs) are constructed using Monte Carlo simulation to sample the entire possible set of release outcomes. As long as the sampling is conducted properly and a sufficient number of samples is collected, the PDF of the sample should successfully approximate the PDF of the sample "universe" of all possible releases.

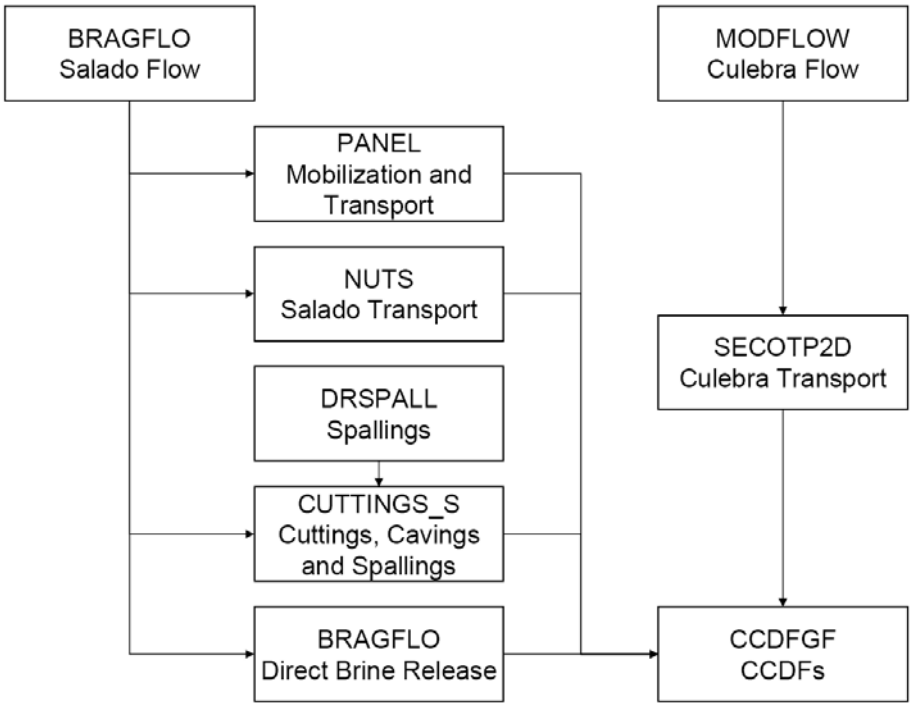


Figure PA-2. Computational Models Used in PA

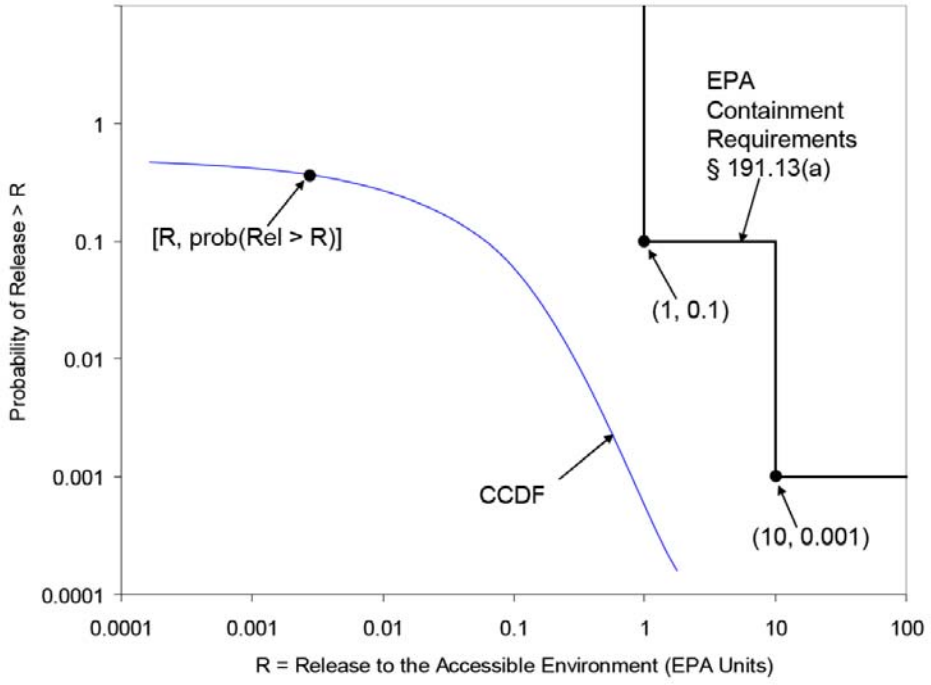


Figure PA-3. Construction of the CCDF Specified in 40 CFR Part 191 Subpart B

In PA, the number of samples *nR* used to construct a CCDF is 10,000. However, the models in Figure PA-2 are also too computationally intensive to permit their evaluation for each of these 10,000 futures. Due to this constraint, the models in Figure PA-2 are evaluated for a relatively small number of specific scenarios, and the results of these evaluations are used to construct CCDFs. The representative scenarios are labeled E0, E1, E2, and E1E2, and are defined in Section PA-3.10; the procedure for constructing a CCDF from these scenarios is described in Section PA-6.0.

PA-2.2.4 Probabilistic Characterization of Parameter Uncertainty

If the parameters used in the process-level models of Figure PA-2 were precisely known and if the models could accurately predict the future behavior of the repository, the evaluation of repository performance alone would be sufficient to answer the first three questions related to repository performance. However, the models do not perfectly represent the dynamics of the system and their parameters are not precisely known. Therefore, it is necessary to estimate the confidence one has in the CCDFs being constructed. The confidence in the CCDFs is established using Monte Carlo methods to evaluate how the uncertainty in the model parameters impacts the CCDFs or releases. The probabilistic characterization of the uncertainty in the model parameters is the outcome of the data development effort for the WIPP (summarized in Section 8.0 in Fox 2008).

Formally, uncertainty in the parameters that underlie the WIPP PA can be characterized by a second probability space $(\mathcal{S}_{su}, \mathbb{S}_{su}, p_{su})$, where the sample space $\mathcal{S}_{su}$ is defined by

$$\mathcal{S}_{su} = \{\mathbf{v}_{su}: \ \mathbf{v}_{su} \text{ is a sampled vector of parameter values}\} \qquad \text{(PA.5)}$$

The subscript *su* indicates that epistemic (i.e., subjective) uncertainty is being considered; the letters *su* are retained for historical context. An element $\mathbf{v}_{su} \in \mathcal{S}_{su}$ is a vector $\mathbf{v}_{su} = v_{su,1}, v_{su,2}, \ldots, v_{su,N})$ of length N, where each element $v_{su,k}$ is an uncertain parameter used in the models to estimate releases. In practice, the probability measure p_{su} is defined by specifying probability distributions for each element of $\mathbf{v}_{su}$, discussed further in Section PA-5.0.

If the actual value for $\mathbf{v}_{su}$ were known, the CCDF resulting from evaluation of Equation (PA.4) could be determined with certainty and compared with the criteria specified in Part 191. However, given the complexity of the WIPP site, the 10,000-year period under consideration, and the state of knowledge about the natural and engineered system, values for $\mathbf{v}_{su}$ are not known with certainty. Rather, the uncertainty in $\mathbf{v}_{su}$ is characterized probabilistically, as described above, leading to a distribution of CCDFs (Figure PA-4) with each CCDF resulting from one of many vectors of values of $\mathbf{v}_{su}$. The uncertainty associated with the parameters is termed epistemic uncertainty, and has been referred to in WIPP PA documentation as subjective uncertainty.

WIPP PA uses a Monte Carlo procedure for evaluating the effects of epistemic uncertainty on releases. The procedure involves sampling the distributions assigned to the uncertain parameters and generating a CCDF of releases based on the results of the process-level models generated using those parameters values. By repeating this process many times, a distribution of the

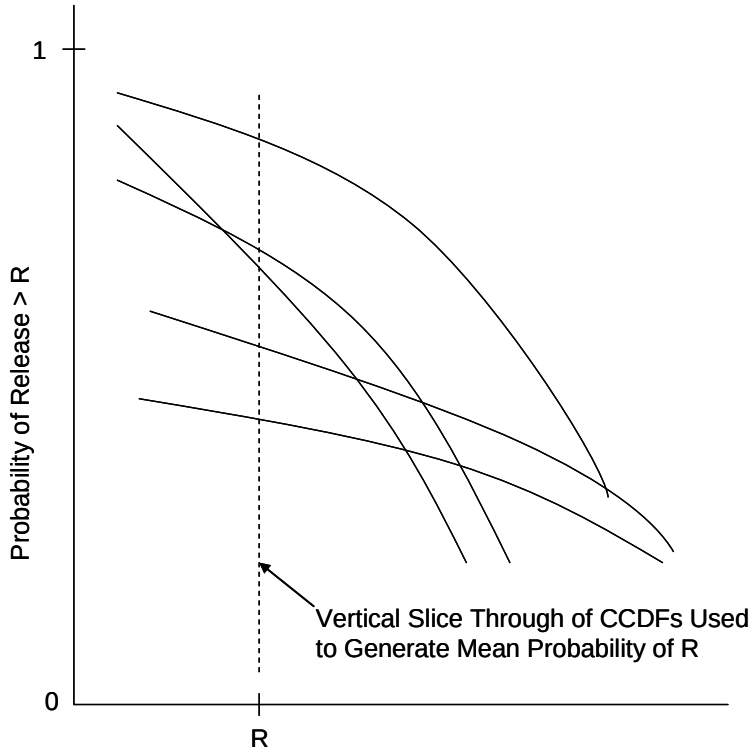


Figure PA-4. Distribution of CCDFs Resulting from Possible Values for the Sampled Parameters

CCDFs can be constructed. The requirements of section 191.13 are evaluated, in part, using the mean probability of release. The overall mean probability curve is created by averaging across the CCDFs for releases, i.e., averaging the CCDFs across vertical slices (Figure PA-4) (a formal definition is provided in Helton et al. 1998). In addition, confidence limits on the mean are computed using standard t-statistics (Figure PA-5). The proximity of these curves to the boundary line in Figure PA-3 indicates the confidence with which Part 191 will be met. Confidence is also established by examining the distribution of the CCDFs in relation to the release limits (Figure PA-6).

WIPP PA uses a stratified sampling design called LHS (McKay, Beckman, and Conover 1979) to generate a sample $\mathbf{v}_{su}$, $i = 1, \ldots, nLHS$, from $\mathcal{S}_{su}$ consistent with the probability distribution p_{su}. LHS is an efficient scheme for sampling the range of a distribution using a relatively small sample. Based on order statistics, the sample size of $nLHS = 300$ replicates would provide coverage of 99% of the CCDF distribution with a confidence of 95%.

In Part 194, the EPA decided that the statistical portion of the determination of compliance with Part 191 will be based on the sample mean. The LHS sample sizes should be demonstrated operationally to improve (reduce the size of) the confidence interval for the estimated mean. The underlying principle is to show convergence of the mean (U.S. Environmental Protection Agency 1996b, p. 8-41).

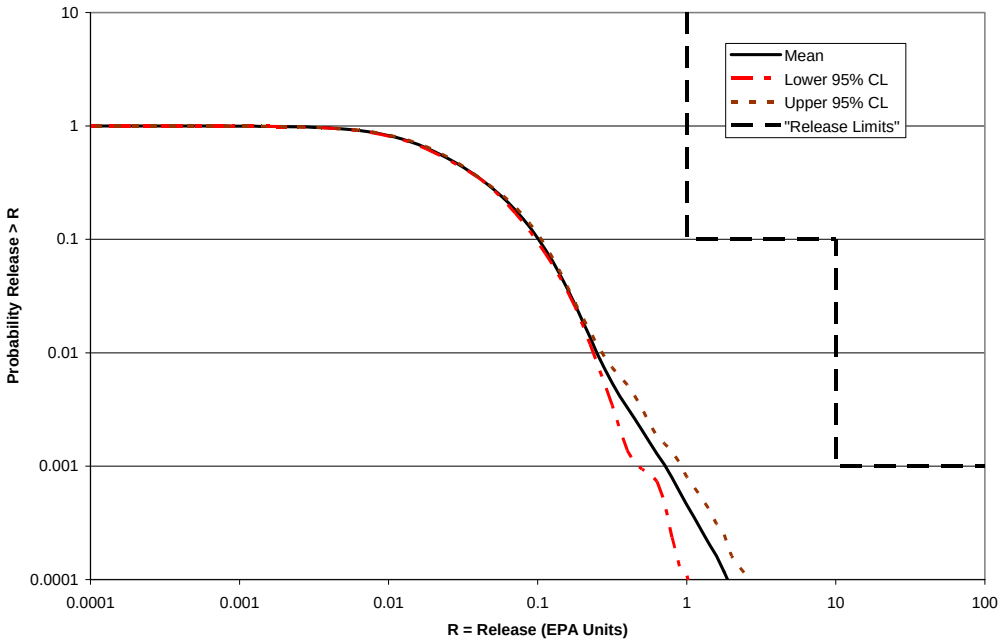


Figure PA-5. Example Mean Probability of Release and the Confidence Limits on the Mean from CRA-2009 PA

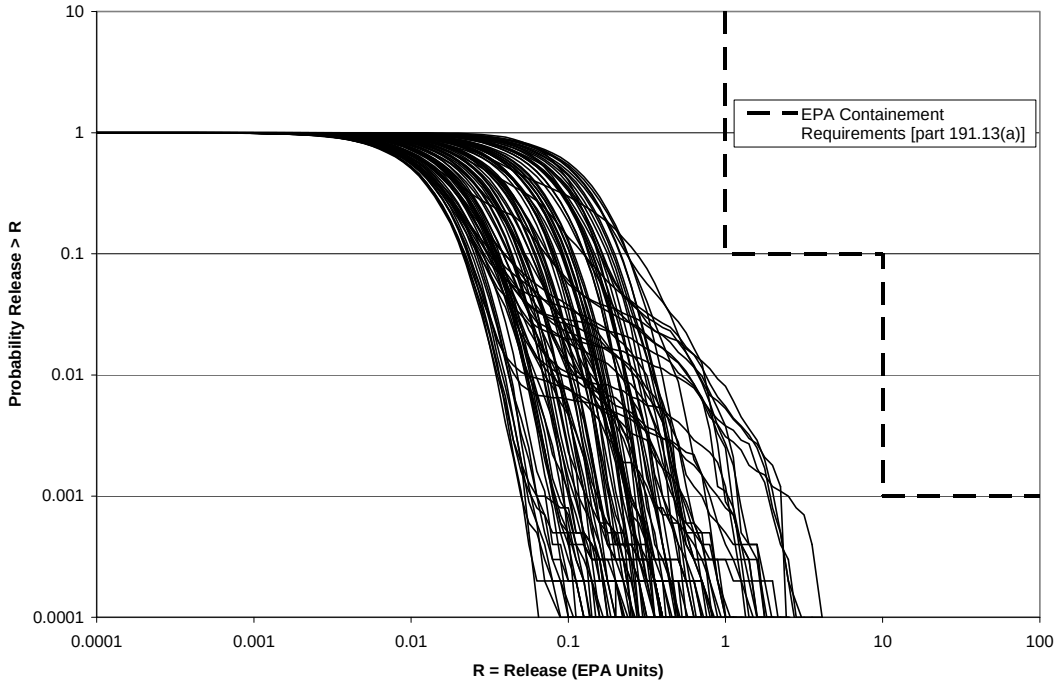


Figure PA-6. Example CCDF Distribution From CRA-2009 PA (Replicate 1)

The DOE has chosen to demonstrate repeatability of the mean and to address the associated criteria of Part 194 using an operational approach of multiple replication, as proposed by Iman (1982). The complete set of PA calculations was repeated three times with all aspects of the analysis identical except for the random seed used to initiate the LHS procedure. Thus, PA results are available for 3 replicates, each based on an independent set of 100 LHS vectors drawn from identical distributions for imprecisely known parameters and propagated through an identical modeling system. This technique of multiple replication allows the adequacy of the sample size chosen in the Monte Carlo analysis to be evaluated and provides a suitable measure of confidence in the mean CCDF estimation used to demonstrate compliance with section 191.13(a).

PA-2.3 PA Methodology

This section addresses scenarios formed from FEPs that were retained for PA calculations, and introduces the specification of scenarios for consequence analysis.

PA-2.3.1 Identification and Screening of FEPs

The EPA has provided criteria concerning the scope of PAs in 40 CFR § 194.32. In particular, criteria relating to the identification of potential processes and events that may affect disposal system performance are provided in 40 CFR § 194.32(e), which states

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;
>
> (2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and
>
> (3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

Section 32 of this application fulfills these criteria by documenting the DOE's identification, screening, and screening results of all potential processes and events consistent with the criteria specified in section 194.32(e).

The first two steps in scenario development involve identifying and screening FEPs that are potentially relevant to the performance of the disposal system. The CRA-2004, Chapter 6.0, Section 6.2 discusses the development of a comprehensive initial FEPs set used in the CCA, the methodology and criteria used for screening, the method used to reassess the CCA FEPs for the CRA-2004, and a summary of the FEPs retained for scenario development. Changes to FEPs since the CRA-2004 are outlined in Section 32 and Appendix SCR-2009 of this application.

The original FEPs generation and screening were documented in the CCA, and the resulting FEPs list became the FEPs compliance baseline. The baseline contained 237 FEPs and was documented the CCA, Appendix SCR. The EPA compliance review of FEPs was documented in EPA's Technical Support Document 194.32: Scope of PA (U.S. Environmental Protection

Agency 1998c). The EPA numbered each FEP with a different scheme than the DOE used for the CCA. The DOE has since adopted the EPA's numbering scheme.

PA-2.3.2 Scenario Development and Selection

Logic diagrams illustrate the formation of scenarios for consequence analysis from combinations of events that remain after FEP screening (Cranwell et al. 1990) (Figure PA-7). Each scenario shown in Figure PA-7 is defined by a combination of occurrence and nonoccurrence for all potentially disruptive events. Disruptive events are defined as those that create new pathways or significantly alter existing pathways for fluid flow and, potentially, radionuclide transport within the disposal system. Each of these scenarios also contains a set of features and nondisruptive events and processes that remain after FEP screening. As shown in Figure PA-7, undisturbed repository performance (UP) and disturbed repository performance (DP) scenarios are considered in consequence modeling for the WIPP PA. The UP scenario is used for compliance assessments (40 CFR § 194.54 and 40 CFR § 194.55). Important aspects of UP and DP scenarios are summarized in this section.

PA-2.3.2.1 Undisturbed Repository Performance

The UP scenario is defined in 40 CFR § 191.12 to mean "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." For compliance assessments with respect to the Individual and Groundwater Protection Requirements (section 191.15; Appendix IGP-2009), it is only necessary to consider the UP scenario. The UP scenario is also considered with DP scenario for PA with respect to the containment requirements (section 191.13).

No potentially disruptive natural events and processes are likely to occur during the regulatory time frame. Therefore, all naturally occurring events and processes retained for scenario construction are nondisruptive and are considered part of the UP scenario. Mining outside the LWB is assumed at the end of AIC for all scenarios. The M scenario involves future mining within the controlled area. The disturbed repository E scenario involves at least one deep drilling event that intersects the waste disposal region. The M scenario and the E scenario may both occur in the future. The DOE calls a future in which both of these events occur the ME scenario. More detailed descriptions are found in Section PA-2.3.2.2.

The only natural features and waste- and repository-induced FEPs retained after screening that are excluded in the UP scenario, but included in the DP scenario, are those directly associated with the potential effects of future deep drilling within the controlled area. Among the most significant FEPs that will affect the UP scenario within the disposal system are excavation-induced fracturing, gas generation, salt creep, and MgO in the disposal rooms.

- The repository excavation and consequent changes in the rock stress field surrounding the excavated opening will create a DRZ immediately adjacent to excavated openings. The DRZ will exhibit mechanical and hydrological properties different than those of the intact rock.

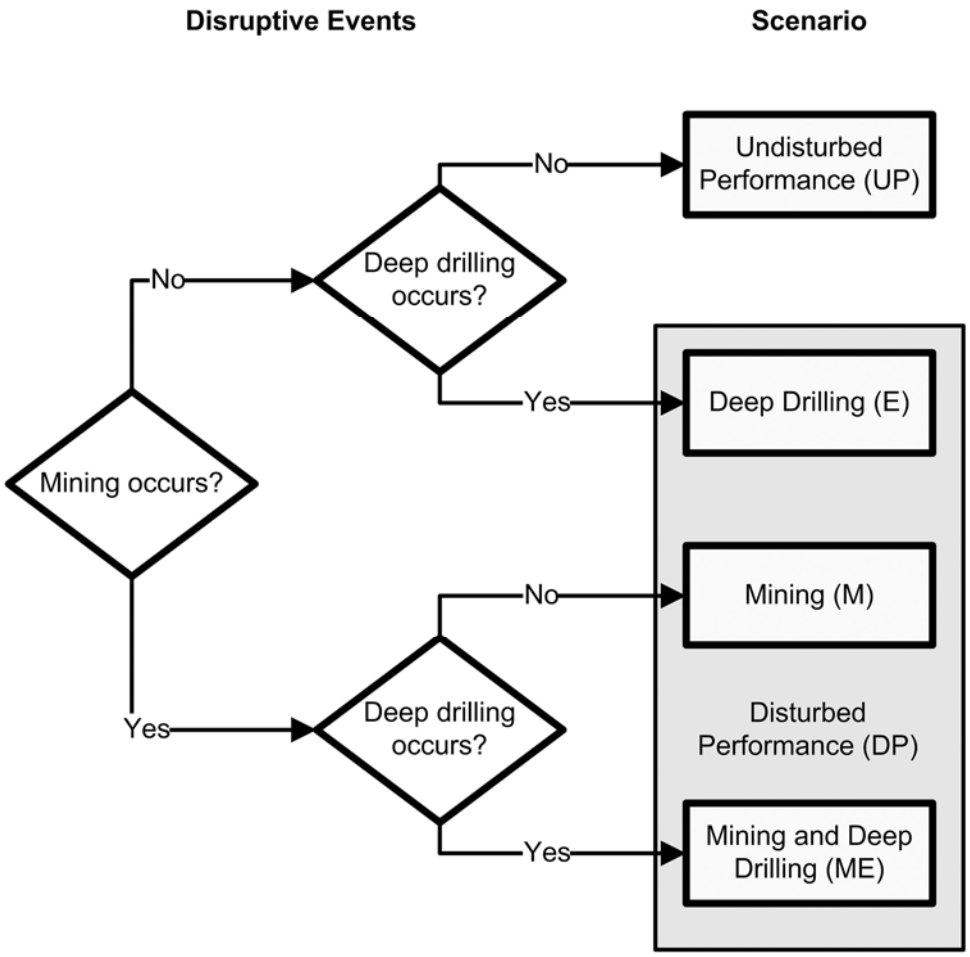


Figure PA-7. Logic Diagram for Scenario Analysis

- Organic material in the waste may degrade because of microbial activity, and brine will corrode metals in the waste and waste containers, with concomitant generation of gases. Gas generation may result in pressures sufficient to both maintain or develop fractures and change the fluid flow pattern around the waste disposal region.

- At the repository depth, salt creep will tend to heal fractures and reduce the permeability of the DRZ and the crushed salt component of the long-term shaft seals to near that of the host rock salt.

- The MgO engineered barrier emplaced in the disposal rooms will react with CO_2 and maintain mildly alkaline conditions. Metal corrosion in the waste and waste containers will maintain reducing conditions. These effects will maintain low radionuclide solubility.

Radionuclides can become mobile as a result of waste dissolution and colloid generation following brine flow into the disposal rooms. Colloids may be generated from the waste (humics, mineral fragments, and An intrinsic colloids) or from other sources (humics, mineral fragments, and microbes).

Conceptually, there are several pathways for radionuclide transport within the undisturbed disposal system that may result in releases to the accessible environment (Figure PA-8). Contaminated brine may migrate away from the waste-disposal panels if pressure within the panels is elevated by gas generated from corrosion or microbial consumption. Radionuclide transport may occur laterally, through the anhydrite interbeds toward the subsurface boundary of the accessible environment in the Salado, or through access drifts or anhydrite interbeds to the base of the shafts. In the latter case, if the pressure gradient between the panels and overlying strata is sufficient, contaminated brine may migrate up the shafts. As a result, radionuclides may be transported directly to the ground surface, or laterally away from the shafts through permeable strata such as the Culebra, toward the subsurface boundary of the accessible environment. These conceptual pathways are shown in Figure PA-8.

The modeling system described in Section PA-4.0 includes potential radionuclide transport along other pathways, such as migration through Salado halite. However, the natural properties of the undisturbed system make radionuclide transport to the accessible environment via these other pathways unlikely.

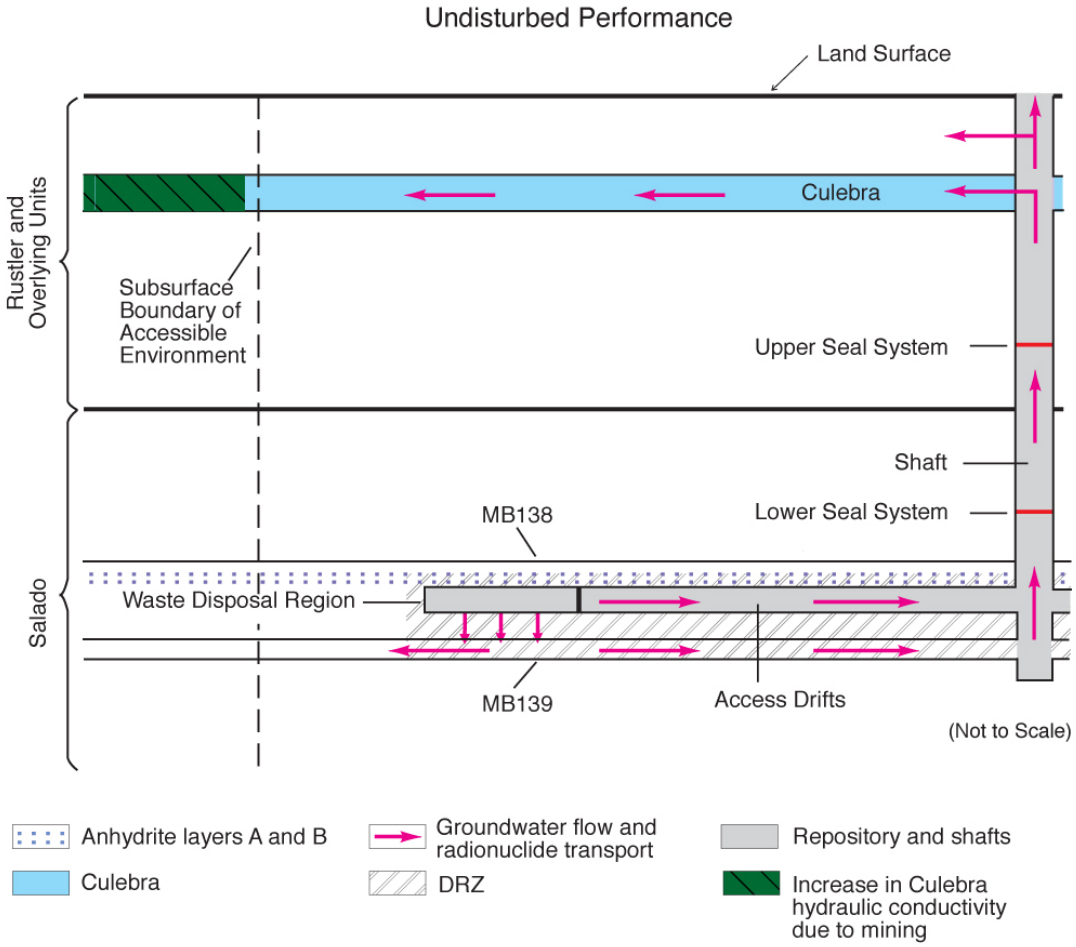


Figure PA-8. Conceptual Release Pathways for the UP Scenario

PA-2.3.2.2 Disturbed Repository Performance

Assessments for compliance with section 191.13 need to consider the potential effects of future disruptive natural and human-initiated events and processes on the performance of the disposal system. No potentially disruptive natural events and processes are considered sufficiently likely to require inclusion in analyses of either the UP or DP scenario. The only future human-initiated events and processes retained after FEP screening are those associated with mining and deep drilling (but not the subsequent use of a borehole) within the controlled area or LWB when institutional controls cannot be assumed to eliminate the possibility of such activities (Section PA-3.2 and the CRA-2004, Chapter 6.0, Section 6.4.12.1). In total, 21 disturbed repository FEPs associated with future mining and deep drilling have been identified. These FEPs were assigned a screening designator of the DP scenario.

For evaluating the consequences of disturbed repository performance, the DOE has defined the mining scenario (M), the deep drilling scenario (E), and a mining and drilling scenario (ME). These scenarios are described in the following sections.

PA-2.3.2.2.1 Disturbed Repository M Scenario

The M scenario involves future mining within the controlled area. Consistent with the criteria stated by the EPA in 40 CFR § 194.32(b) for PA calculations, the effects of potential future mining within the controlled area are limited to changes in hydraulic conductivity of the Culebra that result from subsidence (as described in Section PA-3.9).

Radionuclide transport may be affected in the M scenario if a head gradient between the waste-disposal panels and the Culebra causes brine contaminated with radionuclides to move from the waste-disposal panels to the base of the shafts and up to the Culebra. The changes in the Culebra T field may affect the rate and direction of radionuclide transport within the Culebra. Features of the M scenario are illustrated in Figure PA-9.

The three disturbed repository FEPs labeled M in the CRA-2004, Chapter 6.0, Table 6-9 are related to the occurrence and effects of future mining. The modeling system used for the M scenario is similar to that developed for the UP scenario, but with a modified Culebra T field in the controlled area to account for the mining effects.

PA-2.3.2.2.2 Disturbed Repository E Scenario

The disturbed repository E scenario involves at least one deep drilling event that intersects the waste disposal region. The EPA provides criteria for analyzing the consequences of future drilling events in PA in 40 CFR § 194.33(c).

> Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:
>
> (1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: the types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; and

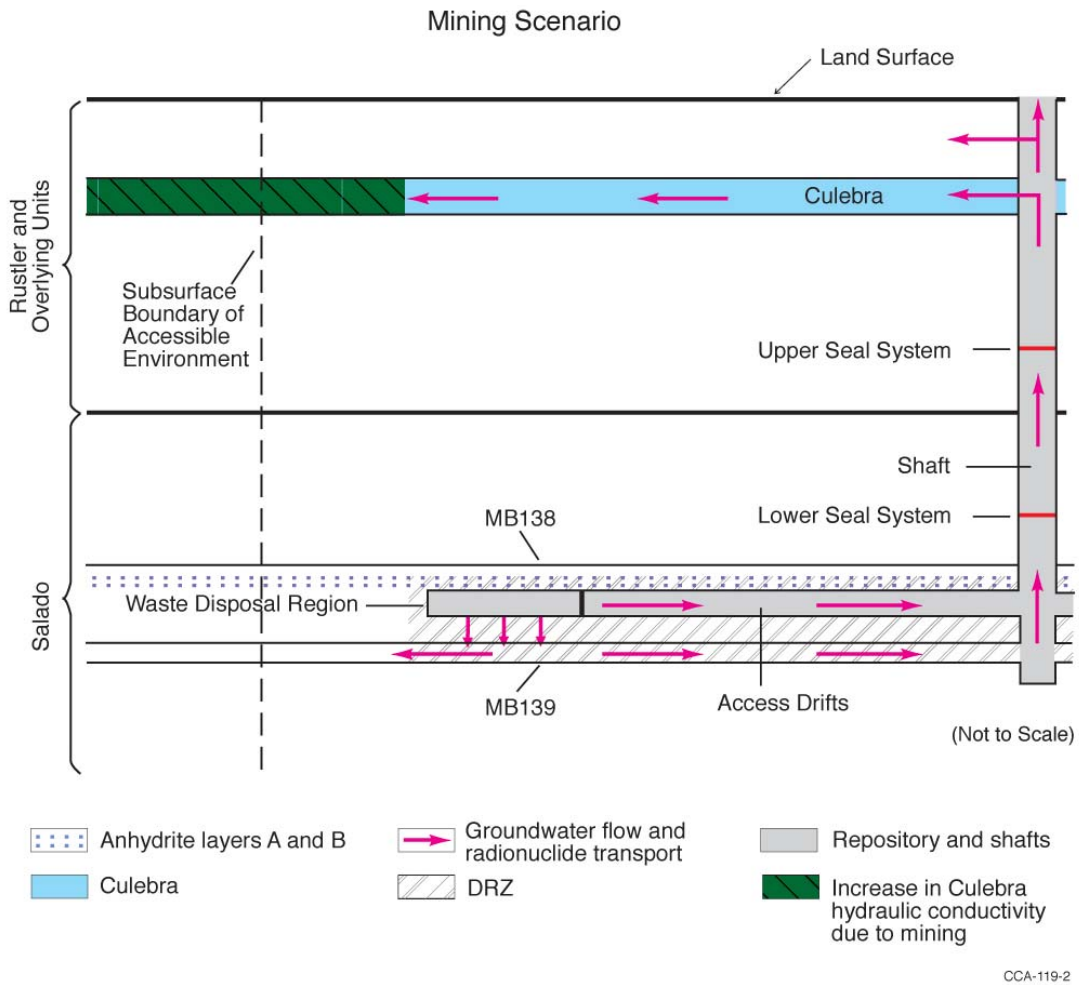


Figure PA-9. Conceptual Release Pathways for the Disturbed Repository M Scenario

(2) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.

Consistent with these criteria, there are several pathways for radionuclides to reach the accessible environment in the E scenario. Before any deep drilling intersects the waste, potential release pathways are identical to those in the undisturbed repository scenario.

If a borehole intersects the waste in the disposal rooms, releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface. Particulate waste brought to the surface may include cuttings, cavings, and spallings. Cuttings are the materials cut by the drill bit as it passes through waste. Cavings are the materials eroded by the drilling fluid in the annulus around the drill bit. Spallings are the materials forced into the circulating drilling fluid if there is sufficient pressure in the waste disposal panels. During drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels.

When abandoned, the borehole is assumed to be plugged in a manner consistent with current practices in the Delaware Basin as prescribed in 40 CFR § 194.33(c)(1). An abandoned intrusion

borehole with degraded casing and/or plugs may provide a pathway for fluid flow and contaminant transport from the intersected waste panel to the ground surface if the fluid pressure within the panel is sufficiently greater than hydrostatic. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units.

Alternatively, the units intersected by an intrusion borehole may provide sources for brine flow to a waste panel during or after drilling. For example, in the northern Delaware Basin, the Castile, which underlies the Salado, contains isolated volumes of brine at fluid pressures greater than hydrostatic (as discussed in the CRA-2004, Chapter 2.0, Section 2.2.1.2.2). The WIPP-12 penetration of one of these reservoirs provided data on one brine reservoir within the controlled area. The location and properties of brine reservoirs cannot be reliably predicted; thus, the possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in consequence analysis of the WIPP, as discussed in the CRA-2004, Chapter 6.0, Section 6.4.8. Such a borehole could provide a connection for brine flow from the Castile to the waste panel, thus increasing fluid pressure and brine volume in the waste panel.

A borehole that is drilled through a disposal room pillar, but does not intersect waste, could also penetrate the brine reservoir underlying the waste disposal region. Such an event would, to some extent, depressurize the brine reservoir, and thus would affect the consequences of any subsequent reservoir intersections. The PA does not take credit for possible brine reservoir depressurization.

The DOE has distinguished two types of deep drilling events by whether or not the borehole intersects a Castile brine reservoir. A borehole that intersects a waste disposal panel and penetrates a Castile brine reservoir is designated an E1 event. A borehole that intersects a waste panel but does not penetrate a Castile brine reservoir is designated an E2 event. The consequences of deep drilling intrusions depend not only on the type of a drilling event, but on whether the repository was penetrated by an earlier E2 event or flooded due to an earlier E1 event. The PA also does not take credit for depressurization of brine reservoirs from multiple drilling intrusions. These scenarios are described in order of increasing complexity in the following sections.

PA-2.3.2.2.3 The E2 Scenario

The E2 scenario is the simplest scenario for inadvertent human intrusion into a waste disposal panel. In this scenario, a panel is penetrated by a drill bit; cuttings, cavings, spallings, and brine flow releases may occur; and brine flow may occur in the borehole after it is plugged and abandoned. Sources for brine that may contribute to long-term flow up the abandoned borehole are the Salado or, under certain conditions, the units above the Salado. An E2 scenario may involve more than one E2 drilling event, although the flow and transport model configuration developed for the E2 scenario evaluates the consequences of futures that have only one E2 event. Features of the E2 scenario are illustrated in Figure PA-10.

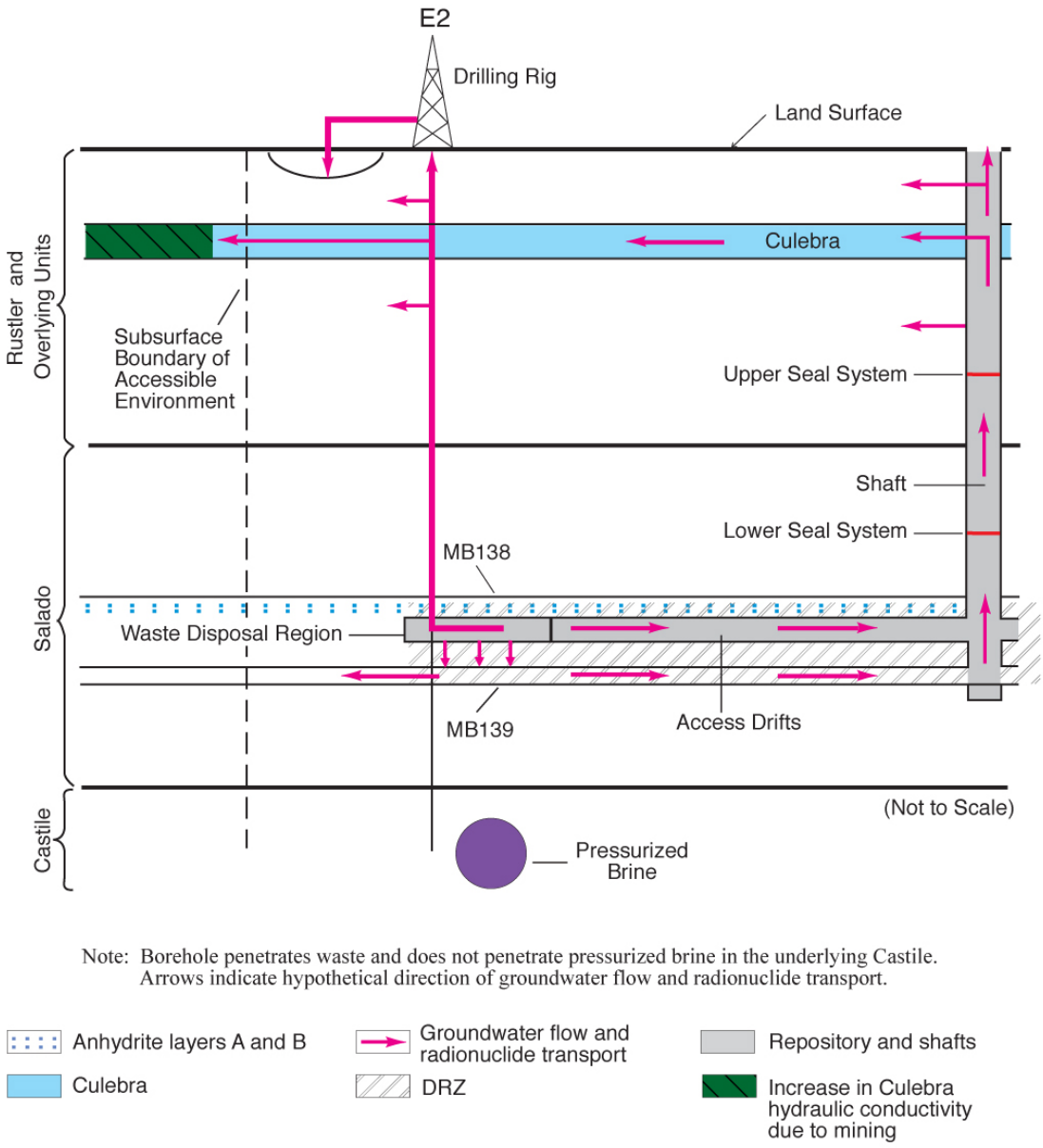


Figure PA-10. Conceptual Release Pathways for the Disturbed Repository Deep Drilling E2 Scenario

PA-2.3.2.2.4 The E1 Scenario

Any scenario with exactly one inadvertent penetration of a waste panel that also penetrates a Castile brine reservoir is called E1. Features of this scenario are illustrated in Figure PA-11.

Sources of brine in the E1 scenario are the brine reservoir, the Salado, and, under certain conditions, the units above the Salado. However, the brine reservoir is conceptually the dominant source of brine in this scenario. The flow and transport model configuration developed for the E1 scenario evaluates the consequences of futures that have only one E1 event.

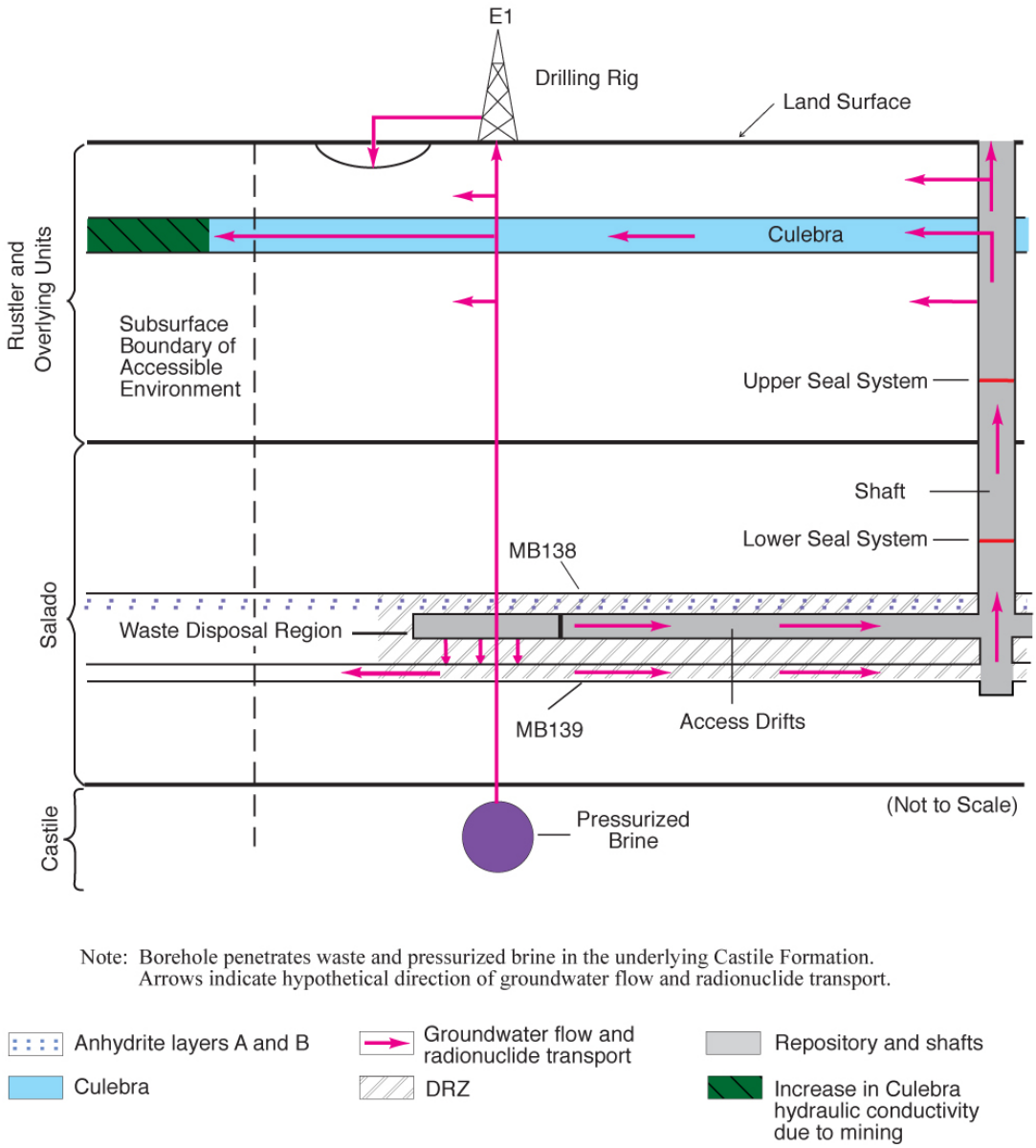


Figure PA-11. Conceptual Release Pathways for the Disturbed Repository Deep Drilling E1 Scenario

PA-2.3.2.2.5 The E1E2 Scenario

The E1E2 scenario is defined as all futures with multiple penetrations of a waste panel of which at least one intrusion is an E1. One example of this scenario, with a single E1 event and a single E2 event penetrating the same panel, is illustrated in Figure PA-12. However, the E1E2 scenario can include many possible combinations of intrusion times, locations, and types of event (E1 or E2). The sources of brine in this scenario are those listed for the E1 scenario, and multiple E1 sources may be present. The E1E2 scenario has a potential flow path not present in the E1 or E2 scenarios: flow from an E1 borehole through the waste to another borehole. This flow path has the potential to (1) bring large quantities of brine in direct contact with waste and (2) provide a

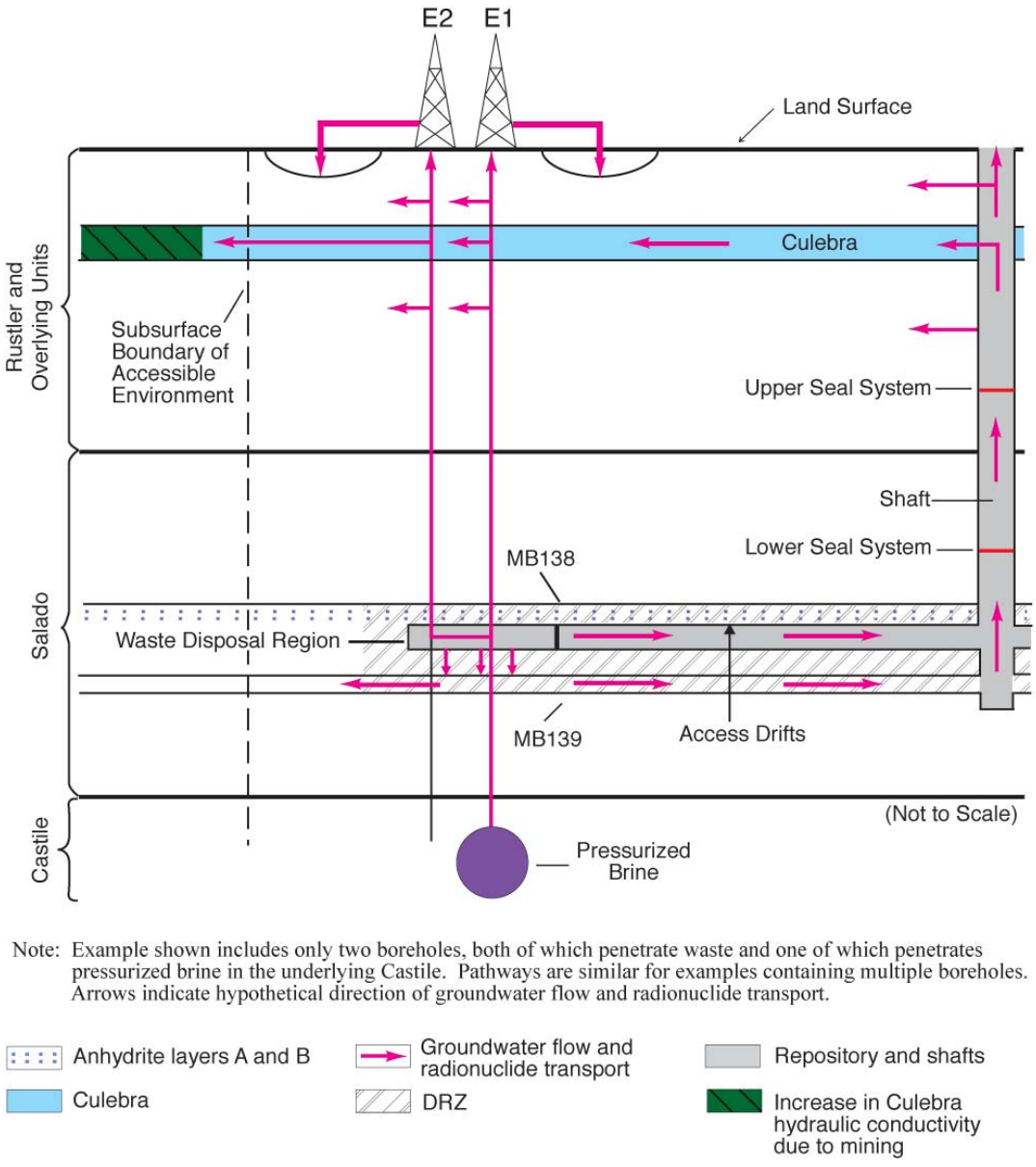


Figure PA-12. Conceptual Release Pathways for the Disturbed Repository Deep Drilling E1E2 Scenario

less restrictive path for this brine to flow to the units above the Salado (via multiple boreholes) compared to either the individual E1 or E2 scenarios. It is both the presence of brine reservoirs and the potential for flow through the waste to other boreholes that make this scenario different from combinations of E2 boreholes in terms of potential consequences. Estimates from flow and transport modeling are used to determine the extent of flow between boreholes and whether modeled combinations of E1 and E2 boreholes at specific locations in the repository should be treated as E1E2 scenarios or as independent E1 and E2 scenarios in the consequence analysis.

PA-2.3.2.3 Disturbed Repository ME Scenario

The M scenario and the E scenario may both occur in the future. The DOE calls a future in which both of these events occur the ME scenario. The occurrence of both mining and deep drilling do not create processes beyond those already described separately for the M and E scenarios. For example, the occurrence of mining does not influence any of the interactions between deep boreholes and the repository or brine reservoirs, nor does the occurrence of drilling impact the effects of mining on Culebra hydrogeology.

PA-2.3.2.4 Scenarios Retained for Consequence Analysis

The scenarios described in Section PA-2.3.2.1, Section PA-2.3.2.2, and Section PA-2.3.2.3 have been retained for consequence analysis to determine compliance with the containment requirements in section 191.13. The modeling systems used to evaluate the consequences of these undisturbed and disturbed scenarios are discussed in Section PA-2.3.3.

PA-2.3.3 Calculation of Scenario Consequences

Calculating scenario consequences requires quantitative modeling. This section discusses the conceptual and computational models and some parameter values used to estimate the consequence of the scenarios described in Section PA-2.3.2. Additional discussion of conceptual models and modeling assumptions is provided in Section PA-4.0. Additional descriptions of sampled parameter values are included in Fox (2008).

A single modeling system was used to represent the disposal system and calculate the CCDFs. The modeling system, however, can be conveniently described in terms of various submodels, with each describing a part of the overall system. The models used in the WIPP PA, as in other complex analyses, exist at four different levels.

1. **Conceptual models** are a set of qualitative assumptions that describe a system or subsystem for a given purpose. At a minimum, these assumptions concern the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical and chemical processes. The assumptions should be consistent with one another and with existing information within the context of the given purpose.

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

3. **Numerical models** are developed to approximate mathematical model solutions because most mathematical models do not have closed-form solutions.

4. The complexity of the system requires computer codes to solve the numerical models. The implementation of the numerical model in the computer code with specific initial and boundary conditions and parameter values is generally referred to as the *computational model*.

Data are descriptors of the physical system being considered, normally obtained by experiment or observation. Parameters are values necessary in mathematical, numerical, or computational models. The distinction between data and parameters can be subtle. Parameters are distinct from data, however, for three reasons: (1) Data may be evaluated, statistically or otherwise, to generate model parameters to account for uncertainty in data. (2) Some parameters have no relation to the physical system, such as the parameters in a numerical model to determine when an iterative solution scheme has converged. (3) Many model parameters are applied at a different scale than one directly observed or measured in the physical system. The distinction between data and parameter values is described further in Fox (2008) and Tierney (1990), where distribution derivations for specific parameters are given. The interpretation and scaling of experimental and field data are discussed in Fox (2008) for individual and sampled parameters, as appropriate.

PA-3.0 Probabilistic Characterization of Futures

The PA for the WIPP identifies uncertainty in parameters and uncertainty in future events as distinctly different entities and requires sampling to be conducted in two dimensions. One dimension focuses on characterizing the uncertainty in terms of the probability that various possible futures will occur at the WIPP site over the next 10,000 years. The other dimension characterizes the uncertainty due to lack of knowledge about the precise values of model parameters appropriate for the WIPP repository. Each dimension of the analysis is characterized by a probability space. Monte Carlo methods are used with the WIPP PA modeling system to sample each of the two probability spaces.

Characterizing the probability distribution for the first dimension of the PA depends on identifying the kinds of events that could impact releases from the repository over the next 10,000 years. Screening analyses of possible future events concluded that the only significant events with the potential to affect radionuclide releases to the accessible environment are drilling and mining within the LWB (Appendix SCR-2009, Section SCR-5.0). Consequently, modeling the future states of the repository focuses on representing the occurrences and effects of these two events. CCDFGF uses stochastic processes to simulate intrusion events by drilling and the occurrence of mining for natural resources. CCDFGF assembles the results from the deterministic models and selects the most appropriate scenario data provided by these models to use as the simulation of a 10,000-year future progresses. Ten thousand potential futures are simulated and used to create distributions of potential releases, and then compiled into a single CCDF of potential releases.

WIPP PA is required not only to estimate the likelihood of future releases, but to establish confidence in those estimates. Confidence is established using the second dimension of the analysis, which is based on the evaluation of uncertainty in the values of some of the parameters of the deterministic models. This uncertainty is assumed to represent a lack of knowledge about the true values of the parameters, and is labeled epistemic uncertainty. Epistemic uncertainty can be viewed as the representation of potential systematic errors in the results. The impact of epistemic uncertainty on the results is determined by generating 300 sets of parameter values using a stratified random sampling design, LHS, and then running the deterministic models and CCDFGF with each set of sampled parameters. Thus, 300 CCDFs are generated by CCDFGF. One set of parameters is often referred to as a vector. The 300 simulations are organized as 3 replicates of 100 vectors each. Because the uncertainty assigned to the parameters represents a lack of knowledge, this epistemic uncertainty could theoretically be reduced by collecting data to improve knowledge about the parameters. Epistemic uncertainty is represented in the projections of potential releases from the repository by the variability among the 300 CCDFs.

The WIPP PA modeling system consists of a set of loosely coupled deterministic models (BRAGFLO, PANEL, NUTS, SECOTP2D, and CUTTINGS_S) that provide scenario-specific results to the code CCDFGF (Figure PA-2). CCDFGF is, in contrast, a stochastic simulation model used to simulate potential futures of repository performance where drilling and mining intrusions can impact the state of the repository and produce release events. CCDFGF implements intrusions as stochastic events, thus incorporating the aleatory uncertainty associated with projections of future events. This section describes how aleatory uncertainty is implemented in PA. Epistemic uncertainty is discussed in Section PA-6.0.

PA-3.1 Probability Space

As discussed in Section PA-2.2.2, aleatory uncertainty is defined by the possible futures $\mathbf{x}_{st,i}$ conditional on the set i of parameters used in Equation (PA.2). Section PA-3.2, Section PA-3.3, Section PA-3.4, Section PA-3.5, Section PA-3.6, Section PA-3.7, Section PA-3.8, and Section PA-3.9 describe the individual components t_j, e_j, l_j, b_j, p_j, $\mathbf{a}_j$, and t_{min} of $\mathbf{x}_{st,i}$ and their associated probability distributions. The concept of a scenario as a subset of the sample space of $\mathbf{x}_{st,i}$ is discussed in Section PA-3.10. The procedure used to sample the individual elements $\mathbf{x}_{st,i}$ is described in Section PA-6.5.

PA-3.2 AICs and PICs

AICs and PICs will be implemented at the WIPP site to deter human activity detrimental to repository performance. AICs and PICs are described in detail in the CRA-2004, Chapter 7.0 and in appendices referenced in Chapter 7.0. In this section, the impact of AICs and PICs on PA is described.

AICs will be implemented at the WIPP after final facility closure to control site access and ensure that activities detrimental to disposal system performance do not occur within the controlled area. The AICs will preclude human intrusion in the disposal system. A 100-year limit on the effectiveness of AICs in PA is established in 40 CFR § 191.14(a). Because of the regulatory restrictions and the nature of the AICs that will be implemented, PA assumes there are no inadvertent human intrusions or mining in the controlled area for 100 years following repository closure.

PICs are designed to deter inadvertent human intrusion into the disposal system. Only minimal assumptions were made about the nature of future society when designing the PICs to comply with the assurance requirements. The preamble to Part 194 limits any credit for PICs in deterring human intrusion to 700 years after disposal (U.S. Environmental Protection Agency 1996a p. 5231). Although the DOE originally took credit for PICs in the CCA PA, but has not taken credit since. Not including PICs is a conservative implementation, as no credit is taken for a beneficial process.

PA-3.3 Drilling Intrusion

As described in Section PA-2.3.2.2, drilling intrusions in PA are assumed to occur randomly in time and space following a Poisson process. Specifically, the drilling rate considered within the area marked by a berm as part of the system for PICs (Fox 2008, Table 46) is 5.85×10^{-3} intrusions per square kilometer per year (km^2/yr). AICs are assumed to prevent any drilling intrusions for the first 100 years after the decommissioning of the WIPP (Section PA-3.2). In the computational implementation of PA, it is convenient to represent the Poisson process for drilling intrusions by its corresponding rate term $\lambda_d(t)$ for intrusions into the area marked by the berm. Specifically,

$$\lambda_d(t) = \begin{cases} 0 & 0 \le t < 100\,yr \\ \left(0.6285\,\mathrm{km}^2\right)\left(5.85\times10^{-3}\,\mathrm{km}^{-2}\mathrm{yr}^{-1}\right) = 3.68\times10^{-3}\,\mathrm{yr}^{-1} & 100 \le t \le 10{,}000\,yr \end{cases} \quad \text{(PA.6)}$$

where 0.6285 km^2 is the area enclosed by the berm (Fox 2008, Table 45) and t is elapsed time since decommissioning the WIPP.

The function $\lambda_d(t)$ defines the parameter of the exponential distribution that gives rise to the times of intrusions, t_j of Equation (PA.2). In the computational implementation of the analysis, the exponential distribution is sampled to define the times between successive drilling intrusions (Figure PA-13, Section PA-6.5). A key assumption of the exponential distribution is that events are independent of each other, so the occurrence of one has no effect on the occurrence of the next event. The process giving rise to such events is sometimes called a Poisson process because the distribution of such events over a fixed interval of time is a Poisson distribution. Due to the 10,000-year regulatory period specified in section 191.13, t_j is assumed to be bounded above by 10,000 years in the definition of $\mathbf{x}_{st,i}$. Further, t_j is bounded below by 100 years as defined in Equation (PA.6).

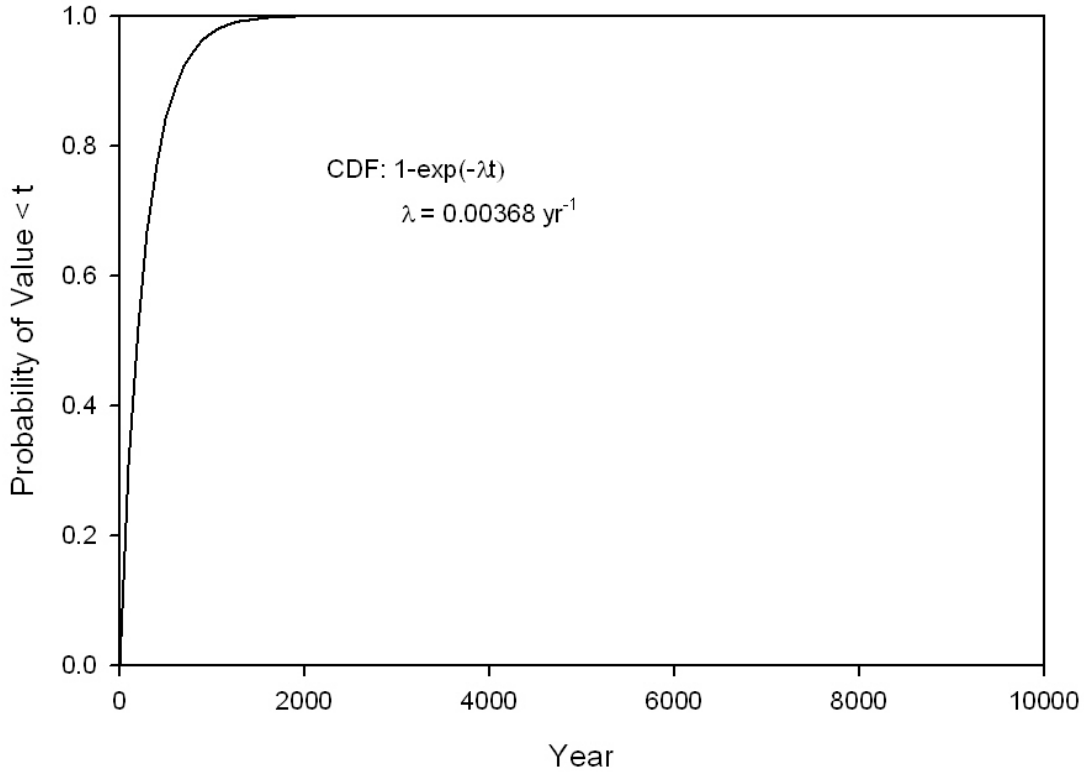


Figure PA-13. CDF for Time Between Drilling Intrusions

PA-3.4 Penetration of Excavated/Nonexcavated Area

The variable e_j is a designator for whether or not the j^{th} drilling intrusion penetrates an excavated, waste-filled area of the repository: $e_j = 0$ or 1 implies penetration of nonexcavated or

excavated area, respectively. The corresponding probabilities $P[e_j = 0]$ and $P[e_j = 1]$ for $e_j = 0$ and $e_j = 1$ are

$$pEx_1 = P\left[e_j = 1\right] = 0.1273 \text{ km}^2 / 0.6285 \text{ km}^2 = 0.203 \quad \text{(PA.7)}$$

$$pEx_0 = P\left[e_j = 0\right] = 1 - pEx_1 = 0.797 \quad \text{(PA.8)}$$

where 0.1273 km^2 and 0.6285 km^2 are the excavated area of the repository and the area of the berm, respectively (Fox 2008, Table 45).

PA-3.5 Drilling Location

Locations of drilling intrusions through the excavated, waste-filled area of the repository are discretized to the 144 locations in Figure PA-14. Assuming that a drilling intrusion occurs within the excavated area, it is assumed to be equally likely to occur at each of these 144 locations. Thus, the probability pL_k that drilling intrusion j will occur at location l_k, $k = 1, 2, \ldots, 144$ in Figure PA-14 is

$$pL_{k;k=1,2,3} = P\left[k = 1\right] = P\left[k = 2\right] = \ldots = P[k = 144] = 1/144 = 6.94 \times 10^{-3} \quad \text{(PA.9)}$$

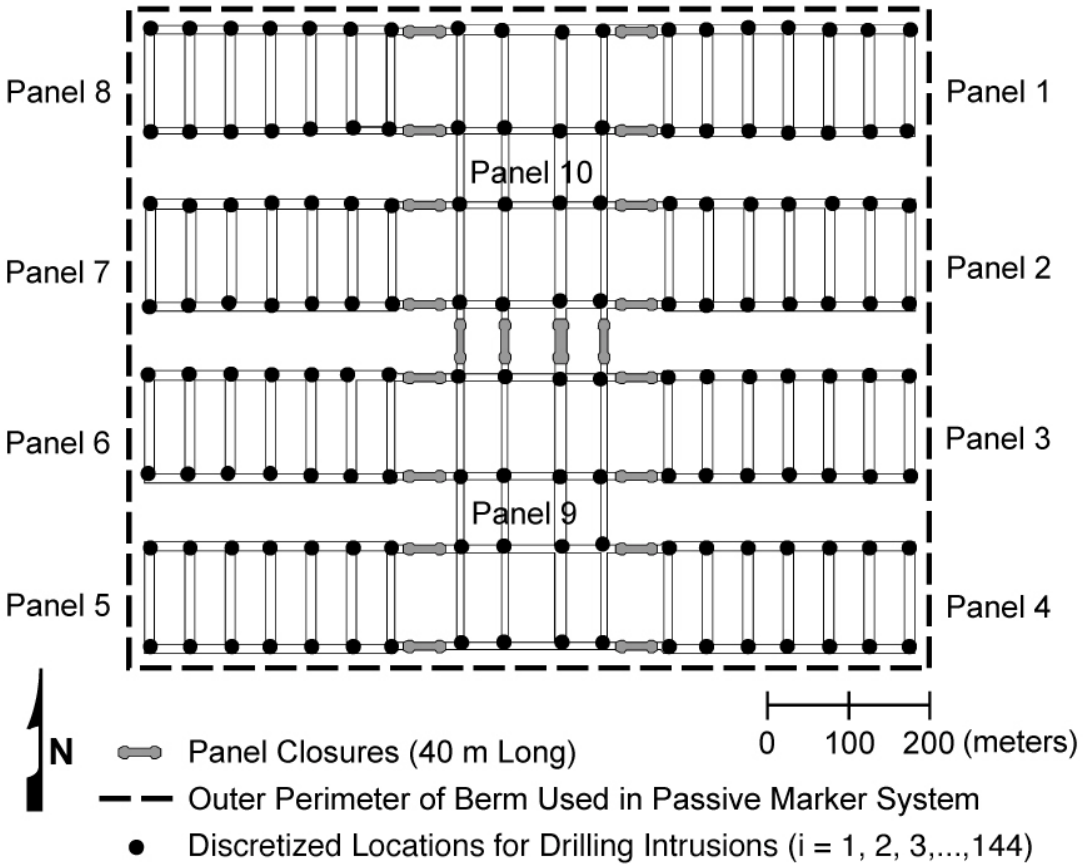


Figure PA-14. Discretized Locations for Drilling Intrusions

PA-3.6 Penetration of Pressurized Brine

The conceptual models for the Castile include the possibility that pressurized brine reservoirs underlie the repository (Section PA-4.2.10). The variable b_j is a designator for whether or not the j^{th} drilling intrusion penetrates pressurized brine, where $b_j = 0$ signifies nonpenetration and $b_j = 1$ signifies penetration of pressurized brine. In PA, the probability $pB_1 = P[b_j = 1]$ is sampled from a uniform distribution ranging from 0.01 to 0.60 (see GLOBAL:PBRINE in Table PA-19).

PA-3.7 Plugging Pattern

Three borehole plugging patterns, p_k, are considered in PA: (1) p_1, a full concrete plug through the Salado to the Bell Canyon Formation (hereafter referred to as Bell Canyon), (2) p_2, a two-plug configuration with concrete plugs at the Rustler/Salado interface and the Castile/Bell Canyon interface, and (3) p_3, a three-plug configuration with concrete plugs at the Rustler/Salado, Salado/Castile, and Castile/Bell Canyon interfaces. The probability that a given drilling intrusion will be sealed with plugging pattern p_k, k= 1, 2, 3, is given by pPL_k, where $pPL_1 = P[k = 1] = 0.015$, $pPL_2 = P[k = 2] = 0.696$, $pPL_3 = P[k = 3] = 0.289$ (Fox 2008, Table 46).

PA-3.8 Activity Level

The waste intended for disposal at the WIPP is represented by 767 distinct waste streams, with 690 of these waste streams designated as CH-TRU waste and 77 designated as RH-TRU waste (Leigh, Trone and Fox 2005, Section 4.4). For the CRA-2009 PA, the 77 separate RH-TRU waste streams are represented by a single, combined RH-TRU waste stream. The activity levels for the waste streams are given in Fox (2008, Table 48 and Table 49). Each waste container emplaced in the repository contains waste from a single CH-TRU waste stream. Waste packaged in 55-gallon (gal) drums is stacked 3 drums high within the repository. Although waste in other packages (e.g., standard waste boxes, 10-drum overpacks, etc.) may not be stacked 3 high, PA assumes that each drilling intrusion into CH-TRU waste intersects 3 different waste streams. In contrast, all RH-TRU waste is represented by a single waste stream, and so each drilling intrusion through RH-TRU waste is assumed to intersect this single waste stream. Appendix MASS-2009, Section MASS-21.0 examines the sensitivity of PA results to the assumption that three waste streams are intersected by each drilling intrusion into CH-TRU waste.

The vector $\mathbf{a}_j$ characterizes the type of waste penetrated by the j^{th} drilling intrusion. Specifically,

$$\mathbf{a}_j = 0 \text{ if } e_j = 0 \qquad \text{(PA.10)}$$

(i.e., if the i^{th} drilling intrusion does not penetrate an excavated area of the repository);

$$\mathbf{a}_j = 1 \text{ if } e_j = 1 \text{ and RH-TRU is penetrated} \qquad \text{(PA.11)}$$

$$\mathbf{a}_j = [iCH_{j1}, iCH_{j2}, iCH_{j3}] \text{ if } e_j = 1 \text{ and CH-TRU is penetrated} \qquad \text{(PA.12)}$$

where iCH_{j1}, iCH_{j2}, and iCH_{j3} are integer designators for the CH-TRU waste streams intersected by the j^{th} drilling intrusion (i.e., each of iCH_{j1}, iCH_{j2}, and iCH_{j3} is an integer between 1 and 690).

Whether the j^{th} intrusion penetrates a nonexcavated or excavated area is determined by the probabilities pE_0 and pE_1 discussed in Section PA-3.4. The type of waste penetrated is determined by the probabilities pCH and pRH. The excavated area used for disposal of CH-TRU waste (aCH) is 1.115×10^5 square meters (m^2) and the area used for disposal of RH-TRU waste (aRH) is 1.576×10^4 m^2 (Fox 2008, Table 45), for a total disposal area of $aEX = aCH + aRH = 1.273 \times 10^5$ m^2. Given that the j^{th} intrusion penetrates an excavated area, the probabilities pCH and pRH of penetrating CH-TRU and RH-TRU waste are given by

$$pCH = P[\text{CH waste area penetrated}] = aCH / aEX = \left(1.115 \times 10^5 \text{ m}^2\right) / \left(1.273 \times 10^5 \text{ m}^2\right) = 0.876 \quad \text{(PA.13)}$$

$$pRH = P[\text{RH waste area penetrated}] = aRH / aEX = \left(1.576 \times 10^4 \text{ m}^2\right) / \left(1.273 \times 10^5 \text{ m}^2\right) = 0.124 \quad \text{(PA.14)}$$

As indicated in this section, the probabilistic characterization of $\mathbf{a}_j$ depends on a number of individual probabilities. Specifically, pEx_0 and pEx_1 determine whether a nonexcavated or excavated area is penetrated (Section PA-3.5); pCH and pRH determine whether CH-TRU or RH-TRU waste is encountered, given penetration of an excavated area; and the individual waste stream probabilities in Fox (2008, Table 48 and Table 49), determine the specific waste streams iCH_{j1}, iCH_{j2}, and iCH_{j3} encountered given a penetration of CH-TRU waste. The probability of encountering a particular CH-TRU waste stream is computed as the ratio of the volume of that waste stream to the volume of CH-TRU waste.

PA-3.9 Mining Time

Full mining of known potash reserves within the LWB is assumed to occur at time t_{min}. The occurrence of mining within the LWB in the absence of institutional controls is specified as following a Poisson process with a rate of $\lambda_m = 1 \times 10^{-4}$ yr^{-1} (Fox 2008, Table 46). However, this rate can be reduced by AICs and PICs. Specifically, AICs are assumed to result in no possibility of mining for the first 100 years after decommissioning of the WIPP. In PA, PICs do not affect the mining rate. Thus, the mining rate $\lambda_m(t)$ is

$$\lambda_m(t) = 0 \text{ yr}^{-1} \quad \text{for } 0 \le t < 100 \text{ yrs} \quad \text{(PA.15)}$$

$$\lambda_m(t) = 1 \times 10^{-4} \text{ yr}^{-1} \quad \text{for } 100 \le t \le 10{,}000 \text{ yrs} \quad \text{(PA.16)}$$

where t is the elapsed time since decommissioning of the WIPP.

In the computational implementation of the analysis, $\lambda_m(t)$ is used to define the distribution of time to mining. The use of $\lambda_m(t)$ to characterize t_{min} is analogous to the use of λ_d to

characterize the t_j, except that only one mining event is assumed to occur (i.e., $\mathbf{x}_{st,i}$ contains only one value for t_{min}) in order to be consistent with guidance given in Part 194 that mining within the LWB should be assumed to remove all economically viable potash reserves. Due to the 10,000-year regulatory period specified in section 191.13, t_{min} is assumed to be bounded above by 10,000 years in the definition of $\mathbf{x}_{st,i}$.

PA-3.10 Scenarios and Scenario Probabilities

A scenario is a subset of the sample space for aleatory uncertainty. The underlying goal of scenario definition is to define the state of repository conditions prior to and following intrusion events. Scenarios are specific cases of inputs or system states that are selected to cover the range of possible cases. Given the complexity of the futures $\mathbf{x}_{st,i}$ (see Equation (PA.2)), many different scenarios can be defined. The computational complexity of the function $f(\mathbf{x}_{st}|\mathbf{v}_{su})$ in Section PA-2.2.3 limits evaluation to only a few intrusion scenarios. As presented in Section PA-2.3.2, PA considers four fundamental intrusion scenarios:

E0 = no drilling intrusion through an excavated area of the repository

E1 = a drilling intrusion through an excavated area of the repository that penetrates pressurized brine in the Castile

E2 = a drilling intrusion through an excavated area of the repository that does not penetrate pressurized brine in the Castile

E1E2 = two or more previous intrusions, at least one of which is an E1 intrusion

These definitions of intrusion scenarios capture the most important events impacting the state of the repository: whether or not the repository is inundated by the penetration of a brine pocket, and whether or not there exists a possible route of release upward via a borehole. The state of the repository is also designated as E0, E1, E2, or E1E2. Scenarios for some of the process-level models consist of a single intrusion scenario occurring at specific times. CCDFGF is used to simulate multiple intrusions over 10,000 years.

If only the intrusion scenarios controlled the state of the repository, then the state would be defined by the sequence of drilling events alone. However, CCDFGF also considers the impact of plugging pattern on boreholes. A borehole with a full plugging pattern that penetrates the waste area is also assumed to have no impact, and leaves the repository in its previous state, including the undisturbed state (see Section PA-6.8.4.1 and Figure PA-41 for more details). Thus, an E2 intrusion event into an E0 repository will result in an E0 state if a full plugging pattern is used, or an E2 state otherwise. An E1 intrusion subsequent to an E2 intrusion will leave the repository in an E1E2 state, where it will remain, regardless of subsequent intrusions. It is therefore important to distinguish between the type of intrusion, listed above, and the state of the repository.

The probability that no excavated area will be penetrated during the 10,000-year interval can be computed using a distribution of the number of penetration events and the probability that a

drilling event will penetrate the excavated area. For the Poisson distribution of drilling events, the probability of there being *n* events in the 10,000-year history is

$$\frac{e^{-\lambda_d \times 9900}\left(\lambda_d \times 9900\right)^n}{n!} \text{ for } n = 1, 2, 3, \ldots \quad \text{(PA.17)}$$

where λ_d is the mean drilling rate per year in the period following the period of AICs, 9,900 is the number of years in which drilling can occur after the institutional control period of 100 years, and *n* is the number of drilling events. The probability of having *n* events all within the nonexcavated area is pEx_0^n, or specifically 0.797^n. Thus, the probability of having only events in the nonexcavated area over 10,000 years, i.e., having no drilling intrusions into the excavated area, is just the sum across all *n* of the products of the probability of having exactly *n* drilling events and the probability that all *n* events penetrate the unexcavated area:

$$\sum_{n=0}^{\infty} \frac{e^{-\lambda_d \times 9900}\left(\lambda_d \times 9900\right)^n}{n!} pEx_o^n = e^{-\lambda_d \times 9900 \times pEx_1} \quad \text{(PA.18)}$$

The calculated probability becomes

$$\exp\left(-0.203 \times 3.68 \times 10^{-3} \times \left(10000 - 100\right)\right) = 6.1 \times 10^{-4} \quad \text{(PA.19)}$$

This probability is the lower bound on the probability of the repository being in an E0 state, given that it does not include the consideration of the plugging pattern.

The probability of a single E1, E2, or E1E2 intrusion over 10,000 years is relatively small. Assuming that pB_1 takes on its mean value of 0.305 (see Section PA-3.6), and ignoring the impact of the plugging pattern, for a constant rate of drilling, λ_d, these equations are

$$e^{-pEx_1\lambda_d \times 9900}\left(pEx_1\lambda_d \times 9900\right) pB_1 = 1.4 \times 10^{-3} \quad \text{(PA.20)}$$

and

$$e^{-pEx_1\lambda_d \times 9900}\left(pEx_1\lambda_d \times 9900\right) pB_0 = 3.2 \times 10^{-3} \quad \text{(PA.21)}$$

respectively, where $(pEx_1 \times \lambda_d)$ represents the annual rate of drilling into the excavated region of the repository which is multiplied by *9900* to give the rate per 9,900 years. The probability of an intrusion into the excavated area is subsequently multiplied by the probability of hitting or missing a brine pocket. In this form, it can be seen that the term for the probability for intrusion is equivalent to the PDF of the Poisson distribution for $n = 1$:

$$f(n) = \frac{e^{-\lambda}\lambda^n}{n!} \quad \text{(PA.22)}$$

The expressions defining the probability of being in the E0 state after 10,000 years and of having a single E1 or E2 intrusion event after 10,000 years are relatively simple because the scenarios E0, E1, and E2 are relatively simple. The scenario E1E2 is more complex and, as a result, computing its probability is also more complex. Closed-form formulas for the probabilities of quite complex scenarios can be derived, but they are very complicated and involve large numbers of iterated integrals (Helton 1993). These probabilities of single E1 and E2 intrusions are relevant to the scenarios used by the process-level models.

PA-3.11 CCDF Construction

CCDFGF simulates histories that can have many intrusion events (WIPP Performance Assessment 2003a). The process-level models evaluate the releases at a small number of specific times for each of the four intrusion scenarios. Releases from the repository are calculated using results from these fundamental scenarios (Section PA-6.7 and Section PA-6.8). Releases for an arbitrary future are estimated from the results of these fundamental scenarios (Section PA-6.8); these releases are used to construct CCDFs by Equation (PA.4).

Previous WIPP PAs have used the Monte Carlo approach to construct the CCDF indicated in Equation (PA.4). The Monte Carlo approach generates releases for 10,000 possible futures. CCDFs are constructed by treating the 10,000 releases values as order statistics; each release is assigned a probability of 1×10^{-4}, and the CCDF can be constructed by plotting the complement of the sum of the probabilities ordered by the release value. The CRA-2009 PA uses the same approach as the CRA-2004 PA.

PA-4.0 Estimation of Releases

This section describes how releases to the accessible environment are estimated for a particular future in PA.

PA-4.1 Results for Specific Futures

The function $f(\mathbf{x}_{st,i})$ estimates the radionuclide releases to the accessible environment associated with each of the possible futures ($\mathbf{x}_{st,i}$) that could occur at the WIPP site over the next 10,000 years. In practice, $f(\mathbf{x}_{st,i})$ is quite complex and is constructed by the models implemented in computer programs used to simulate important processes and releases at the WIPP. In the context of these models, $f(\mathbf{x}_{st,i})$ has the form

$$\begin{aligned} f\left(\mathbf{x}_{st,i}\right) = {} & f_C\left(\mathbf{x}_{st,i}\right) + f_{SP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right] + f_{DBR}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right] \\ & + f_{MB}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right] + f_{DL}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right] + f_S\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right] \\ & + f_{ST}\left[f_{MF}\left(\mathbf{x}_{st,0}\right), f_{NP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]\right] \end{aligned} \qquad \text{(PA.23)}$$

where

- $\mathbf{x}_{st,i}$ ~ particular future under consideration
- $\mathbf{x}_{st,0}$ ~ future involving no drilling intrusions but a mining event at the same time t_{min} as in x_{st}
- $f_C(\mathbf{x}_{st,i})$ ~ cuttings and cavings release to accessible environment for $\mathbf{x}_{st,i}$ calculated with CUTTINGS_S
- $f_B(\mathbf{x}_{st,i})$ ~ two-phase flow in and around the repository calculated for $\mathbf{x}_{st,i}$ with BRAGFLO; in practice, $f_B(\mathbf{x}_{st,i})$ is a vector containing a large amount of information, including pressure and brine saturation in various geologic members
- $f_{SP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ spallings release to accessible environment for $\mathbf{x}_{st,i}$ calculated with the spallings model contained in DRSPALL and CUTTINGS_S; this calculation requires repository conditions calculated by $f_B(\mathbf{x}_{st,i})$ as input
- $f_{DBR}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ DBR to accessible environment for $\mathbf{x}_{st,i}$ also calculated with BRAGFLO; this calculation requires repository conditions calculated by $f_B(\mathbf{x}_{st,i})$ as input
- $f_{MB}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ release through anhydrite MBs to accessible environment for $\mathbf{x}_{st,i}$ calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B(\mathbf{x}_{st,i})$ as input

$f_{DL}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ release through Dewey Lake to accessible environment for $\mathbf{x}_{st,i}$ calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B(\mathbf{x}_{st,i})$ as input

$f_S\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ release to land surface due to brine flow up a plugged borehole for $\mathbf{x}_{st,i}$ calculated with NUTS; this calculation requires flows in and around the repository calculated by $f_B(\mathbf{x}_{st,i})$ as input

$f_{MF}\left(\mathbf{x}_{st,0}\right)$ ~ flow field in the Culebra calculated for $\mathbf{x}_{st,0}$ with MODFLOW; $\mathbf{x}_{st,0}$ is used as an argument to f_{MF} because drilling intrusions are assumed to cause no perturbations to the flow field in the Culebra

$f_{NP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$ ~ release to Culebra for $\mathbf{x}_{st,i}$ calculated with NUTS or PANEL as appropriate; this calculation requires flows in and around the repository calculated by $f_B(\mathbf{x}_{st,i})$ as input

$f_{ST}\left[f_{MF}\left(\mathbf{x}_{st,0}\right), f_{NP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]\right]$ ~ groundwater transport release through Culebra to accessible environment calculated with SECOTP2D. This calculation requires MODFLOW results (i.e., $f_{MF}(\mathbf{x}_{st,i})$) and NUTS or PANEL results (i.e., $f_{NP}\left[\mathbf{x}_{st,i}, f_B\left(\mathbf{x}_{st,i}\right)\right]$) as input

The remainder of this section describes the mathematical structure of the mechanistic models that underlie the component functions of $f(\mathbf{x}_{st,i})$ in Equation (PA.23).

The Monte Carlo CCDF construction procedure, implemented in the code CCDFGF (WIPP Performance Assessment 2003a), uses a sample of size $nS = 10{,}000$ in PA. The individual programs that estimate releases do not run fast enough to allow this many evaluations of f. As a result, a two-step procedure is being used to evaluate f in calculating the summation in Equation (PA.23). First, f and its component functions are evaluated with the procedures (i.e., models) described in this section for a group of preselected futures. Second, values of $f(\mathbf{x}_{st})$ for the randomly selected futures $\mathbf{x}_{st,i}$ used in the numerical evaluation of the summation in Equation (PA.23) are then constructed from results obtained in the first step. These constructions are described in Section PA-6.7 and Section PA-6.8, and produce the evaluations of $f(\mathbf{x}_{st})$ that are actually used in Equation (PA.23).

For notational simplicity, the functions on the right-hand side of Equation (PA.23) will typically be written with only $\mathbf{x}_{st}$ as an argument (e.g., $f_{SP}(\mathbf{x}_{st})$ will be used instead of $f_{SP}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$). However, the underlying dependency on the other arguments will still be present.

The major topics considered in this chapter are two-phase flow in the vicinity of the repository as modeled by BRAGFLO (i.e., f_B) (Section PA-4.2), radionuclide transport in the vicinity of the repository as modeled by NUTS (i.e., $f_{MB}, f_{DL}, f_S, f_{NP}$) (Section PA-4.3), radionuclide transport in the vicinity of the repository as modeled by PANEL (i.e., f_{NP}) (Section PA-4.4), cuttings and cavings releases to the surface as modeled by CUTTINGS_S (i.e., f_C) (Section PA-4.5), spallings releases to the surface as modeled by DRSPALL and CUTTINGS_S (i.e., f_{SP}) (Section PA-4.6),

DBRs to the surface as modeled by BRAGFLO (i.e., f_{DBR}) (Section PA-4.7), brine flow in the Culebra as modeled by MODFLOW (i.e., f_{MF}) (Section PA-4.8), and radionuclide transport in the Culebra as modeled by SECOTP2D (i.e., f_{ST}) (Section PA-4.9).

PA-4.2 Two-Phase Flow: BRAGFLO

Quantifying the effects of gas and brine flow on radionuclide transport from the repository requires a two-phase (brine and gas) flow code. The two-phase flow code BRAGFLO is used to simulate gas and brine flow in and around the repository (Nemer 2007b and 2007c). Additionally, the BRAGFLO code incorporates the effects of disposal room consolidation and closure, gas generation, and rock fracturing in response to gas pressure. This section describes the mathematical models on which BRAGFLO is based, the representation of the repository in the model, and the numerical techniques employed in the solution.

PA-4.2.1 Mathematical Description

Two-phase flow in the vicinity of the repository is represented by the following system of two conservation equations, two constraint equations, and three equations of state:

Gas Conservation

$$\nabla\cdot\left[\frac{\alpha\rho_g K_g k_{rg}}{\mu_g}\left(\nabla P_g+\rho_g g\nabla h\right)\right]+\alpha q_g+\alpha q_{rg}=\alpha\frac{\partial\left(\phi\rho_g S_g\right)}{\partial t} \qquad \text{(PA.24)}$$

Brine Conservation

$$\nabla\cdot\left[\frac{\alpha\rho_b K k_{rb}}{\mu_b}\left(\nabla P_b+\rho_b g\nabla h\right)\right]+\alpha q_b+\alpha q_{rb}=\alpha\frac{\partial\left(\phi\rho_b S_b\right)}{\partial t} \qquad \text{(PA.25)}$$

Saturation Constraint

$$S_g+S_b=1 \qquad \text{(PA.26)}$$

Capillary Pressure Constraint

$$P_c=P_g-P_b=P_c(S_b) \qquad \text{(PA.27)}$$

Gas Density

ρ_g (determined by Redlich-Kwong-Soave (RKS) equation of state; see Equation (PA.51)) (PA.28)

Brine Density

$$\rho_b=\rho_{b0}\exp\left[c_b\left(P_b-P_{b0}\right)\right] \qquad \text{(PA.29)}$$

Formation Porosity

$$\phi = \phi_0 \exp\left[c_\phi \left(P_b - P_{b0}\right)\right] \quad \text{(PA.30)}$$

where

g = acceleration due to gravity (meters per second squared [m])
h = vertical distance from a reference location (m)
k_{rl} = relative permeability (dimensionless) to fluid l, $l = b$ (brine), g (gas)
P_c = capillary pressure in Pascals (Pa)
P_l = pressure of fluid l (Pa)
q_{rl} = rate of production (or consumption, if negative) of fluid l due to chemical reaction (kilograms per cubic meter per seconds [kg/m^3/s])
q_l = rate of injection (or removal, if negative) of fluid l (kg/m^3/s)
S_l = saturation of fluid l (dimensionless)
t = time (s)
α = geometry factor (m)
ρ_l = density of fluid l (kg/m^3)
μ_l = viscosity of fluid l (Pa s)
ϕ = porosity (dimensionless)
ϕ_0 = reference (i.e., initial) porosity (dimensionless)
P_{b0} = reference (i.e., initial) brine pressure (Pa), constant in Equation (PA.29) and spatially variable in Equation (PA.30)
ρ_0 = reference (i.e., initial) brine density (kg/m^3)
c_ϕ = pore compressibility (Pa^{-1})
c_b = brine compressibility (Pa^{-1})
K = permeability of the material (m^2), isotropic for PA (Howarth and Christian-Frear 1997)

For the brine transport Equation (PA.25), the intrinsic permeability of the material is used. For the gas transport Equation (PA.24), the permeability K is modified to account for the Klinkenberg effect (Klinkenberg 1941). Specifically,

$$K_g = K\left(\frac{1 + bK^a}{P_g}\right) \quad \text{(PA.31)}$$

where a and b are gas and formation-dependent constants. Values of $a = -0.3410$ and $b = 0.2710$ were determined from data obtained for MB 139 (Christian-Frear 1996), with these values used for all regions in Figure PA-15.

The conservation equations are valid in one (i.e., $\nabla = [\partial/\partial x]$), two (i.e., $\nabla = [\partial/\partial x, \partial/\partial y]$), and three (i.e., $\nabla = [\partial/\partial x, \partial/\partial y, \partial/\partial z]$) dimensions. In PA, the preceding system of equations is used

to model two-phase fluid flow within the two-dimensional region shown in Figure PA-15. The details of this system are now discussed.

The α term in Equation (PA.24) and Equation (PA.25) is a dimension-dependent geometry factor and is specified by

α = area normal to flow direction in one-dimensional flow (i.e., $\Delta y \Delta z$; units = m^2)
= thickness normal to flow plane in two-dimensional flow (i.e., Δz; units = m)
= 1 in three-dimensional flow (dimensionless) (PA.32)

PA uses a two-dimensional geometry to compute two-phase flow in the vicinity of the repository, and as a result, α is the thickness of the modeled region (i.e., Δz) normal to the flow plane (Figure PA-15). Due to the use of the two-dimensional grid in Figure PA-15, α is spatially dependent, with the values used for α defined in the column labeled "Δz." Specifically, α increases with distance away from the repository edge in both directions to incorporate the increasing pore volume through which fluid flow occurs. The method used in PA, called rectangular flaring, is illustrated in Figure PA-16 and ensures that the total volume surrounding the repository is conserved in the numerical grid. The equations and method used to determine α for the grid shown in Figure PA-15 are described in detail by Stein (2002).

The h term in Equation (PA.24) and Equation (PA.25) defines vertical distance from a reference point. In PA, this reference point is taken to be the center of MB 139 at the location of the shaft (i.e., (x_{ref}, y_{ref}) = (23664.9 m, 378.685 m), which is the center of cell 1266 in Figure PA-17). Specifically, h is defined by

$$h(x,y) = \left(x - x_{ref}\right)\sin\theta + \left(y - y_{ref}\right)\cos\theta \qquad \text{(PA.33)}$$

where θ is the inclination of the formation in which the point (x, y) is located. In PA, the Salado is modeled as having an inclination of 1 degree from north to south, and all other formations are modeled as being horizontal. Thus, θ = 1 degree for points within the Salado, and θ = 0 degrees otherwise. Treating the Salado as an inclined formation and treating the Castile, Castile brine reservoir, Rustler, and overlying units as horizontal creates discontinuities in the grid at the lower and upper boundaries of the Salado. However, this treatment does not create a computational problem, since the Salado is isolated from vertical flow; its upper boundary adjoins the impermeable Los Medaños Member (formerly referred to as the Unnamed Member) at the base of the Rustler, and its lower boundary adjoins the impermeable Castile.

In the solution of Equations (PA.24) through (PA.30), S_b and S_g are functions of location and time. Thus, P_c, k_{rb}, and k_{rg} are functions of the form $P_c(x, y, t)$, $k_{rb}(x, y, t)$, and $k_{rg}(x, y, t)$. In the computational implementation of the solution of the preceding equations, flow of phase l out of a computational cell (Figure PA-17) cannot occur when $S_l(x, y, t) \le S_{lr}(x, y, t)$, where S_{lr} denotes the residual saturation for phase l. The values used for S_{lr}, $l = b, g$ are summarized in Table PA-3.

Values for ϕ_0 and c_ϕ (Equation (PA.30)) are also given in Table PA-3. Initial porosity ϕ_0 for the DRZ is a function of the uncertain parameter for initial halite porosity ϕ_{0H} (HALPOR; see Table PA-19) and is given by Martell (1996a) and Bean et al. (1996), Section 4):

$$\phi_0 = \phi_{0H} + 0.0029 \tag{PA.34}$$

Initial porosity ϕ_0 of the Castile brine reservoir is calculated from the uncertain sampled parameter for the bulk Castile rock compressibility (BPCOMP; see Table PA-19), according to the following relationship:

$$\phi_0 = \frac{BPCOMP}{1.0860 \times 10^{-10}} \tag{PA.35}$$

where 1.0860×10^{-10} is a scaling constant that ensures that the productivity ratio, *PR*, remains constant at 2.0×10^{-3} m^3/Pa. The productivity ratio *PR* is computed by

$$PR = V \frac{BPCOMP}{\phi_0} \tag{PA.36}$$

where *V* is the volume of the grid block representing the Castile brine reservoir in Figure PA-15. Because of this relationship, the initial porosity of the brine reservoir ranges from 0.1842 to 0.9208. This range of porosity is not meant to represent an actual reservoir, but rather allows a reservoir to supply a volume of brine to the repository in the event of an E1 intrusion consistent with observed brine flows in the Delaware Basin.

The compressibility c_ϕ in Equation (PA.30) and Table PA-3 is pore compressibility. Compressibility is treated as uncertain for Salado anhydrite, Salado halite, and regions of pressurized brine in the Castile. However, the sampled value for each of these variables corresponds to bulk compressibility rather than to the pore compressibility actually used in the calculation. Assuming all of the change in volume during compression occurs in the pore volume, the conversion from bulk compressibility c_r to pore compressibility c_ϕ is approximated by

$$C_\phi = \frac{Cr}{\phi_0} \tag{PA.37}$$

where ϕ_0 is the initial porosity in the region under consideration.

The primary model used in PA for capillary pressure P_c and relative permeability k_{rl} is a modification of the Brooks-Corey model (Brooks and Corey 1964). In this model, P_c, k_{rb}, and k_{rg} are defined by

$$P_c = P_t(k) \Big/ S_{e2}^{1/\lambda} \tag{PA.38}$$

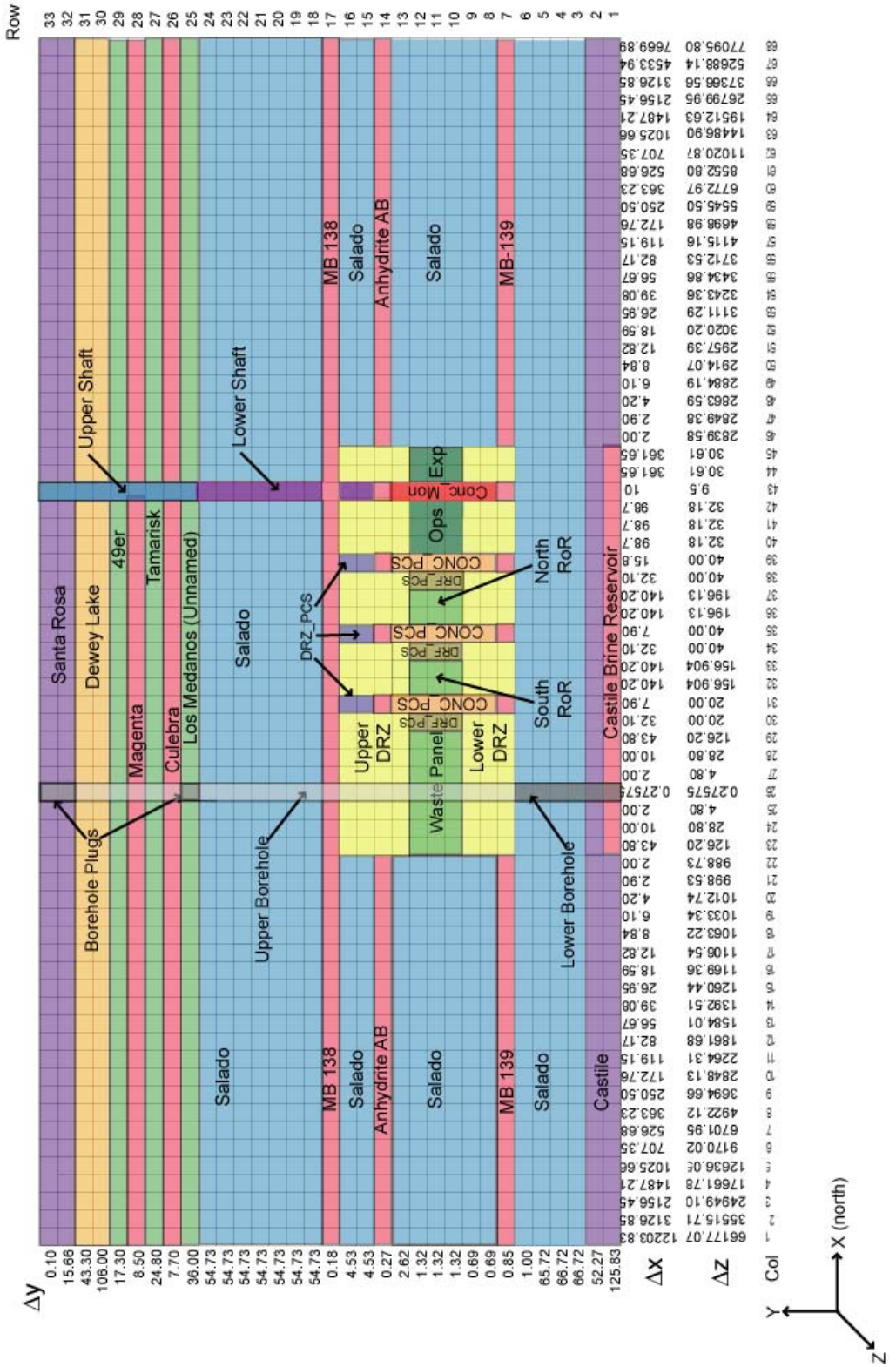


Figure PA-15. Computational Grid Used in BRAGFLO for PA

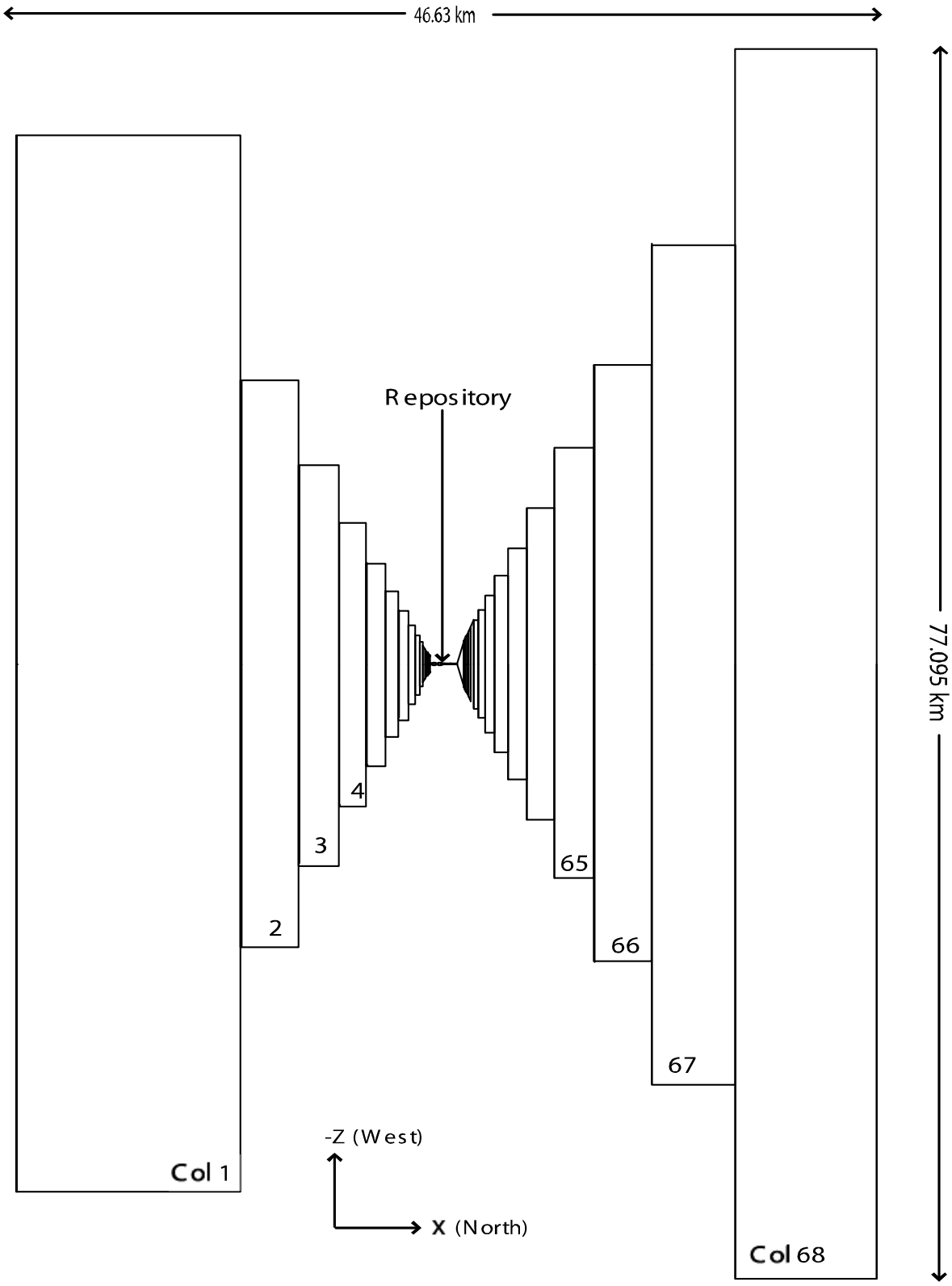


Figure PA-16. Definition of Element Depth in BRAGFLO Grid

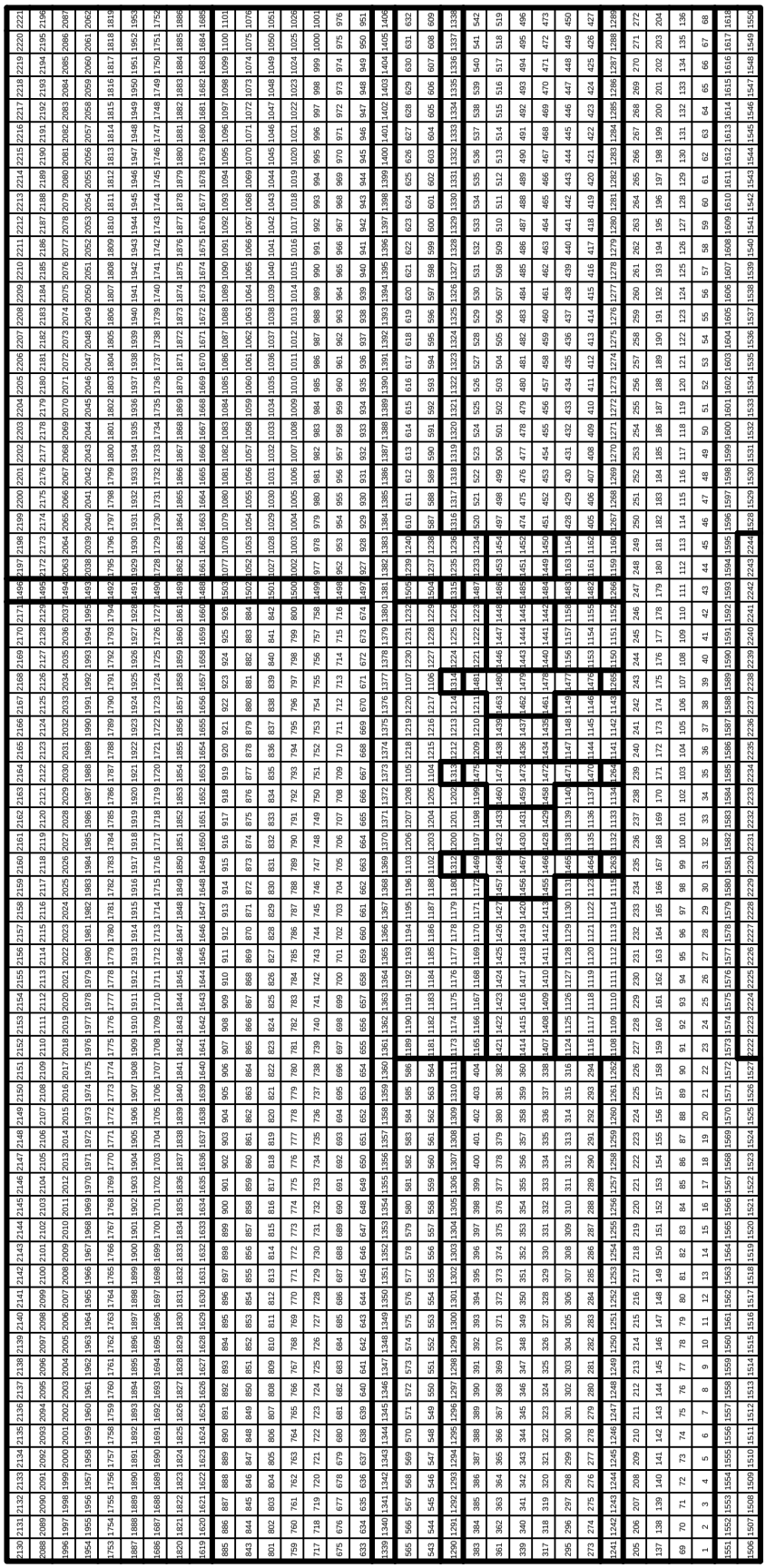


Figure PA-17. Identification of Individual Cells in BRAGFLO Grid

Table PA-3. Parameter Values Used in Representation of Two-Phase Flow

Region	Material	Material Description	Brooks-Corey Pore Distribution (PORE_DIS)[a] λ	Threshold Pressure Linear Parameter (PCT_A)[a] a	Threshold Pressure Exponential Parameter (PCT_EXP)[a] η	Residual Brine Saturation (SAT_RBRN)[a] S_{br}	Residual Gas Saturation (SAT_RGAS)[a] S_{gr}	Porosity (POROSITY)[a] ϕ_0	Pore Compressibility[a] $c\phi$, Pa^{-1}	Intrinsic Permeability (PRMX_LOG)[a] k, m^2
Salado	S_HALITE	Undisturbed halite	0.7	0.56	–0.346	0.3	0.2	HALPOR[b]	f(HALCOMP)[b,d]	10^x, x = HALPRM[b]
DRZ	DRZ_0	DRZ, –5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR)[b,c]	f(HALCOMP)[b,d]	1.0 × 10-17
	DRZ_1	DRZ, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR)[b,c]	f(HALCOMP)[b,d]	10^x, x = DRZPRM[b]
MB 138	S_MB138	Anhydrite MB in Salado	ANHBCEXP[b]	0.26	–0.348	ANRBSAT[b]	ANRGSSAT[b]	0.011	f(ANHCOMP)[b,d]	10^x, x = ANHPRM[b]
Anhydrite AB	S_ANH_AB	Anhydrite layers A and B in Salado	ANHBCEXP[b]	0.26	–0.348	ANRBSAT[b]	ANRGSSAT[b]	0.011	f(ANHCOMP)[b,d]	10^x, x = ANHPRM[b]
MB 139	S_MB139	Anhydrite MB in Salado	ANHBCEXP[b]	0.26	–0.348	ANRBSAT[b]	ANRGSSAT[b]	0.011	f(ANHCOMP)[b,d]	10^x, x = ANHPRM[b]
Waste Panel	CAVITY_1	Single waste panel, –5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	WAS_AREA	Single waste panel, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT[b]	WRGSSAT[b]	0.848[f]	0.0	2.4×10^{-13}
Rest of Repository (RoR)	CAVITY_2	RoR, –5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	REPOSIT	RoR, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT[b]	WRGSSAT[b]	0.848[f]	0.0	2.4×10^{-13}
Ops and Exp	CAVITY_3	Operations area, –5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	OPS_AREA	Operations area, 0 to 10,000 years	NA[e]	NA[e]	NA[e]	0.0	0.0	0.18	0.0	1.0×10^{-11}
Exp	CAVITY_3	Experimental area, –5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}

a Parenthetical parameter names are property names for the corresponding material, as indicated in.

b Uncertain variable; see Table PA-19.

c See Equation (PA.34).

d See Equation (PA.37); ϕ_0 can also be defined by an uncertain variable.

e These materials are using relative permeability model = 11; see Table PA-4.

f Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).

g See Equation (PA.35).

Table PA-3. Parameter Values Used in Representation of Two-Phase Flow (Continued)

Region	Material	Material Description	Brooks-Corey Pore Distribution (PORE_DIS)[a] λ	Threshold Pressure Linear Parameter (PCT_A)[a] a	Threshold Pressure Exponential Parameter (PCT_EXP)[a] η	Residual Brine Saturation (SAT_RBRN)[a] S_{br}	Residual Gas Saturation (SAT_RGAS)[a] S_{gr}	Porosity (POROSITY)[a] ϕ_0	Pore Compressibility[a] $c\phi$, Pa^{-1}	Intrinsic Permeability (PRMX_LOG)[a] k, m^2
—	EXP_AREA	Experimental area, 0 to 10,000 years	NA[e]	NA[e]	NA[e]	0.0	0.0	0.18	0.0	1.0×10^{-11}
Castile	IMPERM_Z	Castile	0.7	0.0	0.0	0.0	0.0	0.005	0.0	1.0×10^{-35}
Castile Brine Reservoir	CASTILER	Brine Reservoir in Castile	0.7	0.56	–0.346	0.2	0.2	f(BPCOMP)[b,g]	f(BPCOMP)[b,d]	10^x, x = BPPRM[b]
Culebra	CULEBRA	Culebra Member of Rustler	0.6436	0.26	–0.348	0.08363	0.07711	0.151	6.622517×10^{-10}	7.72681×10^{-14}
Magenta	MAGENTA	Magenta Member of Rustler	0.6436	0.26	–0.348	0.08363	0.07711	0.138	1.915942×10^{-9}	6.309576×10^{-16}
Dewey Lake	DEWYLAKE	Dewey Lake Redbeds	0.6436	0.0	0.0	0.08363	0.07711	0.143	6.993007×10^{-8}	5.011881×10^{-17}
Santa Rosa	SANTAROS	Santa Rosa Formation	0.6436	0.0	0.0	0.08363	0.07711	0.175	5.714286×10^{-8}	1.0×10^{-10}
Los Medaños	UNNAMED	Los Medaños Member of Rustler	0.7	0.0	0.0	0.2	0.2	0.181	0.0	1.0×10^{-35}
Tamarisk	TAMARISK	Tamarisk Member of Rustler	0.7	0.0	0.0	0.2	0.2	0.064	0.0	1.0×10^{-35}
Forty-niner	FORTYNIN	Forty-niner Member of Rustler	0.7	0.0	0.0	0.2	0.2	0.082	0.0	1.0×10^{-35}
DRZ_PCS	DRZ_0	DRZ, -5 to 0 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR)[b,c]	f(HALCOMP)[b,d]	1.0×10^{-17}
DRZ_PCS	DRZ_PCS	DRZ above the panel closures, 0 to 10,000 years	0.7	0.0	0.0	0.0	0.0	f(HALPOR)[b,c]	f(HALCOMP)[b,d]	10^x, x = DRZPCPRM[b]

a Parenthetical parameter names are property names for the corresponding material, as indicated in Table PA-19.

b Uncertain variable; see Table PA-19.

c See Equation (PA.34).

d See Equation (PA.37); ϕ_0 can also be defined by an uncertain variable.

e These materials are using relative permeability model = 11; see Table PA-4.

f Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).

g See Equation (PA.35).

Table PA-3. Parameter Values Used in Representation of Two-Phase Flow (Continued)

Region	Material	Material Description	Brooks-Corey Pore Distribution (PORE_DIS)[a] λ	Threshold Pressure Linear Parameter (PCT_A)[a] a	Threshold Pressure Exponential Parameter (PCT_EXP)[a] η	Residual Brine Saturation (SAT_RBRN)[a] S_{br}	Residual Gas Saturation (SAT_RGAS)[a] S_{gr}	Porosity (POROSITY)[a] ϕ_0	Pore Compressibility[a] $c\phi$, Pa^{-1}	Intrinsic Permeability (PRMX_LOG)[a] k, m^2
CONC_PCS	CAVITY_4	Concrete portion of panel closures, −5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	CONC_PCS	Concrete portion of panel closures, 0 to 10,000 years	CONBCEXP[b]	0.0	0.0	CONBRSAT[b]	CONGSSAT[b]	0.05	1.2×10^{-9}	10^x, x = CONPRM[b]
DRF_PCS	CAVITY_4	Drift adjacent to panel closures, −5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	DRF_PCS	Drift adjacent to panel closures, 0 to 10,000 years	2.89	0.0	0.0	WRBRNSAT[b]	WRGSSAT[b]	0.848[f]	0.0	2.4×10^{-13}
CONC_MON	CAVITY_4	Concrete monolith portion of shaft seals, −5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	CONC_MON	Concrete monolith portion of shaft seals, 0 to 10,000 years	0.94	0.0	0.0	SHURBRN[b]	SHURGAS[b]	0.05	1.2×10^{-9}	1.0×10^{-14}
Upper Shaft	CAVITY_4	Upper portion of shaft seals, −5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	SHFTU	Upper portion of shaft seals, 0 to 10,000 years	CONBCEXP[b]	0.0	0.0	SHURBRN[b]	SHURGAS[b]	0.005	2.05×10^{-8}	10^x, x = SHUPRM[b]

a Parenthetical parameter names are property names for the corresponding material, as indicated in Table PA-19.

b Uncertain variable; see Table PA-19.

c See Equation (PA.34).

d See Equation (PA.37); ϕ_0 can also be defined by an uncertain variable.

e These materials are using relative permeability model = 11; see Table PA-4.

f Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).

g See Equation (PA.35).

Table PA-3. Parameter Values Used in Representation of Two-Phase Flow (Continued)

Region	Material	Material Description	Brooks-Corey Pore Distribution (PORE_DIS)[a] λ	Threshold Pressure Linear Parameter (PCT_A)[a] a	Threshold Pressure Exponential Parameter (PCT_EXP)[a] η	Residual Brine Saturation (SAT_RBRN)[a] S_{br}	Residual Gas Saturation (SAT_RGAS)[a] S_{gr}	Porosity (POROSITY)[a] ϕ_0	Pore Compressibility[a] $c\phi$, Pa^{-1}	Intrinsic Permeability (PRMX_LOG)[a] k, m^2
Lower Shaft	CAVITY_4	Lower portion of shaft seals, −5 to 0 years	NA[e]	NA[e]	NA[e]	0.0	0.0	1.0	0.0	1.0×10^{-10}
—	SHFTL_T1	Lower portion of shaft seals, 0 to 200 years	CONBCEXP[b]	0.0	0.0	SHURBRN[b]	SHURGAS[b]	0.005	4.28×10^{-9}	10^x, x = SHLPRM1[b]
—	SHFTL_T2	Lower portion of shaft seals, 200 to 10,000 years	CONBCEXP[b]	0.0	0.0	SHURBRN[b]	SHURGAS[b]	0.005	4.28×10^{-9}	10^x, x = SHLPRM2[b]
Borehole plugs	CONC_PLG	Concrete borehole plug, before plug degradation	0.94	0.0	0.0	0.0	0.0	0.32	1.1875×10^{-9}	10^x, x = PLGPRM[b]
—	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10^x, x = BHPRM[b]
Upper Borehole	BH_OPEN	Borehole above repository before plug degradation	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}
—	BH_SAND	Borehole after plug degradation, 200 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	10^x, x = BHPRM[b]
Lower Borehole	BH_OPEN	Borehole below repository before creep closure	0.7	0.0	0.0	0.0	0.0	0.32	0.0	1.0×10^{-9}
—	BH_CREEP	Borehole below repository after creep closure, 1,000 years after intrusion	0.94	0.0	0.0	0.0	0.0	0.32	0.0	$10^x/10$, x = BHPRM[a]

a Parenthetical parameter names are property names for the corresponding material, as indicated in Table PA-19.
b Uncertain variable; see Table PA-19.
c See Equation (PA.34).
d See Equation (PA.37); ϕ_0 can also be defined by an uncertain variable.
e These materials are using relative permeability model = 11; see Table PA-4.
f Initial value of porosity ϕ_0; porosity changes dynamically to account for creep closure (see Section PA-4.2.3).
g See Equation (PA.35).

$$k_{rb} = S_{el}^{(2+3\lambda)/\lambda} \quad \text{(PA.39)}$$

$$k_{rg} = \left(1 - S_{e2}\right)^2 \left(1 - S_{e2}^{(2+\lambda)/\lambda}\right) \quad \text{(PA.40)}$$

where

λ = pore distribution parameter (dimensionless)

$P_t(k)$ = capillary threshold pressure (Pa) as a function of intrinsic permeability k (Webb 1992)

$$= ak^{\eta} \quad \text{(PA.41)}$$

S_{e1} = effective brine saturation (dimensionless) without correction for residual gas saturation

$$= \left(S_b - S_{br}\right)/\left(1 - S_{br}\right) \quad \text{(PA.42)}$$

S_{e2} = effective brine saturation (dimensionless) with correction for residual gas saturation

$$= \left(S_b - S_{br}\right)/\left(1 - S_{gr} - S_{br}\right) \quad \text{(PA.43)}$$

The values used for λ, a, η, S_{br}, S_{gr}, and k are summarized in Table PA-3. The statement that the Brooks-Corey model is in use means that P_c, k_{rb}, and k_{rg} are defined by Equation (PA.38) through Equation (PA.40).

In the anhydrite MBs, either the Brooks-Corey model or the van Genuchten-Parker model is used as determined by the subjectively uncertain parameter ANHBCVGP (see Table PA-19). A linear model is used to represent two-phase flow in an open borehole (i.e., for the first 200 years after a drilling intrusion for boreholes with two-plug or three-plug configurations, in the open cavities [CAVITY_1, . . , CAVITY_4], and for the experimental and operations areas). This is discussed further below.

In the van Genuchten-Parker model, P_c, k_{rb}, and k_{rg} are defined by (van Genuchten 1978)

$$P_c = P_{VGP}\left(S_{e2}^{-1/m} - 1\right)^{1-m} \quad \text{(PA.44)}$$

$$k_{rb} = S_{e1}^{1/2}\left[1 - \left(1 - S_{e1}^{1/m}\right)^m\right]^2 \quad \text{(PA.45)}$$

$$k_{rg} = \left(1 - S_{e2}\right)^{1/2}\left(1 - S_{e2}^{1/m}\right)^{2m} \quad \text{(PA.46)}$$

where $m = \lambda/(1 + \lambda)$ and the capillary pressure parameter P_{VGP} is determined by requiring that the capillary pressures defined in Equation (PA.38) and Equation (PA.44) are equal at an effective brine saturation of $S_{e2} = 0.5$ (Webb 1992). The van Genuchten-Parker model is only used for the anhydrite MBs in the Salado and uses the same values for λ, S_{br}, and S_{gr} as the Brooks-Corey model (Table PA-3).

In the linear model used for the open borehole (RELP_MOD = 5), P_c, k_{rb}, and k_{rg} are defined by

$$P_c = 0,\ k_{rb} = S_{e1},\ k_{rg} = 1 - S_{e1} \tag{PA.47}$$

Another linear model (RELP_MOD = 11) is used for the open cavities (CAVITY_1, . . . , CAVITY_4) for the −5 to 0 year portion of the simulation (see Section PA-4.2.2) and the experimental and operations areas (t = 0 to 10,000 years) which, in PA, are modeled without a time-dependent creep closure:

$$k_{rl} = 0 \quad for \quad S_l < S_{lr} \tag{PA.48}$$

$$k_{rl} = \frac{(S_l - S_{lr})}{tol} \quad for \quad S_{lr} \le S_l \le S_{lr} + tol \tag{PA.49}$$

$$k_{rl} = 1 \quad for \quad S_l > S_{lr} + tol \tag{PA.50}$$

where l = gas or brine and tol is a tolerance (slope) over which the relative permeability changes linearly from 0 to 1. In PA, $tol = 1 \times 10^{-2}$ (dimensionless). Thus, the relative permeabilities are ~ 1 for saturations away from residual saturation.

Capillary pressure P_c for both the van Genuchten-Parker and Brooks-Corey models becomes unbounded as brine saturation S_b approaches the residual brine saturation, S_{br}. To avoid unbounded values, P_c is capped at 1×10^8 Pa in selected regions (Table PA-4).

Gas density is computed using the RKS equation of state, with the gas assumed to be pure H_2. For a pure gas, the RKS equation of state has the form (Walas 1985, pp. 43−54)

$$P_g = \frac{RT}{V - b} - \frac{a\alpha}{V(V + b)} \tag{PA.51}$$

where

R = gas constant = 8.31451 Joules (J) mole (mol)$^{-1}$ K^{-1}
T = temperature (K) = 300.15 K (= 30 °C; 81 °F)
V = molar volume (m^3 mol^{-1})
$a = 0.42747\, R^2 T_{crit}^2 / P_{crit}$
$b = 0.08664\, RT_{crit} / P_{crit}$

Table PA-4. Models for Relative Permeability and Capillary Pressure in Two-Phase Flow

Material	Relative Permeability[a] (RELP_MOD)	Capillary Pressure[b] (CAP_MOD)	Material	Relative Permeability[a] (RELP_MOD)	Capillary Pressure[b] (CAP_MOD)
S_HALITE	4	2	WAS_AREA	12	1
DRZ_0	4	1	DRZ_1	4	1
S_MB139	ANHBCVGP[c]	2	DRZ_PCS	Sampled	1
S_ANH_AB	ANHBCVGP[c]	2	CONC_PCS	4	2
S_MB138	ANHBCVGP[c]	2	UNNAMED	4	1
CAVITY_1	11	1	TAMARISK	4	1
CAVITY_2	11	1	FORTYNIN	4	1
CAVITY_3	11	1	DRF_PCS	12	1
CAVITY_4	11	1	REPOSIT	12	1
IMPERM_Z	4	1	CONC_MON	4	2
CASTILER	4	2	SHFTU	4	1
OPS_AREA	11	1	SHFTL_T1	4	1
EXP_AREA	11	1	SHFTL_T2	4	1
CULEBRA	4	2	CONC_PLG	4	1
MAGENTA	4	2	BH_OPEN	5	1
DEWYLAKE	4	2	BH_SAND	4	1
SANTAROS	4	1	BH_CREEP	4	1

[a] Relative permeability model, where 4 = Brooks-Corey model given by Equation (PA.38) through Equation (PA.40), 5 = linear model given by Equation (PA.47), 11 = linear model given by Equation (PA.48) through Equation (PA.50), 12 = modified Brooks-Corey model to account for cutoff saturation (Nemer 2007c), and ANHBCVGP ~ use of Brooks-Corey or van Genuchten-Parker model treated as a subjective uncertainty.

[b] Capillary pressure model, where 1 = capillary pressure is unbounded, 2 = P_c bounded above by 1×10^8 Pa as S_b approaches S_{br}.

[c] See ANHBCVGP in Table PA-19.

$$\alpha = \left[1+\left(0.48508+1.55171\omega-0.15613\omega^2\right)\left(1-T_r^{0.5}\right)\right]^2$$

$$\approx 1.202\exp\left(-0.30288T_r\right) \text{ for } H_2 \text{ (Graboski and Daubert 1979)}$$

T_{crit} = critical temperature (K)

P_{crit} = critical pressure (Pa)

$T_r = T / T_{crit}$ = reduced temperature

ω = acentric factor

= 0 for H_2 (Graboski and Daubert 1979)

In order to account for quantum effects in H_2, effective critical temperature and pressure values of $T_{crit} = 43.6$ K and $P_{crit} = 2.047 \times 10^6$ Pa are used instead of the true values for these properties (Prausnitz 1969). Equation (PA.51) is solved for molar volume V. The gas density ρ_g then is given by

$$\rho_g = \frac{M_{w,H_2}}{V} \tag{PA.52}$$

where M_{w,H_2} is the molecular weight of H_2 (i.e., 2.01588×10^{-3} kg/mol; see Weast 1969, p. B-26).

Brine density ρ_b is defined by Equation (PA.29), with $\rho_{b0} = 1230.0$ kg/m^3 at a pressure of $P_{b0} = 1.0132 \times 10^5$ Pa and $c_b = 2.5 \times 10^{-10}$ Pa^{-1} (Roberts 1996). Porosity, ϕ, is used as defined by Equation (PA.30) with two exceptions: in the repository (see Section PA-4.2.3) and in the DRZ and MBs subsequent to fracturing (see Section PA-4.2.4). The values of ϕ_0 and c_ϕ used in conjunction with Equation (PA.30) are listed in Table PA-3. The reference pressure P_{b0} in Equation (PA.30) is spatially variable and corresponds to the initial pressures $P_b(x, y, -5)$ (here, -5 means at time equal to -5 years; see Section PA-4.2.2). The gas and brine viscosities μ_l, $l = g$, b in Equation (PA.24) and Equation (PA.25) were assumed to have values of $\mu_g = 8.93 \times 10^{-6}$ Pa s (H2:VISCO; see Vargaftik 1975) and $\mu_b = 2.1 \times 10^{-3}$ Pa s (BRINESAL:VISCO; see McTigue 1993).

The terms q_g, q_{rg}, q_b, and q_{rb} in Equation (PA.24) and Equation (PA.25) relate to well injection or removal (i.e., q_g, q_b) and reaction, production, or consumption (i.e., q_{rg}, q_{rb}) of gas and brine, with positive signs corresponding to injection or production and negative signs corresponding to removal or consumption. In the long-term Salado flow calculations, no injection or removal of gas or brine is calculated using q_g and q_b. Thus, q_g and q_b are equal to zero. That is, after an intrusion, the borehole is treated as a porous media, rather than a point source or sink of brine and gas. Furthermore, the mass and pressure lost to a DBR during the intrusion is conservatively ignored in the BRAGFLO calculations. In the DBR calculations discussed in Section PA-4.7, q_g and q_b are used to describe injection and production wells in the DBR grid.

In PA, no gas consumption occurs through the term q_{rg} (see below), and gas production has the potential to occur (due to corrosion of steel or microbial degradation of CPR materials) only in the waste disposal regions of the repository (i.e., Waste Panel, South RoR, and North RoR in Figure PA-15). Thus,

$$q_{rg} \geq 0 \text{ in waste disposal regions of Figure PA-15}$$

$$= 0 \text{ elsewhere} \tag{PA.53}$$

Gas consumption occurs due to the reaction of CO_2 with MgO in the waste panels, and potentially from the sulfidation of steel. This gas consumption is not modeled using q_{rg}, but is accounted for by reducing the gas generation rate q_{rg}, as discussed in Section PA-4.2.5. Finally, no brine production occurs, and brine consumption has the potential to occur (due to the consumption of brine during steel corrosion) only in the waste disposal regions of the repository. Thus,

$q_{rb} \leq 0$ in waste disposal regions of Figure PA-15

$= 0$ elsewhere (PA.54)

More detail on the definition of q_{rg} and q_{rb} is provided in Section PA-4.2.5.

PA-4.2.2 Initial Conditions

In each two-phase flow simulation, a short period of time representing disposal operations is simulated. This period of time is called the start-up period, and covers 5 years from $t = -5$ years to 0 years, corresponding to the amount of time a typical panel is expected to be open during disposal operations. All grid locations require initial brine pressure and gas saturation at the beginning of the simulation (t = –5 years).

The Rustler and overlying units (except in the shaft) are modeled as horizontal with spatially constant initial pressure in each layer (see Figure PA-15). Table PA-5 lists the initial brine pressure, P_b, and gas saturation, S_g, for the Rustler.

The Salado (Mesh Rows 3–24 in Figure PA-15) is assumed to dip uniformly $\theta = 1$ degree downward from north to south (right to left in Figure PA-15). Except in the repository excavations and the shaft, brine is initially assumed (i.e., at –5 years) to be in hydrostatic equilibrium relative to an uncertain initial pressure $P_{b,ref}$ (SALPRES; see Table PA-19) at a reference point located at shaft center at the elevation of the midpoint of MB 139, which is the center of Cell 1266 in Figure PA-17. This gives rise to the condition

$$P_b(x, y, -5) = P_{b,ref} + \frac{1}{c_b} \ln\left[\frac{\rho_b(x, y, -5)}{\rho_{b0}}\right] \quad \text{(PA.55)}$$

$$\rho_b\left(x, y, -5\right) = \frac{1}{g\, c_b \left[y_e - \Phi\left(x_{ref}, y_{ref}, -5\right) + \frac{1}{g\, c_b\, \rho_{b0}} \right]} \quad \text{(PA.56)}$$

$$\Phi\left(x_{ref}, y_{ref}, -5\right) = y_{ref} + \frac{1}{g\, c_b}\left[\frac{1}{\rho_{b0}} - \frac{1}{\rho_b\left(x_{ref}, y_{ref}, -5\right)}\right] \quad \text{(PA.57)}$$

$$\rho_b\left(x_{ref}, y_{ref}, -5\right) = \rho_{b0} \exp\left[-c_b\left(P_{b,ref} - P_{b0}\right)\right] \quad \text{(PA.58)}$$

$$y_e = y_{ref} + h(x, y) \quad \text{(PA.59)}$$

Table PA-5. Initial Conditions in the Rustler

Name	Mesh Row (Figure PA-15)	$P^b(x, y, -5)$, Pa	$S^g(x, y, -5)$
Santa Rosa [c]	33	1.013250×10^5	$1 - S_b = 0.916$ (S_b = SANTAROS:SAT_IBRN)[a]
Santa Rosa [c]	32	1.013250×10^5	$1 - S_b = 0.916$ (S_b = SANTAROS:SAT_IBRN)[a]
Dewey Lake[c]	31	1.013250×10^5	$1 - S_b = 0.916$ (S_b = SANTAROS:SAT_USAT)[a]
Dewey Lake[c]	30	7.355092×10^5	$1 - S_b = 0.916$ (S_b = SANTAROS:SAT_USAT)[a]
Forty-niner[c]	29	1.47328×10^6	0[b]
Magenta	28	9.465×10^5 (MAGENTA:PRESSURE)	0[b]
Tamarisk[c]	27	1.82709×10^6	0[b]
Culebra	26	9.141×10^5 (CULEBRA:PRESSURE)	0[b]
Los Medaños [c]	25	2.28346×10^6	0[b]

[a] The names in parenthesis are parameters in the WIPP PA Parameter Database.

[b] The Rustler is assumed to be fully saturated. This initial condition is set in the program ICSET. See Nemer and Clayton (2008, Section 3.2).

[c] These pressures are calculated in the ALGEBRA1 step analogously to Equation (PA.55) below, using the brine density of 1220 kg/m^3. See subsequent discussion taking $\theta = 0$ and the reference point (x_{ref}, y_{ref}) at the top of the Dewey Lake. See the ALGEBRA input file ALG1_BF_CRA09.INP in library LIBCRA09_BF, class CRA09-1 on the WIPP PA cluster for details. See Nemer and Clayton (2008, Section 4.1.7) for details on the ALGEBRA1 step.

where

$h(x, y)$ is defined in Equation (PA.33)

ρ_{b0} = 1220 kg/m^3 (BRINESAL:DNSFLUID)

c_b = 3.1×10^{-10} Pa^{-1} (BRINESAL:COMPRES)

g = 9.80665 m/s^2

$P_{b,ref}$ = 1.01325×10^5 Pa (BRINESAL:REF_PRES)

P_{b0} = sampled far-field pressure in the undisturbed halite (S_HALITE:PRESSURE)

In the Salado, initial gas saturation $S_g(x, y, -5) = 0$ (see Nemer and Clayton 2008, Section 4.1.6).

The Castile (Mesh Rows 1 and 2) is modeled as horizontal, and initial brine pressure is spatially constant within each layer (no dip), except that the brine reservoir is treated as a different material from rest of Castile and has a different initial pressure which is a sampled parameter. Specifically, outside the brine reservoir, pressure is calculated using Equation (PA.55) above with no dip ($\theta = 0$) in the ALGEBRA1 step. Within the reservoir, $P_b(x, y, -5) = BPINTPRS$, the uncertain initial pressure in the reservoir (see Table PA-19). Initial gas saturation $S_g(x, y, -5) = 0$.

Within the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $P_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 0$. Within the excavated areas (Waste Panel, South RoR, and North RoR, Ops and Exp), $P_b(x, y, -5) = 1.01325 \times 10^5$ Pa and $S_g(x, y, -5) = 0$.

At the end of the initial five-year start-up period and the beginning of the regulatory period ($t = 0$ years), brine pressure and gas saturation are reset in the shaft, panel closures, and excavated areas. In the shaft (areas Upper Shaft, Lower Shaft, and CONC_MON) and panel closures (areas CONC_PCS and DRF_PCS), $P_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1 \times 10^{-7}$ (see CONC_MON:SAT_IBRN). In the waste disposal regions (areas Waste Panel, South RoR, and North RoR), $P_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 05) = 0.985$ (see WAS_AREA:SAT_IBRN). In the other excavated areas, $P_b(x, y, 0) = 1.01325 \times 10^5$ Pa and $S_g(x, y, 0) = 1.0$.

PA-4.2.3 Creep Closure of Repository

Salt creep occurs naturally in the Salado halite in response to deviatoric stress. Inward creep of rock is generally referred to as creep closure. Creep closure of excavated regions begins immediately from excavation-induced deviatoric stress. If the rooms were empty, closure would proceed to the point where the void volume created by the excavation would be eliminated as the surrounding formation returned to a uniform stress state. In the waste disposal region, inward creep of salt causes consolidation of the waste, and this waste consolidation continues until loading in the surrounding rock is uniform, at which point salt creep and waste consolidation ceases. The amount of waste consolidation that occurs and the time it takes to consolidate are governed by the waste properties (e.g., waste strength, modulus, etc.), the surrounding rock properties, the dimensions and location of the room, and relative quantities of brine and gas present.

The porosity of the waste disposal regions and neighboring access drifts (i.e., Waste Panel, South RoR, North RoR, and DRF_PCS in Figure PA-15) is assumed to change through time due to creep closure of the halite surrounding the excavations. The equations on which BRAGFLO is based do not incorporate this type of deformation. Therefore, the changes in repository porosity due to halite deformation are modeled in a separate analysis with the geomechanical program SANTOS, which implements a quasi-static, large-deformation, finite-element procedure (Stone 1997). Interpolation procedures are then used with the SANTOS results to define porosity (ϕ) within the repository as a function of time, pressure, and gas generation rate.

For more information on the generation of the porosity surface for BRAGFLO in PA, see Appendix PORSURF-2009.

PA-4.2.4 Fracturing of MBs and DRZ

Fracturing within the anhydrite MBs (i.e., regions MB 138, Anhydrite AB, and MB 139 in Figure PA-15) and in the DRZ (region DRZ in Figure PA-15) is assumed to occur at pressures slightly above lithostatic pressure, and is implemented through a pressure-dependent

compressibility $c_r(P_b)$ (Mendenhall and Gerstle 1995). Specifically, MB fracturing begins at a brine pressure of

$$P_{bi} = P_{b0} + \Delta P_i \tag{PA.60}$$

where P_{bi} and P_{b0} are spatially dependent (i.e., $P_{b0} = P(x, y, 0)$ as in Section PA-4.2.2) and $\Delta P_i = 2 \times 10^5$ Pa (see S_MB138:PI_DELTA in Fox 2008, Table 30)

Fracturing ceases at a pressure of

$$P_{ba} = P_{b0} + \Delta P_a \tag{PA.61}$$

and a fully fractured porosity of

$$\phi\left(P_{ba}\right) = \phi_a = \phi_0 + \Delta\phi_a \tag{PA.62}$$

where $\Delta P_a = 3.8 \times 10^6$ Pa (see S_MB138:PF_DELTA in Fox 2008, Table 30), ϕ_0 is spatially dependent (Table PA-3), and $\Delta\phi_a = 0.04$, 0.24, and 0.04 for anhydrite materials S_MB138, S_ANH_AB, and S_MB139, respectively (see S_MB138:DPHIMAX in Fox 2008, Table 30).

Once fractured, compressibility c_r becomes a linear function

$$c_r\left(P_b\right) = c_r + \left(\frac{P_b - P_{bi}}{P_{ba} - P_{bi}}\right)\left(c_{ra} - c_r\right) \tag{PA.63}$$

of brine pressure for $P_{bi} \le P_b \le P_{ba}$, with c_{ra} defined so that the solution ϕ of

$$\frac{d\phi}{dP_b} = c_{ra}(P_b)\phi, \quad \text{where} \quad \phi(P_{bi}) = \phi_0 \exp\left[c_r(P_{bi} - P_{b0})\right] \tag{PA.64}$$

satisfies $\phi(P_{ba}) = \phi_a$; specifically, c_{ra} is given by

$$c_{ra} = c_r\left[1 - \frac{2\left(P_{ba} - P_{b0}\right)}{P_{ba} - P_{bi}}\right] + \left[\frac{2}{P_{ba} - P_{bi}}\right]\ln\left(\frac{\phi_a}{\phi_0}\right) \tag{PA.65}$$

The permeability $k_f(P_b)$ of fractured material at brine pressure P_b is related to the permeability of unfractured material at brine pressure P_{bi} by

$$k_f(P_b) = \left[\frac{\phi(P_b)}{\phi(P_{bi})}\right]^n k \tag{PA.66}$$

where k is the permeability of unfractured material (i.e., at P_{bi}) and n is defined so that $k_f(P_{ba}) = 1 \times 10^{-9}$ m^2 (i.e., n is a function of k, which is an uncertain input to the analysis; see ANHPRM in Table PA-19). When fracturing occurs, $k_f(P_b)$ is used instead of k in the definition of the permeability for the fractured areas of the anhydrite MBs.

Fracturing is also modeled in the DRZ region in Figure PA-15. The fracture model implementation is the same as for the anhydrite materials. In this case, fracturing would be in halite rather than anhydrite, but because of the limited extent of the DRZ and the proximity of the nearby interbeds, this representation was deemed acceptable by the Salado Flow Peer Review panel (Caporuscio, Gibbons, and Oswald 2003).

PA-4.2.5 Gas Generation

Gas production is assumed to result from anoxic corrosion of steel and the microbial degradation of CPR materials. Thus, the gas generation rate q_{rg} in Equation (PA.24) is of the form

$$q_{rg} = q_{rgc} + q_{rgm} \tag{PA.67}$$

where q_{rgc} is the rate of gas production per unit volume of waste (kg/m^3/s) due to anoxic corrosion of Fe-base metals, and q_{rgm} is the rate of gas production per unit volume of waste (kg/m^3/s) due to microbial degradation of CPR materials. Furthermore, q_{rb} in Equation (PA.25) is used to describe the consumption of brine during the corrosion process.

Gas generation takes place only within the waste disposal regions (i.e., Waste Panel, South RoR, and North RoR in Figure PA-15) and all the generated gas is assumed to have the same properties as H_2 (see discussion in Appendix MASS-2009, Section MASS-3.2). In PA, the consumable materials are assumed to be homogeneously distributed throughout the waste disposal regions (i.e., the concentration of Fe-base metals and CPR materials in the waste is not spatially dependent). A separate analysis examined the potential effects on PA results of spatially varying Fe-base metal and CPR material concentrations, and concluded that PA results are not affected by representing these materials with spatially varying concentrations (see Appendix MASS-2009, Section MASS-21.0).

The rates q_{rgc}, q_{rb}, and q_{rgm} (kg/m^3/s) are defined by

gas generation by corrosion

$$q_{rgc} = \left(R_{ci} S_{b,eff} + R_{ch} S_g^*\right) D_s \rho_{Fe} X_c\left(\mathrm{H_2}\,|\,\mathrm{Fe}\right) M_{\mathrm{H_2}} \tag{PA.68}$$

brine consumption by corrosion

$$q_{rb} = \left(q_{rgc} / M_{\mathrm{H_2}}\right) X_c\left(\mathrm{H_2O}\,|\,\mathrm{H_2}\right) M_{\mathrm{H_2O}} \tag{PA.69}$$

and microbial gas generation

$$q_{rgm} = \left(R_{mi} S_{b,eff} + R_{mh} S_g^*\right) D_c \, y\left(\mathrm{H_2}\middle|C\right) M_{\mathrm{H_2}} \; B_{fc} \qquad \text{(PA.70)}$$

where

D_s = surface area concentration of steel in the repository (m^2 surface area steel/ m^3 disposal volume)

D_c = mass concentration of cellulosics in the repository (kg biodegradable material/m^3 disposal volume)

$M_{\mathrm{H_2}}$ = molecular weight of H_2 (kg H_2/mol H_2)

$M_{\mathrm{H_2O}}$ = molecular weight of water (H_2O) (kg H_2O/mol H_2O)

R_{ci} = corrosion rate under inundated conditions (m/s)

R_{ch} = corrosion rate under humid conditions (m/s)

R_{mi} = rate of cellulose biodegradation under inundated conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s)

R_{mh} = rate of cellulose biodegradation under humid conditions (mol $C_6H_{10}O_5$/kg $C_6H_{10}O_5$/s)

$S_{b,eff}$ = effective brine saturation due to capillary action in the waste materials (see Equation (PA.90) in Section PA-4.2.6)

$$S_g^* = \begin{cases} 1 - S_{b,eff} & \text{if } S_{b,eff} > 0 \\ 0 & \text{if } S_{b,eff} = 0 \end{cases}$$

$X_c\left(\mathrm{H_2}\middle|\mathrm{Fe}\right)$ = stoichiometric coefficient for gas generation due to corrosion of steel, i.e., moles of H_2 produced by the corrosion of 1 mole of Fe (mol H_2/mol Fe)

$X_c\left(\mathrm{H_2O}\middle|\mathrm{H_2}\right)$ = stoichiometric coefficient for brine consumption due to corrosion of steel, i.e., moles of H_2O consumed per mole of H_2 generated by corrosion (mol H_2O/mol H_2)

$y\left(\mathrm{H_2}\middle|C\right)$ = average stoichiometric factor for microbial degradation of cellulose, i.e., the moles of H_2 generated per mole of carbon consumed by microbial action (mol H_2/mol C)

ρ_{Fe} = molar density of steel (mol/m^3)

B_{fc} = parameter (WAS_AREA:BIOGENFC; discussed in detail later in this section) uniformly sampled from 0 to 1, used to account for the uncertainty in whether microbial gas generation could be realized in the WIPP at experimentally measured rates.

The products $R_{ci}\, D_s\, \rho_{Fe}\, X_c$, $R_{ch}\, D_s\, \rho_{Fe}\, X_c$, $R_{mi}\, D_c\, y$, and R_{mh} in Equation (PA.68) and Equation (PA.70) define constant rates of gas generation (mol/m^3/s) that continue until the associated substrate (i.e., steel or cellulose) is exhausted (i.e., zero order kinetics are assumed). The terms $S_{b,eff}$ and S_g^* in Equation (PA.68) and Equation (PA.70), which are functions of location and time, correct for the amount of substrate exposed to inundated and humid conditions, respectively. All the corrosion and microbial action is assumed to cease when no brine is present, which is the reason that 0 replaces $S_g = 1$ in the definition of S_g^*. In PA, $R_{ch} = 0$ and R_{ci}, R_{mh}, and R_{mi} are defined by uncertain variables (see WGRCOR, WGRMICH, WGRMICI in Table PA-19). However, R_{mh} is now sampled based on the sampled value of R_{mi}: see Nemer and Clayton (2008, Section 5.1.3). Further, $M_{H_2} = 2.02 \times 10^{-3}$ kg/mol (Lide 1991, pp. 1-7, 1-8), $M_{H_2O} = 1.80 \times 10^{-2}$ kg/mol (Lide 1991, pp. 1-7, 1-8), $\rho_{Fe} = 1.41 \times 10^5$ mol/m^3 (Telander and Westerman 1993), and D_s, D_c, $X_c(H_2O|H_2)$, $X_c(H_2|Fe)$, and $y(H_2|C)$ are discussed below.

The concentration D_s in Equation (PA.68) is defined by

$$D_s = A_d n_d / V_R \qquad \text{(PA.71)}$$

where

A_d = surface area of steel associated with a waste disposal drum (m^2/drum)
V_R = initial volume of a single room in the repository (m^3)
n_d = ideal number of waste drums that can be close-packed into a single room

In PA, $A_d = 6$ m^2/drum (REFCON:ASDRUM), $V_R = 3{,}644$ m^3 (REFCON:VROOM), and $n_d =$ 6804 drums (REFCON:DRROOM).

The biodegradable materials to be disposed at the WIPP consist of cellulosic materials, plastics, and rubbers. Cellulosics have been demonstrated experimentally to be the most biodegradable of these materials (Francis, Gillow, and Giles 1997). The occurrence of significant microbial gas generation in the repository will depend on whether (1) microbes capable of consuming the emplaced organic materials will be present and active, (2) sufficient electron acceptors will be present and available, and (3) enough nutrients will be present and available.

During the CRA-2004 PABC, the EPA (Cotsworth 2005) indicated that the probability that microbial gas generation could occur (WMICDFLG) should be set equal to 1 in PA calculations. In the CRA-2004, the probability that microbial gas generation could occur was assigned a value of 0.5. To comply with the EPA's letter, in the CRA-2004 PABC and the CRA-2009 PA the parameter WMICDFLG was changed so that the probability that microbial gas generation could occur was set to 1 while preserving the previous probability distribution on whether CPR could be degraded. This is summarized in Table PA-6, and is discussed further in Nemer and Stein

Table PA-6. Probabilities for Biodegradation of Different Organic Materials (WAS_AREA:PROBDEG) in the CRA-2009 PA and the CRA-2004 PA

WAS_AREA:PROBDEG	Meaning	Probability CRA-2004	Probability CRA-2009
0	No microbial degradation can occur	0.5	0.0
1	Biodegradation of only cellulose can occur	0.25	0.75
2	Biodegradation of CPR materials can occur	0.25	0.25

(2005, Section 5.4). Because there are significant uncertainties in whether the experimentally observed gas-generation rates could be realized in the WIPP repository, during the CRA-2004 PABC the EPA agreed to allow the DOE to multiply the sampled microbial rates by a parameter (WAS_AREA:BIOGENFC) uniformly sampled from 0 to 1. This is discussed further in Nemer, Stein, and Zelinski (2005, Section 4.2.2).

In cases where biodegradation of rubbers and plastics occur, rubbers and plastics are converted to an equivalent quantity of cellulosics based on their carbon equivalence (Wang and Brush 1996a). This produces the density calculation

$$D_c = \begin{cases} m_{cel} / V_R & \text{for biodegradation of cellulosics only} \\ \left(m_{cel} + m_r + 1.7 m_p \right) / V_R & \text{for biodegradation of CPR materials} \end{cases} \quad \text{(PA.72)}$$

where m_{cel} is the mass of cellulosics (kg), m_r is the mass of rubbers (kg), and m_p is the mass of plastics (kg).

In the CRA-2009 PA, the emplacement materials (cellulose and plastic) have been added to m_{cel} and m_p. This is discussed further in Nemer and Clayton (2008, Section 5.1.1). Density values for CPR materials can be found in Fox (2008, Table 34).

The most plausible corrosion reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

$$Fe + 2H_2O = Fe(OH)_2 + H_2 \quad \text{(PA.73)}$$

and

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2 \quad \text{(PA.74)}$$

When normalized to 1 mole of Fe and linearly weighted by the factors x and $1 - x$ $\left(0 \le x \le 1\right)$, the two preceding reactions become

$$\mathrm{Fe}+\left(\frac{4+2x}{3}\right)\mathrm{H_2O}=\left(\frac{4-x}{3}\right)\mathrm{H_2}+x\mathrm{Fe(OH)_2}+\left(\frac{1-x}{3}\right)\mathrm{Fe_3O_4} \quad \text{(PA.75)}$$

where x and $1-x$ are the fractions of Fe consumed in the reactions in Equation (PA.73) and Equation (PA.74), respectively. Although magnetite (Fe_3O_4) has been observed to form on Fe as a corrosion product in low-Mg anoxic brines at elevated temperatures (Telander and Westerman 1997) and in oxic brine (Haberman and Frydrych 1988), there is no evidence that it will form at WIPP repository temperatures. If Fe_3O_4 were to form, H_2 would be produced (on a molar basis) in excess of the amount of Fe consumed. However, anoxic corrosion experiments (Telander and Westerman 1993) did not indicate the production of H_2 in excess of the amount of Fe consumed. Therefore, the stoichiometric factor x in Reaction (PA.75) is set to 1.0 (i.e., x = 1), which implies that Reaction (PA.73) represents corrosion. Thus, the stoichiometric factor for corrosion is

$$X_c\left(\mathrm{H_2}\middle|\mathrm{Fe}\right)=\left(4-x\right)/3=1\ \mathrm{mol/mol} \quad \text{(PA.76)}$$

which implies that one mole of H_2 is produced for each mole of Fe consumed, and the stoichiometric factor for brine consumption is

$$X_c\left(\mathrm{H_2O}\middle|\mathrm{H_2}\right)=\left(4+2x\right)/3=2\ \mathrm{mol/mol} \quad \text{(PA.77)}$$

which implies that two moles of H_2O are consumed for each mole of H_2 produced.

The most plausible biodegradation reactions after closure of the WIPP are believed to be (Wang and Brush 1996a)

denitrification $\mathrm{C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- = 7.4H_2O + 6CO_2 + 2.4N_2}$ (PA.78)

sulfate reduction $\mathrm{C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} = 5H_2O + 6CO_2 + 3H_2S}$ (PA.79)

methanogenesis $\mathrm{C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2}$ (PA.80)

Accumulation of CO_2 produced by the above reactions could decrease pH and add carbonate to increase An solubility in the repository (Wang and Brush 1996b).

However, in the CRA-2004 PABC, the EPA (Cotsworth 2005) directed the DOE to remove methanogenesis (Equation (PA.80)) from PA. The EPA cited the presence of calcium sulfate as gypsum and anhydrite in the bedded salt surrounding the repository as possible sources of sulfate. These sources of sulfate would, if accessible, promote sulfate reduction (Equation (PA.82)), which is energetically and kinetically favored over methanogenesis. In response, the DOE removed methanogenesis from PA. Additionally, the DOE removed Fe sulfidation from PA as a gas-consuming reaction because sulfidation of steel produces one mole of H_2 for every mole of H_2S consumed,

$$\mathrm{Fe + H_2S = FeS + H_2} \quad \text{(PA.81)}$$

This and the removal of methanogenesis are discussed fully in Nemer and Zelinski (2005).

To provide added assurance of WIPP performance, a sufficient amount of MgO is added to the repository to remove CO_2 (Bynum et al. 1997). MgO in polypropylene "supersacks" is emplaced on top of the three-layer waste stacks to create conditions that reduce An solubilities in the repository (see Appendix MgO-2009 and Appendix SOTERM-2009, Section SOTERM-2.3). If brine flows into the repository, MgO will react with water in brine and in the gaseous phase to produce brucite ($Mg[OH]_2$). MgO will react with essentially all of the CO_2 that could be produced by complete microbial consumption of the CPR materials in the waste, and will create hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ (Appendix MgO-2009; Appendix SOTERM-2009, Section SOTERM-2.0). The most important MgO hydration and carbonation reactions that will occur in the WIPP are

$$MgO + H_2O(\text{aq and/or g}) \rightarrow Mg(OH)_2 \tag{PA.82}$$

$$5Mg(OH)_2 + 4CO_2(\text{aq and/or g}) \rightarrow Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O \tag{PA.83}$$

In these equations, "aq and/or g" indicates that the H_2O or CO_2 that reacts with MgO and/or brucite could be present in the aqueous phase (brine) and/or the gaseous phase. The removal of CO_2 by MgO is not explicitly modeled as a separate reaction in PA. Rather, the effect of CO_2 consumption is accounted for by modifying the stoichiometry of Reaction (PA.78), Reaction (PA.79), and Reaction (PA.80) to remove the CO_2 from the mass of gas produced by microbial action.

The average stoichiometry of Reaction (PA.78), Reaction (PA.79), and Reaction (PA.80), is

$$C_6H_{10}O_5 + \text{unknowns} = 6y\ \text{(mol) gas} + \text{unknowns} \tag{PA.84}$$

where the average stoichiometric factor y in Reaction (PA.84) represents the number of moles of gas produced and retained in the repository from each mole of carbon consumed. This factor y depends on the extent of the individual biodegradation pathways in Reaction (PA.84), and the consumption of CO_2 by MgO. A range of values for y is estimated by considering the maximum mass of gas that can be produced from consumption of cellulosics (M_{cel}) and Fe-base metals (M_{Fe}), and is derived as follows (Wang and Brush 1996b). Estimates of the maximum quantities M_{cel} and M_{Fe} (mol) of cellulosics (i.e., $C_6H_{10}O_5$) and steels that can be potentially consumed in 10,000 years are given by

$$M_{cel} = \min\left\{\frac{6000 m_{cel}}{162},\ 3.2\times10^{11} R_m m_{cel}\right\} \tag{PA.85}$$

$$M_{Fe} = \min\left\{\frac{1000 m_{Fe}}{56},\ 4.4\times10^{16} R_{ci} A_d n_d\right\} \tag{PA.86}$$

where m_{cel} and m_{Fe} are the masses (kg) of cellulosics (see Equation (PA.72) for definition) and steels initially present in the repository. The mass of cellulosics that can be consumed is

determined by the uncertain parameter WMICDFLG (see Table PA-19). The mass of steels m_{Fe} = 5.16 × 10^7 kg; this value is calculated as

$$V_{CH}\left(\rho_{WCH}+\rho_{CCH}\right)+V_{RH}\left(\rho_{WRH}+\rho_{CRH}\right) \quad \text{(PA.87)}$$

where V_{CH} and V_{RH} are the volumes of CH-TRU and RH-TRU waste, ρ_{WCH} and ρ_{WRH} are the Fe densities in CH-TRU and RH-TRU waste, and ρ_{CCH} and ρ_{CRH} are the Fe densities of the containers of CH-TRU and RH-TRU waste (see Fox 2008, Table 34). The terms 6000 m_{cel}/162 and 1000 m_{Fe}/56 in Equation (PA.85) and Equation (PA.86) equal the inventories in moles of cellulosics and steel, respectively. The terms 3.2 × 10^{11} $R_m m_{cel}$ and 4.4 × 10^{16} $R_{ci} A_d n_d$ equal the maximum amounts of cellulosics and steel that could be consumed over 10,000 years. In Equation (PA.85), $R_m = \max\{R_{mh}, R_{mi}\}$, where R_{mh} and R_{mi} are defined by uncertain variables (see WGRMICH and WGRMICI in Table PA-19, respectively), and 3.2 × 10^{11} = (3.15569 × 10^7 s/yr) (10^4 yr). In Equation (PA.86), $A_d n_d$ is the total surface area of all drums (m^2) and the factor 4.4 × 10^{16} = (3.15569 × 10^7 s/yr) (10^4 yr) (1.41 × 10^5 mol/ m^3), where ρ_{Fe} = 1.41 × 10^5 mol/m^3 (see Equation (PA.72)) (Telander and Westerman 1993), converts the corrosion rate from m/s to mol/m^2/s.

A range of possible values for the average stoichiometric factor y in Reaction (PA.84) can be obtained by considering individual biodegradation pathways involving M_{cel} and accounting for the removal of CO_2 by the MgO.

In the absence of methanogenesis and steel sulfidation, y from Equation (PA.84) becomes

$$y = \frac{\left[\frac{2.4}{4.8}M_{NO3} + \frac{1}{2}\left(M_{cel} - \frac{6}{4.8}M_{NO3}\right)\right]}{M_{cel}} \quad \text{(PA.88)}$$

$$M_{NO3} = \min\left\{M^0_{NO3}, \frac{4}{5}M_{cel}\right\} \quad \text{(PA.89)}$$

where M^0_{NO3} is the quantity of NO_3^- (mols) initially present in the repository. Specifically, M^0_{NO3} = 4.31 × 10^7 mol (Fox 2008, Table 39).

PA-4.2.6 Capillary Action in the Waste

Capillary action (wicking) is the ability of a material to carry a fluid by capillary forces above the level it would normally seek in response to gravity. In the current analysis, this phenomena is accounted for by defining an effective saturation given by

$$S_{b,eff} = \begin{cases} S_b - S_{min} + S_{wick}\left(1 - \mathrm{Exp}\left(200\alpha\left(\mathrm{Max}\left(S_b - S_{min}, 0\right)\right)^2\right)\right) & \text{if } 0 < S_b \le 1 - S_{wick} + S_{min} \\ 0 & \text{if } S_b \le S_{min} \\ 1 & \text{if } S_b > 1 - S_{wick} + S_{min} \end{cases} \quad \text{(PA.90)}$$

where

$S_{b,eff}$ = effective brine saturation
S_b = brine saturation
S_{wick} = wicking saturation
S_{min} = minimum brine saturation at which code can run in the waste-filled areas
α = smoothing parameter = –1000

The effective saturation given by Equation (PA.90) differs from that in the CRA-2004 PA in that $S_{b,eff}$ now approaches zero as S_b approaches a small value S_{min}. In simulations where Fe corrosion dried out the repository, the time required to complete the simulation could be quite long. In order to speed up the code and increase robustness, the parameter S_{min} was added. For PA, S_{min} = 0.015, which was small enough to not affect the results, while greatly reducing run time. This is explained fully in Nemer and Clayton (2008, Section 5.2.2).

The effective saturation is used on a grid block basis within all waste regions (Waste Panel, South RoR, and North RoR in Figure PA-15). The wicking saturation, S_{wick}, is treated as an uncertain variable (see WASTWICK in Table PA-19). The effective brine saturation $S_{b,eff}$ is currently used only to calculate the corrosion of steel (Equation (PA.68)) and the microbial degradation of cellulose (Equation (PA.70)), and does not directly affect the two-phase flow calculations indicated.

PA-4.2.7 Shaft Treatment

The WIPP excavation includes four shafts that connect the repository region to the surface: the air intake shaft, salt handling shaft, waste handling shaft, and exhaust shaft. In PA, these four shafts are modeled as a single shaft. The rationale for this modeling treatment is set forth in SNL (Sandia National Laboratories 1992, Volume 5, Section 2.3).

The shaft seal model included in the PA grid (Column 43 in Figure PA-15) is the simplified shaft model used in the CRA-2004 PA and the CRA-2004 PABC. The simplified shaft seal model used in PA is described by Stein and Zelinski (2003) and is briefly discussed below; this model was approved by the Salado Flow Peer Review Panel (Caporuscio, Gibbons, and Oswald 2003).

The planned design of the shaft seals involves numerous materials, including earth, crushed salt, clay, asphalt, and Salado Mass Concrete (SMC) (see the CCA, Appendix SEAL). The design is intended to control both short-term and long-term fluid flow through the Salado portion of the

shafts. For the CCA PA, each material in the shaft seal was represented in the BRAGFLO grid. Analysis of the flow results from the CCA PA and the subsequent CCA PAVT (Sandia National Laboratories 1997 and U.S. Department of Energy 1997) indicated that no significant flows of brine or gas occurred in the shaft during the 10,000-year regulatory period. As a result of these analyses, a simplified shaft seal model was developed for the CRA-2004 PA.

A conceptual representation of the simplified shaft seal system used in PA is shown in Figure PA-18. The simplified model divides the shaft into three sections: an upper section (shaft seal above the Salado), a lower section (within the Salado), and a concrete monolith section within the repository horizon. A detailed discussion of how the material properties were assigned for the simplified shaft seal model is included in James and Stein (2003). The permeability value used to represent the upper and lower sections is defined as the harmonic mean of the component materials' permeability in the detailed shaft seal model (including permeability adjustments made for the DRZ assumed to surround the lower shaft seal section within the Salado). Porosity is defined as the thickness-weighted mean porosity of the component materials. Other material properties are described in James and Stein (2003).

The lower section of the shaft experiences a change in material properties at 200 years. This change simulates the consolidation of seal materials within the Salado and significantly decreases permeability. This time was chosen as a conservative overestimate of the amount of time expected for this section of the shaft to become consolidated. The concrete monolith section of the shaft is unchanged from the CCA PA and is represented as being highly permeable for 10,000 years to ensure that fluids can access the north end (operations and experimental areas) in the model. In three thin regions at the stratigraphic position of the anhydrite MBs, the shaft seal is modeled as MB material (Figure PA-18). This model feature is included so that fluids flowing in the DRZ and MB fractures can access the interbeds to the north of the repository "around" the shaft seals. Because these layers are so thin, they have virtually no effect on the effective permeability of the shaft seal itself.

The simplified shaft model was tested in the AP-106 analysis (Stein and Zelinski 2003), which supports the Salado Flow Peer Review (Caporuscio, Gibbons, and Oswald 2003). The results of the AP-106 analysis demonstrate that vertical brine flow through the simplified shaft model is comparable to brine flows seen through the detailed shaft model used in the CCA PA and subsequent CCA PAVT calculations.

PA-4.2.8 Option D Panel Closures

PA includes panel closures models that represent the Option D panel closure design (see the CRA-2004, Chapter 6.0, Section 6.4.3), which are unchanged from the CRA-2004. Option D closures (Figure PA-19) are designed to allow minimal fluid flow between panels. PA explicitly represents selected Option D panel closures in the computational grid using a model approved by the Salado Flow Peer Review Panel (Caporuscio, Gibbons, and Oswald 2003). The Option D panel closure design has several components: an SMC monolith, which extends into the DRZ in all directions; an empty drift section; and a block and mortar explosion wall (Figure PA-19). Each set of panel closures are represented in the BRAGFLO grid by 4 materials in 13 grid cells (Figure PA-20):

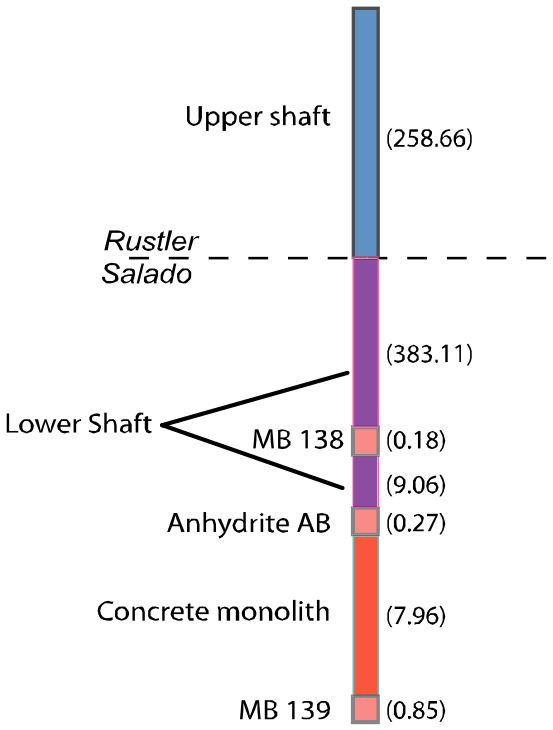


Figure PA-18. Schematic View of the Simplified Shaft Model (numbers on right indicate dimensions in meters)

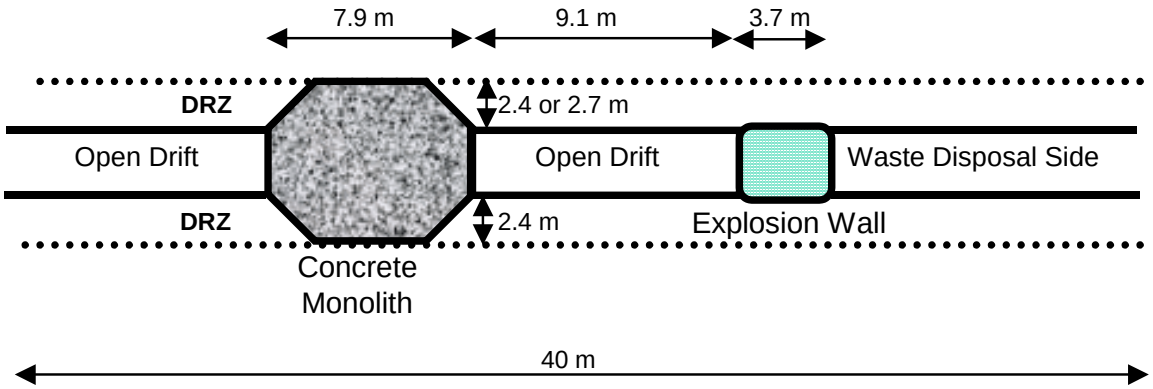


Figure PA-19. Schematic Side View of Option D Panel Closure

- Six cells of panel closure concrete (area CONC_PCS, material CONC_PCS)
- One cell above and one cell below the concrete material consisting of MB anhydrite (areas MB 139 and Anhydrite AB, materials S_MB139 and S_ANH_AB, respectively)
- Two cells of healed DRZ above Anhydrite AB and the panel closure system (PCS) (area DRZ_PCS, material DRZ_PCS)
- Three cells of empty drift and explosion wall (area DRF_PCS, material DRF_PCS)

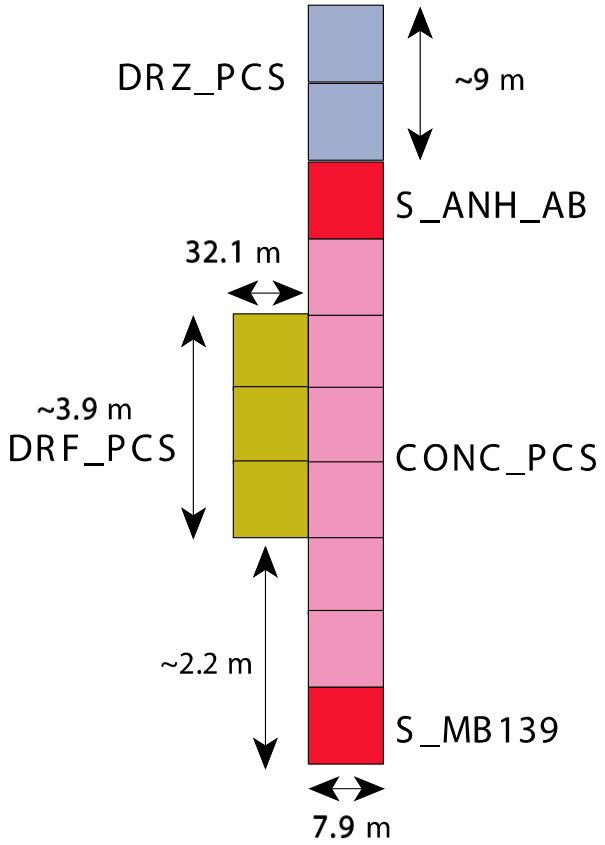


Figure PA-20. Representation of Option D Panel Closures in the BRAGFLO Grid

Properties for the materials making up the panel closure system are listed in Table PA-3.

PA-4.2.8.1 Panel Closure Concrete

The Option D panel closure design requires the use of a salt-saturated concrete, identified as SMC, as specified for the shaft seal system. The design of the shaft seal system and the properties of SMC are described in the CCA, Appendix SEAL. The BRAGFLO grid incorporates the material CONC_PCS, which is assigned the material properties of undegraded SMC and is used to represent the concrete portion of the Option D panel closure system (Figure PA-15). A double-thickness concrete segment represents the northernmost set of panel closures (between the north RoR and the operations area). This feature represents the two sets of panel closures in series that will be emplaced between the waste-filled repository and the shaft.

PA-4.2.8.2 Panel Closure Abutment with MBs

In the BRAGFLO grid, regions where the Option D panel closures intersect the MBs are represented as blocks of MB material (Figure PA-15). This representation is warranted for two reasons:

1. The MB material has a very similar permeability distribution (10^{-21} to $10^{-17.1}$ m^2) to the concrete portion of the Option D panel closures ($10^{-20.699}$ to 10^{-17} m^2), and thus, assigning

this material as anhydrite MB in the model has essentially the same effect as calling it concrete, as long as pressures are below the fracture initiation pressure.

2. In the case of high pressures, it is expected that fracturing may occur in the anhydrite MBs and flow could go "around" the panel closures and out of the two-dimensional plane considered in the model grid. In this case, the flow would be through the MB material, which incorporates a fracture model, as described above.

PA-4.2.8.3 DRZ Above the Panel Closure

After constructing the concrete portion of the panel closure, the salt surrounding the monolith will be subjected to compressive stresses, which will facilitate the rapid healing of disturbed halite. The rounded configuration of the monolith creates a situation very favorable for concrete durability: high compressive stresses and low stress differences. In turn, the compressive stresses developed within the salt will quickly heal any damage caused by construction excavation, thereby eliminating the DRZ along this portion of the panel closure. The permeability of the salt immediately above and below the rigid concrete monolith component of Option D will approach the intrinsic permeability of the undisturbed Salado halite.

To represent the DRZ above the monoliths, PA uses the material DRZ_PCS in the BRAGFLO grid (Figure PA-15). The values assigned to DRZ_PCS are the same as those used for the DRZ above the excavated areas (material DRZ_1, see Table PA-3), except for the properties PRMX_LOG, PRMY_LOG, and PRMZ_LOG, the logarithms of permeability in the x, y, and z directions, respectively. These permeability values are assigned the same distributions used for the material CONC_PCS. In this instance, the values are based on the nature of the model setup, not directly on experimental data (although the general range of the distribution agrees with experimental observations of healed salt). The use of these permeabilities ensures that any fluid flow is equally probable through or around the Option D panel closures, and represents the range of uncertainty that exists in the performance of the panel closure system.

PA-4.2.8.4 Empty Drift and Explosion Wall Materials

The DRF_PCS is the material representing the empty drift and explosion wall. For simplicity, this material is assumed to have hydrologic properties equivalent to the material representing the waste panel and is used for the three sets of panel closures represented in the grid (Figure PA-15). The creep closure model is applied to this material to be consistent with the neighboring materials. The assignment of a high permeability to this region for the PA calculations, which contains the explosion wall, is justified because the explosion wall is not designed to withstand the stresses imposed by creep closure beyond the operational period and will be highly permeable following rapid room closure.

PA-4.2.9 Borehole Model

The major disruptive event in PA is the penetration of the repository by a drilling intrusion. In the undisturbed scenario (see Section PA-6.7.1), these blocks have the material properties of the neighboring stratigraphic or excavated modeling unit, and there is no designation in the borehole grid except for the reduced lateral dimensions of this particular column of grid blocks.

In the scenarios simulating drilling disturbance, these cells start out with the same material properties as in the undisturbed scenario, but at the time of intrusion, the borehole grid blocks are reassigned to borehole material properties. The drilling intrusion is modeled by modifying the permeability of the grid blocks in Column 26 of Figure PA-15 (values listed in Table PA-7). Furthermore, the drilling intrusion is assumed to produce a borehole with a diameter of 12.25 in. (0.31 m) (Vaughn 1996, Howard 1996), borehole fill is assumed to be incompressible, capillary effects are ignored, residual gas and brine saturations are set to zero, and porosity is set to 0.32 (see materials CONC_PLG, BH_OPEN, BH_SAND, and BH_CREEP in Table PA-3). When a borehole that penetrates pressurized brine in the Castile is simulated (i.e., an E1 intrusion), the permeability modifications indicated in Table PA-7 extend from the ground surface (i.e., Grid Cell 2155 in Figure PA-17) to the base of the pressurized brine (i.e., Grid Cell 2225 in Figure PA-17). When a borehole that does not penetrate pressurized brine in the Castile is under consideration (i.e., an E2 intrusion), the permeability modifications indicated in Table PA-7 stop at the bottom of the lower DRZ (i.e., Grid Cell 1111 in Figure PA-17).

PA-4.2.10 Castile Brine Reservoir

High-pressure Castile brine was encountered in several WIPP-area boreholes, including the WIPP-12 borehole within the controlled area and the ERDA-6 borehole northeast of the site. Consequently, the conceptual model for the Castile includes the possibility that brine reservoirs underlie the repository. The E1 and E1E2 scenarios include borehole penetration of both the repository and a brine reservoir in the Castile.

Unless a borehole penetrates both the repository and a brine reservoir in the Castile, the Castile is conceptually unimportant to PA because of its expected low permeability. Two regions are specified in the disposal system geometry of the Castile horizon: the Castile (Rows 1 and 2 in

Table PA-7. Permeabilities for Drilling Intrusions Through the Repository

Time After Intrusion	Assigned Permeabilities
0–200 years	Concrete plugs are assumed to be emplaced at the Santa Rosa (i.e., a surface plug with a length of 15.76 m; corresponds to Grid Cells 2113, 2155 in Figure PA-17) and the Los Medaños Member of the Rustler (i.e., a plug at the top of the Salado with a length of 36 m; corresponds to Grid Cell 1644 in Figure PA-17). Concrete plugs are assumed to have a permeability log-uniformly sampled between 10^{-19} m^2 to $10^{-17}$$m^2$ (see material CONC_PLG in Table PA-4). The open portions of the borehole are assumed to have a permeability of 1×10^{-9} m^2.
200–1200 years	Concrete plugs are assumed to fail after 200 years (U.S. Department of Energy 1995). An entire borehole is assigned a permeability typical of silty sand log-uniformly sampled between $10^{-16.3}$ m^2 and 10^{-11} m^2 (see parameter BHPRM in and material BH_SAND in Table PA-4).
> 1200 years	Permeability of borehole reduced by one order of magnitude in the Salado beneath the repository due to creep closure of borehole (Thompson et al. 1996) (i.e., $k = 10^x/10$, x = BHPRM, in Grid Cells 2225, 1576, 26, 94, 162, 230 of Figure PA-17). No changes are made within and above the lower DRZ (see material BH_CREEP in Table PA-4).

Figure PA-15) and a reservoir (Row 1, Columns 23 to 45 in Figure PA-15). The Castile region has an extremely low permeability, which prevents it from participating in fluid flow processes.

It is unknown whether a brine reservoir exists below the repository. As a result, the conceptual model for the brine reservoirs is somewhat different from those for known major properties of the natural barrier system, such as stratigraphy. The principal difference is that a reasonable treatment of the uncertainty of the existence of a brine reservoir requires assumptions about the spatial distribution of such reservoir and the probability of intersection (see Attachment MASS-2009, Section MASS.18.1). A range of probabilities for a borehole hitting a brine reservoir is used (see Section PA-3.6).

In addition to the stochastic uncertainty in the location and hence in the probability of intersecting reservoirs, there is also uncertainty in the properties of reservoirs. The manner in which brine reservoirs would behave if penetrated is captured by parameter ranges and is incorporated in the BRAGFLO calculations of disposal system performance. The conceptual model for the behavior of such a brine reservoir is discussed below. The properties specified for brine reservoirs are pressure, permeability, compressibility, and porosity, and are sampled from parameter ranges (see Table PA-19).

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures, and therefore not producing brine. Castile brine reservoirs occur in the upper portion of the Castile (Popielak et al. 1983). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the existence of the interconnection between them. Data from WIPP-12 and ERDA-6 indicate that fractures have a variety of apertures and permeabilities, and they deplete at different rates. Brine occurrences in the Castile behave as reservoirs; that is, they are bounded systems.

PA-4.2.11 Numerical Solution

Determining gas and brine flow in the vicinity of the repository requires solving the two nonlinear PDEs in Equation (PA.24) through Equation (PA.30) on the computational domain in Figure PA-15, along with evaluating appropriate auxiliary conditions. The actual unknown functions in this solution are P_b and S_g, although the constraint conditions also give rise to values for P_g and S_b. As two dimensions in space and one dimension in time are in use, P_b, P_g, S_b, and S_g are functions of the form $P_b(x, y, t)$, $P_g(x, y, t)$, $S_b(x, y, t)$, and $S_g(x, y, t)$.

Solving Equation (PA.24) through Equation (PA.30) requires both initial value and boundary value conditions for P_b and S_g. The initial value conditions for P_b and S_g are given in Section PA-4.2.2. As indicated there, the calculation starts at time $t = -5$ years, with a possible resetting of values at $t = 0$ years, which corresponds to final waste emplacement and sealing of the repository. The boundary conditions are such that no brine or gas moves across the exterior grid boundary (Table PA-8). This Neumann-type boundary condition is maintained for all time. Further, BRAGFLO allows the user to maintain a specified pressure and/or saturation at any grid

Table PA-8. Boundary Value Conditions for P_g and P_b

Boundaries below (Row 1, y = 0 m) and above (Row 33, y = 1039 m) system for $0 \le x \le 46630$ m (Columns 1-68) and -5 yr ≤ t. Below, *j* refers to the unit normal vector in the positive *y* direction.	
$\left(\nabla P_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{j} = 0$ Pa / *m*	No gas flow condition
$\left(\nabla P_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{j} = 0$ Pa / *m*	No brine flow condition
Boundaries at left (Column 1, $x = 0$ m) and right (Column 68, $x = 46630$ m) of system for $0 \le y \le 1039$ m (Rows 1-33) and -5 yr ≤ t. Below, *i* refers to the unit normal vector in the positive x direction.	
$\left(\nabla P_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{i} = 0$ Pa / *m*	No gas flow condition
$\left(\nabla P_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{i} = 0$ Pa / *m*	No brine flow condition

block. This is not a boundary condition and is not required to close the problem. This feature is used to specify Dirichlet-type conditions at the surface grid blocks (Columns 1-68, Row 33, Figure PA-15) and at the far-field locations in the Culebra and Magenta (Columns 1 and 68, Row 26, and Columns 1 and 68, Row 28, Figure PA-15). These auxiliary conditions are summarized in **Error! Not a valid bookmark self-reference.**.

A fully implicit finite-difference procedure is used to solve Equation (PA.24) through Equation (PA.30). The associated discretization of the gas mass balance equation is given by

$$\frac{1}{\Delta x_i}\left\{\frac{1}{x_{i+1}-x_i}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i+1/2,j}\left(\Phi^{x-}_{g_{i+1,j}} - \Phi^{x+}_{g_{i,j}}\right)^{n+1}\right.$$

$$\left. - \frac{1}{x_i - x_{i-1}}\left[\frac{\alpha\rho_g k_x k_{rg}}{\mu_g}\right]^{n+1}_{i-1/2,j}\left(\Phi^{x-}_{g_{i,j}} - \Phi^{x+}_{g_{i-1,j}}\right)^{n+1}\right\}$$

$$+ \frac{1}{\Delta y_j}\left\{\frac{1}{y_{j+1}-y_j}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]^{n+1}_{i,j+1/2}\left(\Phi^{y-}_{g_{i,j+1}} - \Phi^{y+}_{g_{i,j}}\right)^{n+1}\right.$$

$$\left. - \frac{1}{y_j - y_{j-1}}\left[\frac{\alpha\rho_g k_y k_{rg}}{\mu_g}\right]^{n+1}_{i,j-1/2}\left(\Phi^{y-}_{g_{i,j}} - \Phi^{y+}_{g_{i,j-1}}\right)^{n+1}\right\}$$

Table PA-9. Auxiliary Dirichlet Conditions for S_g and P_b

Surface Grid Blocks	
$S_g(i,j,t) = 0.08363$	Columns 1–42, 44–68, Row 33, -5 yr ≤ t Saturation is not forced at the shaft cell on the surface because its saturation is reset to 1.0 at t = 0 yr.
$P_b(i,j,t) = 1.01 \times 10^5$ Pa	Columns 1–68, row 33, –5 yr ≤ t
Culebra and Magenta Far Field	
$P_b(i,26,t) = 9.14 \times 10^5$ Pa	i = 1 and 68, j = 26, –5 yr ≤ t (Culebra)
$P_b(i,28,t) = 9.47 \times 10^5$ Pa	i = 1 and 68, j = 28, –5 yr ≤ t (Magenta)

$$+\alpha_{i,j} q^{n+1}_{g_{i,j}} + \alpha_{i,j} q^{n+1}_{rg_{i,j}} - \frac{\left(\alpha\phi\rho_g S_g\right)^{n+1}_{i,j} - \left(\alpha\phi\rho_g S_g\right)^{n}_{i,j}}{\Delta t} = 0 \qquad \text{(PA.91)}$$

where Φ represents the phase potentials given by

$$\Phi^{x+}_{g_{i,j}} = P_{g_{i,j}} + \rho_{g_{i+1/2,j}} g h_{i,j}, \quad \Phi^{x-}_{g_{i,j}} = P_{g_{i,j}} + \rho_{g_{i-1/2\,j}} g h_{i,j}$$

and

$$\Phi^{y+}_{g_{i,j}} = P_{g_{i,j}} + \rho_{g_{i,j+1/2}} g h_{i,j}, \quad \Phi^{y-}_{g_{i,j}} = P_{g_{i,j}} + \rho_{g_{i,j-1/2}} g h_{i,j}$$

the subscripts are defined by

i = x-direction grid index
j = y-direction grid index
$i \pm 1/2$ = x-direction grid block interface
$j \pm 1/2$ = y-direction grid block interface
x_i = grid block center in the x-coordinate direction (m)
y_j = grid block center in the y-coordinate direction (m)
Δx_i = grid block length in the x-coordinate direction (m)
Δy_j = grid block length in the y-coordinate direction (m)

the superscripts are defined by

n = index in the time discretization, known solution time level
n+1 = index in the time discretization, unknown solution time level

and the interblock densities are defined by

$$\rho g_{i+1/2,j} = \frac{\Delta x_{i+1,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}} \rho g_{i,j} + \frac{\Delta x_{i,j}}{\Delta x_{i,j} + \Delta x_{i+1,j}} \rho g_{i+1,j}$$

$$\rho g_{i-1/2,j} = \frac{\Delta x_{i,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho g_{i-1,j} + \frac{\Delta x_{i-1,j}}{\Delta x_{i-1,j} + \Delta x_{i,j}} \rho g_{i,j}$$

$$\rho g_{i,j+1/2} = \frac{\Delta y_{i,j+1}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho g_{i,j} + \frac{\Delta y_{i,j}}{\Delta y_{i,j} + \Delta y_{i,j+1}} \rho g_{i,j+1}$$

$$\rho g_{i,j-1/2} = \frac{\Delta y_{i,j}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho g_{i,j-1} + \frac{\Delta y_{i,j-1}}{\Delta y_{i,j-1} + \Delta y_{i,j}} \rho g_{i,j}$$

The interface values of k_{rg} in Equation (PA.91) are evaluated using upstream weighted values (i.e., the relative permeabilities at each grid block interface are defined to be the relative permeabilities at the center of the adjacent grid block with the highest potential). Further, interface values for $\alpha\rho_g k_x/\mu_g$ and $\alpha\rho_g k_y/\mu_g$ are obtained by harmonic averaging of adjacent grid block values for these expressions. Currently all materials are isotropic, i.e. $k_x = k_y = k_z$.

The discretization of the brine mass balance equation is obtained by replacing the subscript for gas, g, by the subscript for brine, b. As a reminder, P_g and S_b are replaced in the numerical implementation with the substitutions indicated by Equation (PA.27) and Equation (PA.26), respectively. Wells are not used in the conceptual model for long-term Salado flow calculations, but they are used for DBR calculations. Thus, for long-term Salado flow calculations, the terms q_g and q_b are zero. For long-term Salado flow calculations, the wellbore is not treated by a well model, but rather is explicitly modeled within the grid as a distinct material region (i.e., Upper Borehole and Lower Borehole in Figure PA-15).

The resultant coupled system of nonlinear brine and gas mass balance equations is integrated in time using the Newton-Raphson method with upstream weighting of the relative permeabilities, as previously indicated. The primary unknowns at each computational cell center are brine pressure and gas saturation.

PA-4.2.12 Gas and Brine Flow across Specified Boundaries

The Darcy velocity vectors $v_g(x, y, t)$ and $v_b(x, y, t)$ for gas and brine flow ($m^3/m^2/s = m/s$) are defined by the expressions

$$v_g(x,y,t) = k k_{rg} \left(\nabla P_g + \rho_g g \nabla h \right) / \mu_g \qquad \text{(PA.92)}$$

and

$$v_b(x,y,t) = k k_{rb} \left(\nabla P_b + \rho_b g \nabla h \right) / \mu_b \qquad \text{(PA.93)}$$

Values for v_g and v_b are obtained and saved as the numerical solution of Equation (PA.24) through Equation (PA.30) is carried out. Cumulative flows of gas, $C_g(t, B)$, and brine, $C_b(t, B)$, from time 0 to time t across an arbitrary boundary B in the domain of (Figure PA-15) is then given by

$$C_l(t,B) = \int_0^t \left[\int_B \alpha(x,y)\mathbf{v_l}(x,y,t)\cdot\mathbf{n}(x,y)ds \right] dt \qquad \text{(PA.94)}$$

for $l = g, b$, where $\alpha(x, y)$ is the geometry factor defined in Equation (PA.32), $n(x, y)$ is an outward-pointing unit normal vector, and $\int_B ds$ denotes a line integral. As an example, B could correspond to the boundary of the waste disposal regions in Figure PA-15. The integrals defining $C_g(t, B)$ and $C_b(t, B)$ are evaluated using the Darcy velocities defined by Equation (PA.92) and Equation (PA.93). Due to the dependence of gas volume on pressure, $C_g(t, B)$ is typically calculated in moles or cubic meters at standard temperature and pressure, which requires an appropriate change of units for v_g in Equation (PA.95).

PA-4.2.13 Additional Information

Additional information on BRAGFLO and its use in the CRA-2009 PA can be found in the BRAGFLO user's manual (Nemer 2007c), the BRAGFLO design document (Nemer 2007b) and the analysis package for the Salado flow calculations in the CRA-2009 PA (Nemer and Clayton 2008).

PA-4.3 Radionuclide Transport in the Salado: NUTS

The NUTS code is used to model radionuclide transport in the Salado. NUTS models radionuclide transport within all regions for which BRAGFLO computes brine and gas flow, and for each realization uses as input the corresponding BRAGFLO velocity field, pressures, porosities, saturations, and other model parameters, including, for example, the geometrical grid, residual saturation, material map, and compressibility. Of the radionuclides that are transported vertically due to an intrusion or up shaft, it is assumed that the lateral radionuclide transport is in the most transmissive unit, the Culebra. Therefore, the radionuclide transport through the Dewey Lake to the accessible environment (f_{DL} in Equation [PA.33]) and to the land surface due to long-term flow (f_S in Equation [PA.33]) are set to zero for consistency.

The PA uses NUTS in two different modes. First, the code is used in a computationally fast *screening* mode to identify those BRAGFLO realizations for which it is unnecessary to do full transport calculations because the amount of contaminated brine that reaches the Culebra or the LWB within the Salado is insufficient to significantly contribute to the total integrated release of radionuclides from the disposal system. For the remaining realizations, which have the possibility of consequential release, a more computationally intensive calculation of each radionuclide's full transport is performed (see Section PA-6.7.2).

This section describes the model used to compute radionuclide transport in the Salado for E0, E1, and E2 scenarios (defined in Section PA-2.3.2). The model for transport in the E1E2 scenario, which is computed using the PANEL code, is described in Section PA-4.4.

NUTS models radionuclide transport by advection (see Attachment MASS-2009, Section MASS-13.5). NUTS disregards sorptive and other retarding effects throughout the entire flow region. Physically, some degree of retardation must occur at locations within the repository and the geologic media; it is therefore conservative to ignore retardation processes. NUTS also ignores reaction-rate aspects of dissolution and colloid formation processes, and mobilization is assumed to occur instantaneously. Neither molecular nor mechanical dispersion is modeled in NUTS. These processes are assumed to be insignificant compared to advection, as discussed further in Attachment MASS-2009, Section MASS-13.5.

Colloidal actinides are subject to retardation by chemical interaction between colloids and solid surfaces and by clogging of small pore throats (i.e., by sieving). There will be some interaction of colloids with solid surfaces in the anhydrite interbeds. Given the low permeability of intact interbeds, it is likely that pore apertures will be small and some sieving will occur. However, colloidal particles, if not retarded, are transported slightly more rapidly than the average velocity of the bulk liquid flow. Because the effects on transport of slightly increased average pore velocity and retarded interactions with solid surfaces and sieving offset one another, the DOE assumes residual effects of these opposing processes will be either small or beneficial, and does not incorporate them when modeling An transport in the Salado interbeds.

If brine in the repository moves into interbeds, it is likely that mineral precipitation reactions will occur. Precipitated minerals may contain actinides as trace constituents. Furthermore, colloidal-sized precipitates will behave like mineral-fragment colloids, which are destabilized by brines, quickly agglomerating and settling by gravity. The beneficial effects of precipitation and coprecipitation are neglected in PA.

Fractures, channeling, and viscous fingering may also impact transport in Salado interbeds, which contain natural fractures. Because of the low permeability of unfractured anhydrite, most fluid flow in interbeds will occur in fractures. Even though some properties of naturally fractured interbeds are characterized by in situ tests, other uncertainty exists in the characteristics of the fracture network that may be created with high gas pressure in the repository. The PA modeling system accounts for the possible effects on porosity and permeability of fracturing by using a fracturing model (see Section PA-4.2.4). The processes and effects associated with fracture dilation or fracture propagation not already captured by the PA fracture model are negligible (see the CCA, Appendix MASS, Section MASS.13.3 and Appendix MASS Attachment 13.2). Of those processes not already incorporated, channeling has the greatest potential effect.

Channeling is the movement of fluid through the larger-aperture sections of a fracture network with locally high permeabilities. It could locally enhance An transport. However, it is assumed that the effects of channeled flow in existing or altered fractures will be negligible for the length and time scales associated with the disposal system. The DOE believes this assumption is reasonable because processes are likely to occur that limit the effectiveness of channels or the dispersion of actinides in them. First, if gas is present in the fracture network, it will be present

as a nonwetting phase and will occupy the portions of the fracture network with relatively large apertures, where the highest local permeabilities will exist. The presence of gas thus removes the most rapid transport pathways from the contaminated brine and decreases the impact of channeling. Second, brine penetrating the Salado from the repository is likely to be completely miscible with in situ brine. Because of miscibility, diffusion or other local mixing processes will probably broaden fingers (reduce concentration gradients) until the propagating fingers are indistinguishable from the advancing front.

Gas will likely penetrate the liquid-saturated interbeds as a fingered front, rather than a uniform front. Fingers form when there is a difference in viscosity between the invading fluid (gas) and the resident fluid (liquid brine), and because of channeling effects. This process does not affect An transport, however, because actinides of interest are transported only in the liquid phase, which will not displace gas in the relatively high-permeability regions due to capillary effects.

PA-4.3.1 Mathematical Description

The following system of PDEs is used to model radionuclide transport in the Salado:

$$-\nabla\cdot\alpha\boldsymbol{v}_b C_{bl} + \alpha S_l = \alpha\frac{\partial}{\partial t}\left(\phi S_b C_{bl}\right) + \left(\alpha\phi S_b C_{bl}\right)\lambda_l - \alpha\phi S_b \sum_{p\in P(l)} C_{bp}\lambda_p \qquad \text{(PA.95)}$$

$$-S_l = \frac{\partial}{\partial t}\left(C_{sl}\right) + C_{sl}\lambda_l - \sum_{p\in P(l)} C_{sp}\lambda_p \qquad \text{(PA.96)}$$

for $l = 1, 2, \ldots, n_R$, where

- $\boldsymbol{v}_b$ = Darcy velocity vector ($m^3/m^2/s = m/s$) for brine (supplied by BRAGFLO from solution of Equation (PA.93))
- C_{bl} = concentration (kg/m^3) of radionuclide l in brine
- C_{sl} = concentration (kg/m^3) of radionuclide l in solid phase (i.e., not in brine), with concentration defined with respect to total (i.e., bulk) formation volume (only used in repository; see Figure PA-15)
- S_l = linkage term ($kg/m^3/s$) due to dissolution/precipitation between radionuclide l in brine and in solid phase (see Equation (PA.97))
- ϕ = porosity (supplied by BRAGFLO from solution of Equation (PA.24) through Equation (PA.30))
- S_b = brine saturation (supplied by BRAGFLO from solution of Equation (PA.24) through Equation (PA.30))
- λ_l = decay constant (s^{-1}) for radionuclide l
- $P(l)$ = $\{p$: radionuclide p is a parent of radionuclide $l\}$
- n_R = number of radionuclides,

and α is the dimension-dependent geometry factor in Equation (PA.32). PA uses a two-dimensional representation for fluid flow and radionuclide transport in the vicinity of the

repository, with α defined by the element depths in Figure PA-15. Although omitted for brevity, the terms α, $\mathbf{v}_b$, C_{bl}, C_{sl}, S_l, S_b, and ϕ are functions $\alpha(x, y)$, $\mathbf{v}_b(x, y, t)$, $C_{bl}(x, y, t)$, $C_{sl}(x, y, t)$, $S_l(x, y, t)$, $S_b(x, y, t)$, and $\phi(x, y, t)$ of time t and the spatial variables x and y. Equation (PA.95) and Equation (PA.96) are defined and solved on the same computational grid (Figure PA-15) used by BRAGFLO for the solution of Equation (PA.24) through Equation (PA.30).

Radionuclides are assumed to be present in both brine (Equation (PA.95)) and in an immobile solid phase (Equation (PA.96)), although radionuclide transport takes place only by brine flow (Equation (PA.95)). The maximum radionuclide concentration is assumed to equilibrate instantly for each element (Section PA-4.3.2). Then each individual radionuclide equilibrates between the brine and solid phases based on the maximum concentration of its associated element and the mole fractions of other isotopes included in the calculation. The linkage between the brine and solid phases in Equation (PA.95) and Equation (PA.96) is accomplished by the term S_l, where

$$S_l = \begin{cases} \delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{sl} & \text{if } 0 \le Dif\left(S_T, C_{b,El(l)}\right) \le \dfrac{C_{s,El(l)}}{\phi S_b} \text{ and } 0 < S_b \\ \delta(\tau - t)\left[\dfrac{C_{s,El(l)}}{\phi S_b}\right] MF_{sl} & \text{if } 0 \le \dfrac{C_{s,El(l)}}{\phi S_b} < Dif\left(S_T, C_{b,El(l)}\right) \text{ and } 0 < S_b \\ \delta(\tau - t)\, Dif\left(S_T, C_{b,El(l)}\right) MF_{bl} & \text{if } Dif\left(S_T, C_{b,El(l)}\right) < 0 \text{ and } 0 < S_b \\ 0 & \text{otherwise} \end{cases} \tag{PA.97}$$

where

$S_T\left[Br(t), Ox(l), El(l)\right]$ = maximum concentration (kg/m^3) of element $El(l)$ in oxidation state $Ox(l)$ in brine type $Br(t)$, where $El(l)$ denotes the element of which radionuclide l is an isotope, $Ox(l)$ denotes the oxidation state in which element $El(l)$ is present, and $Br(t)$ denotes the type of brine present in the repository at time t (see Section PA-4.3.2 for definition of $S_T\left[Br(t), Ox(l), El(l)\right]$).

$C_{p,El(l)}$ = concentration (kg/m^3) of element $El(l)$ in brine ($p = b$) or solid ($p = s$), which is equal to the sum of concentrations of radionuclides that are isotopes of same element as radionuclide l, where $k \in El(l)$ only if k is an isotope of element $El(l)$:

$$C_{p,El(l)} = \sum_{k \in El(l)} C_{p,k} \tag{PA.98}$$

$Dif\left(S_T, C_{b,El(l)}\right)$ = difference (kg/m^3) between maximum concentration of element *El*(*l*) in brine and existing concentration of element *El*(*l*) in brine

$$Dif\left(S_T, C_{b,El(l)}\right) = S_T\left[Br(t), Ox(l), El(l)\right] - C_{b,El(l)} \quad \text{(PA.99)}$$

MF_{pl} = mole fraction of radionuclide *l* in phase *p*, where *p* = *b* (brine) or *p* = *s* (solid)

$$MF_{pl} = C_{pl} CM_l \Big/ \sum_{k \in El(l)} C_{pk} CM_k \quad \text{(PA.100)}$$

CM_l = conversion factor (mol/kg) from kilograms to moles for radionuclide *l*

$\delta(\tau - t)$ = Dirac delta function (s^{-1}) ($\delta(\tau - t) = 0$ if $\tau \neq t$ and $\int_{-\infty}^{\infty} \delta(\tau - t)\, d\tau = 1$)

In the CCA and the CRA-2004, the function S_T had an additional parameter, *Mi*, representing the presence or absence of microbial activity. However, during preparations for the CRA-2004 PABC, the EPA directed the DOE to change the probability of microbial activity to 1.0 (Cotsworth 2005). The DOE therefore revised the probability distribution so that all vectors would have the possibility for microbial degradation of cellulose, while retaining the percentage of vectors showing microbial degradation of rubbers and plastic at 0.25 (Nemer 2005). This, in effect, sets *Mi* equal to "Yes" for all vectors. *Mi* is therefore suppressed as an argument of S_T in the remainder of this section.

The terms S_l, S_b, $C_{p,El(l)}$, MF_{pl}, and ϕ are functions of time *t* and the spatial variables *x* and *y*, although the dependencies are omitted for brevity. The Dirac delta function, $\delta(\tau - t)$, appears in Equation (PA.97) to indicate that the adjustments to concentration are implemented instantaneously within the numerical solution of Equation (PA.95) and Equation (PA.96) whenever a concentration imbalance is observed.

The velocity vector $\mathbf{v}_b$ in Equation (PA.95) and Equation (PA.96) is defined in Equation (PA.93) and is obtained from the numerical solution of Equation (PA.24) through Equation (PA.30). If *B* denotes an arbitrary boundary (e.g., the LWB) in the domain of Equation (PA.95) and Equation (PA.96) (as shown in Figure PA-15), the cumulative transport of $C_l(t, B)$ of radionuclide *l* from time 0 to time *t* across *B* is given by

$$C_l(t,B) = \int_0^t \left[\int_B \mathbf{v_b}(x,y,t) C_l(x,y,t) \alpha(x,y) \cdot \mathbf{n}(x,y) ds \right] dt \quad \text{(PA.101)}$$

where $\mathbf{n}(x, y)$ is an outward-pointing unit normal vector and $\int_B ds$ denotes a line integral over B.

Equation (PA.95) and Equation (PA.96) models advective radionuclide transport due to the velocity vector $\mathbf{v}_b$. Although the effects of solubility limits are considered, no chemical or physical retardation is included in the model. Molecular diffusion is not included in the model, because the radionuclides under consideration have molecular diffusion coefficients on the order of 10^{-10} m^2/s, and thus can be expected to move only approximately 10 m over 10,000 years due to molecular diffusion. Mechanical dispersion is also omitted in NUTS, as the uniform initial radionuclide concentrations assumed within the repository and the use of time-integrated releases in assessing compliance with section 191.13 mean that mechanical dispersion will have negligible impact on overall performance.

PA-4.3.2 Calculation of Maximum Concentration $S_T(Br, Ox, El)$

A maximum concentration $S_T(Br, Ox, El)$ (mol/liter [L]) is calculated for each brine type ($Br \in$ {Salado, Castile}), oxidation state ($Ox \in$ {III, IV, V, VI}), and element ($El \in$ {Am, Pu, U, Th}). The maximum concentration is given by

$$S_T\left(Br, Ox, El\right) = S_D\left(Br, Ox\right) + S_C\left(Br, Ox, El\right) \quad \text{(PA.102)}$$

where $S_D(Br, Ox)$ is the dissolved solubility (mol/L) and $S_C(Br, Ox, El)$ is the concentration (mol/L) of the element sorbed to colloids.

The dissolved solubility $S_D(Br, Ox)$ is given by

$$S_D\left(Br, Ox\right) = S_{FMT}\left(Br, Ox\right) \times 10^{UF(Ox)} \quad \text{(PA.103)}$$

where

$S_{FMT}(Br, Ox)$ = dissolved solubility (mol/L) calculated by Fracture-Matrix Transport (FMT) model (WIPP Performance Assessment 1998a) for brine type Br and oxidation state Ox

$UF\left(Ox\right)$ = logarithm (base 10) of uncertainty factor for solubilities calculated by FMT expressed as a function of oxidation state Ox

Table PA-10 lists the calculated values of $S_{FMT}(Br, Ox)$; details of the calculation are provided in Appendix SOTERM-2009 and Brush (2005). The uncertainty factors $UF(Ox)$ are determined by the uncertain parameters WSOLVAR3 for the III oxidation state and WSOLVAR4 for the IV oxidation state; definitions of these parameters are provided in Table PA-19, and further details regarding the calculation of the solubilities is given in Appendix SOTERM-2009, Section SOTERM-5.1.3.

Table PA-10. Calculated Values for Dissolved Solubility (see Appendix SOTERM-2009, Table SOTERM-16)

Brine	Oxidation State			
	III	IV	V	VI[a]
Salado	3.87×10^{-7}	5.64×10^{-8}	3.55×10^{-6}	1.0×10^{-3}
Castile	2.88×10^{-7}	6.79×10^{-8}	8.24×10^{-7}	1.0×10^{-3}

[a] Values for the VI solubilities were mandated by the EPA (U.S. Environmental Protection Agency 2005).

The concentration (mol/L) of the element sorbed to colloids $S_C(Br, Ox, El)$ is given by

$$S_C(Br, Ox, El) = S_{Hum}(Br, Ox, El) + S_{Mic}(Br, Ox, El) + S_{Act}(El) + S_{Mn} \quad \text{(PA.104)}$$

where

$S_{Hum}(Br, Ox, El)$ = solubility (concentration expressed in mol/L) in brine type *Br* of element *El* in oxidation state *Ox* resulting from humic colloid formation

$= \min\{SF_{Hum}(Br, Ox, El) \times S_D(Br, Ox), UB_{Hum}\}$

$SF_{Hum}(Br, Ox, El)$ = scale factor used as a multiplier on $S_D(Br, Ox)$ in definition of $S_{Hum}(Br, Ox, El)$ (see Table PA-11)

$UB_{Mic}(Ox, El)$ = upper bound on solubility (concentration expressed in mol/L) of element *El* in oxidation state *Ox* resulting from microbial colloid formation (see Table PA-12)

UB_{Hum} = upper bound on solubility (concentration expressed in mol/L) of individual An elements resulting from humic colloid formation

$= 1.1 \times 10^{-5}$ mol/L

$S_{Mic}(Br, Ox, El)$ = solubility (concentration expressed in mol/L) in brine type *Br* of element *El* in oxidation state *Ox* resulting from microbial colloid formation

$= \min\{SF_{Mic}(Ox, El) \times S_D(Br, Ox), UB_{Mic}(Ox, El)\}$

$SF_{Mic}(Ox, El)$ = scale factor used as multiplier on $S_D(Br, Ox)$ in definition of $S_{Mic}(Br, Ox, El)$ (see Table PA-12)

$UB_{Mic}(Ox, El)$ = upper bound on solubility (concentration expressed in mol/L) of element *El* in oxidation state *Ox* resulting from microbial colloid formation (see Table PA-12)

Table PA-11. Scale Factor $SF_{Hum}(Br, Ox, El)$ Used in Definition of $S_{Hum}(Br, Ox, El)$ (see Appendix SOTERM-2009, Table SOTERM-21)

Brine	Element (Oxidation State)							
	Am(III)	Pu(III)	Pu(IV)	U(IV)	Th(IV)	Np(IV)	Np(V)	U(VI)
Salado	0.19	0.19	6.3	6.3	6.3	6.3	9.1×10^{-4}	0.12
Castile	WPHUMOX3[a]	WPHUMOX3[a]	6.3	6.3	6.3	6.3	7.4×10^{-3}	0.51

[a] See Table PA-19.

Table PA-12. Scale Factor $SF_{Mic}(Ox, El)$ and Upper Bound $UB_{Mic}(Ox, El)$ (mol/L) Used in Definition of $S_{Mic}(Br, Ox, El)$ (see Appendix SOTERM-2009, Table SOTERM-21)

Parameter	Element (Oxidation State)							
	Am(III)	Pu(III)	Pu(IV)	U(IV)	Th(IV)	Np(IV)	Np(V)	U(VI)
$SF_{Mic}(Ox, El)$	3.6	0.3	0.3	0.0021	3.1	12.0	12.0	0.0021
$UB_{Mic}(Ox, El)$	1	6.8×10^{-5}	6.8×10^{-5}	0.0021	0.0019	0.0027	0.0027	0.0021

$S_{Act}(El)$ = solubility (concentration in mol/L) of element *El* resulting from An intrinsic colloid formation

$$= \begin{cases} 1 \times 10^{-9} \text{ mol/L} & \text{if } El = \text{Pu} \\ 0 \text{ mol/L} & \text{otherwise} \end{cases}$$

S_{Mn} = solubility (concentration in mol/L) of individual An element resulting from mineral fragment colloid formation

$= 2.6 \times 10^{-8}$ mol/L

PA-4.3.3 Radionuclides Transported

Since the solution of Equation (PA.95) and Equation (PA.96) for this many radionuclides and decay chains would be very time-consuming, the number of radionuclides for direct inclusion in the analysis was reduced using the algorithm shown in Figure PA-21. The CRA-2009 PA uses the same reduction algorithm as the CCA PA (see the CCA, Appendix WCA); the algorithm was found to be acceptable in the CCA review (U.S. Environmental Protection Agency 1998a, Section 4.6.1.1).

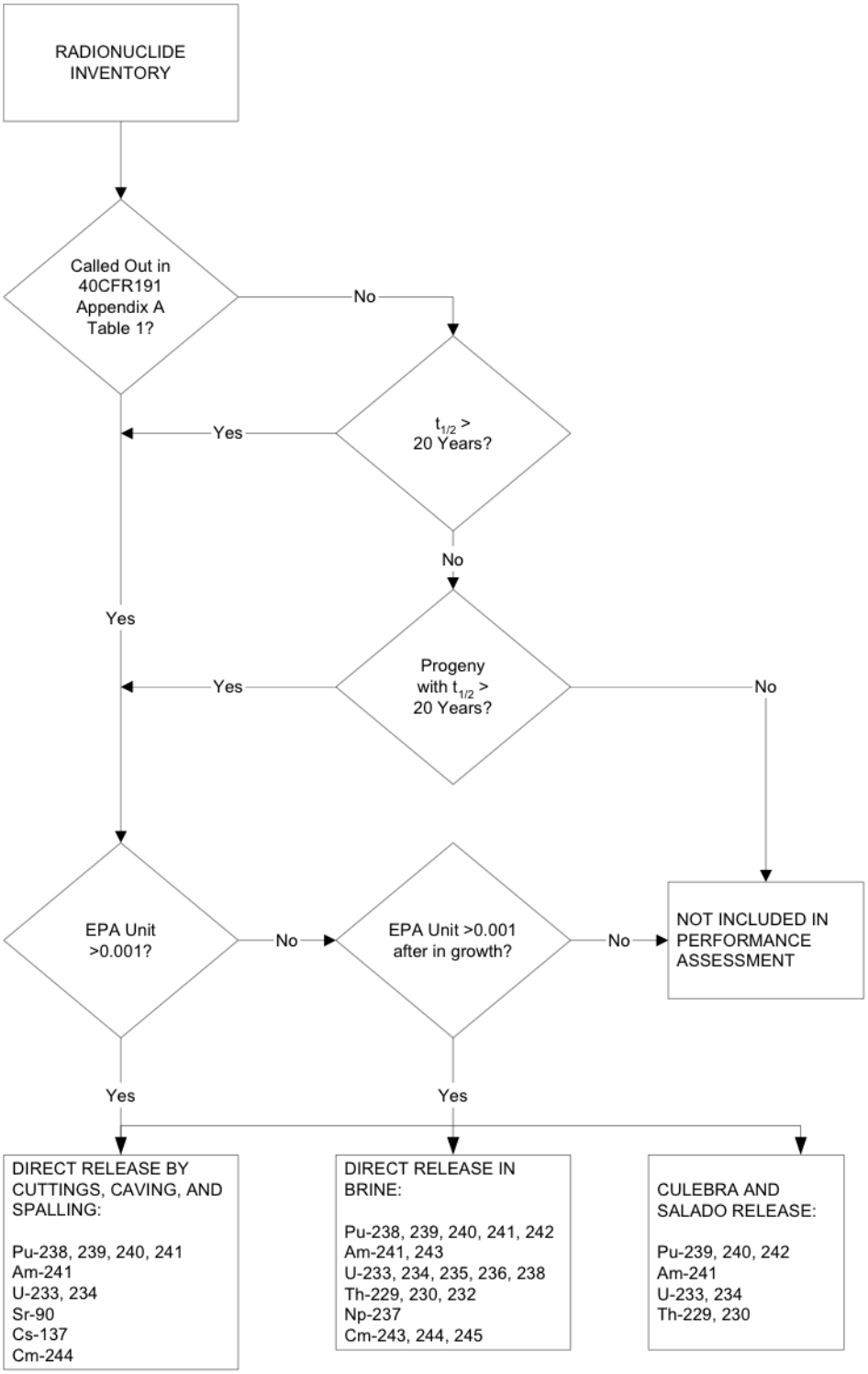


Figure PA-21. Selecting Radionuclides for the Release Pathways Conceptualized by PA

Using Figure PA-21, the number of radionuclides considered was reduced from 135 to a total of 29 included in the decay calculations carried out by the PANEL code (Garner and Leigh 2005). These radionuclides belong to the following decay chains:

$$\begin{array}{c} {}^{238}\mathrm{Pu} \\ \downarrow \\ {}^{242}\mathrm{Pu} \rightarrow {}^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{U} \rightarrow {}^{230}\mathrm{Th} \rightarrow {}^{226}\mathrm{Ra} \rightarrow {}^{210}\mathrm{Pb} \end{array} \quad \text{(PA.105)}$$

$$\begin{array}{c} {}^{243}\mathrm{Cm} \\ \downarrow \\ {}^{243}\mathrm{Am} \rightarrow {}^{239}\mathrm{Pu} \rightarrow {}^{235}\mathrm{U} \rightarrow {}^{231}\mathrm{Pa} \end{array} \quad \text{(PA.106)}$$

$$\begin{array}{c} {}^{244}\mathrm{Cm} \\ \downarrow \\ {}^{252}\mathrm{Cf} \rightarrow {}^{248}\mathrm{Cm} \rightarrow {}^{244}\mathrm{Pu} \rightarrow {}^{240}\mathrm{Pu} \rightarrow {}^{236}\mathrm{U} \rightarrow {}^{232}\mathrm{Th} \rightarrow {}^{228}\mathrm{Ra} \end{array} \quad \text{(PA.107)}$$

$$ {}^{245}\mathrm{Cm} \rightarrow {}^{241}\mathrm{Pu} \rightarrow {}^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} \rightarrow {}^{233}\mathrm{U} \rightarrow {}^{239}\mathrm{Th} \quad \text{(PA.108)}$$

Radionuclides considered in the decay calculations that do not belong to one of the decay chains listed above are ^{147}Pm, ^{137}Cs, and ^{90}Sr. In addition, some intermediates with extremely short half-lives, such as ^{240}U, were omitted from the decay chains.

Further simplification of the decay chains is possible based on the total inventories. Releases of radionuclides whose inventories total less than one EPA unit are essentially insignificant, as any release that transports essentially all of a given species outside the LWB will be dominated by the releases of other species with much larger inventories. In addition, ^{137}Cs and ^{90}Sr can be omitted because their concentrations drop to below 1 EPA unit within 150 years, which makes it improbable that a significant release of these radionuclides will occur. Isotopes such as ^{241}Pu, whose decay could affect the inventory of measurable isotopes, were reinstated.

After the reduction of radionuclides outlined in Figure PA-21 and the above paragraph, the following 10 radionuclides remained from the decay chains shown above:

$$\left({}^{242}\mathrm{Pu}, {}^{238}\mathrm{Pu}\right) \rightarrow {}^{234}\mathrm{U} \rightarrow {}^{230}\mathrm{Th} \quad \text{(PA.109)}$$

$$ {}^{239}\mathrm{Pu} \quad \text{(PA.110)}$$

$$ {}^{240}\mathrm{Pu} \quad \text{(PA.111)}$$

$$ {}^{241}\mathrm{Pu} \rightarrow {}^{241}\mathrm{Am} \rightarrow {}^{233}\mathrm{U} \rightarrow {}^{229}\mathrm{Th} \quad \text{(PA.112)}$$

^{238}Pu does not significantly affect transport calculations because of its short half-life (87.8 years). The remaining nine radionuclides were then further reduced by combining those with similar decay and transport properties. In particular, ^{234}U, ^{230}Th, and ^{239}Pu were used as surrogates for the groups {^{234}U, ^{233}U}, {^{230}Th, ^{229}Th}, and {^{242}Pu, ^{240}Pu, ^{239}Pu}, with the

initial inventories of ^{234}U, ^{230}Th, and ^{239}Pu being increased to account for the additional radionuclide(s) in each group.

In increasing the initial inventories, the individual radionuclides were combined on either a mole or curie basis (i.e., moles added and then converted back to curies, or curies added directly). In each case, the method that maximized the combined inventory was used; thus, ^{233}U was added to ^{234}U, ^{240}Pu to ^{239}Pu, and ^{229}Th to ^{230}Th by curies, while ^{242}Pu was added to ^{239}Pu by moles. In addition, ^{241}Pu was added to ^{241}Am by moles because ^{241}Pu has a half-life of 14 years and will quickly decay to ^{241}Am, and neglect of this ingrowth would underestimate the ^{241}Am inventory by about 4% (Table PA-13). The outcome of this process was the following set of five radionuclides in three simplified decay chains:

$$^{241}\mathrm{Am};\quad ^{238}\mathrm{Pu} \rightarrow ^{234}\mathrm{U} \rightarrow ^{230}\mathrm{Th};\quad ^{239}\mathrm{Pu} \tag{PA.113}$$

which were then used with Equation (PA.95) and Equation (PA.96) for transport in the vicinity of the repository. As ^{238}Pu does not significantly affect transport calculations, only the remaining four radionuclides are used in the Culebra transport calculations (Section PA-4.9). These radionuclides account for 99% of the EPA units in the waste after 2,000 years (Garner and Leigh 2005), and hence will dominate any releases by transport.

Table PA-13. Combination of Radionuclides for Transport

Combination	Isotope Initial Values	Combination Procedure	Combined Inventory
$^{233}U \rightarrow ^{234}U$	1.23×10^{3} Ci ^{233}U 3.44×10^{2} Ci ^{234}U	1.23×10^{3} Ci ^{233}U $\rightarrow 1.23 \times 10^{3}$ Ci ^{234}U	1.57×10^{3} Ci ^{234}U
$^{242}Pu \rightarrow ^{239}Pu$	1.27×10^{1} Ci ^{242}Pu	1.27×10^{1} Ci ^{242}Pu $= 1.32 \times 10^{1}$ moles ^{242}Pu $\rightarrow 1.32 \times 10^{1}$ moles ^{239}Pu $= 1.98 \times 10^{2}$ Ci ^{239}Pu	6.78×10^{5} Ci ^{239}Pu
$^{240}Pu \rightarrow ^{239}Pu$	9.55×10^{4} Ci ^{240}Pu 5.82×10^{5} Ci ^{239}Pu	9.55×10^{4} Ci ^{240}Pu $\rightarrow 9.55 \times 10^{4}$ Ci ^{239}Pu	
$^{229}Th \rightarrow ^{230}Th$	5.21×10^{0} Ci ^{229Th} 1.80×10^{-1} Ci ^{230}Th	5.21×10^{0} Ci ^{229Th} $\rightarrow 5.21 \times 10^{0}$ Ci ^{230}Th	5.39×10^{0} Ci ^{230}Th
$^{241}Pu \rightarrow ^{241}Am$	4.48×10^{5} Ci ^{241}Pu 5.18×10^{5} Ci ^{241}Am	5.38×10^{5} Ci ^{241}Pu $= 1.79 \times 10^{1}$ moles ^{241}Pu $\rightarrow 1.79 \times 10^{1}$ moles ^{241}Am $= 1.50 \times 10^{4}$ Ci ^{241}Am	5.33×10^{5} Ci ^{241}Am

PA-4.3.4 NUTS Tracer Calculations

All BRAGFLO realizations are first evaluated using NUTS in a screening mode to identify those realizations for which a significant release of radionuclides to the LWB cannot occur. The screening simulations consider an infinitely soluble, nondecaying, nondispersive, and nonsorbing species as a tracer element. The tracer is given a unit concentration in all waste disposal areas of 1 kg/m^3. If the amount of tracer that reaches the selected boundaries (the top of the Salado and

the LWB within the Salado) does not exceed a cumulative mass of 10^{-7} kg within 10,000 years, it is assumed there is no consequential release to these boundaries. If the cumulative mass outside the boundaries within 10,000 years exceeds 10^{-7} kg, a complete transport analysis is conducted. The value of 10^{-7} kg is selected because, regardless of the isotopic composition of the release, it corresponds to a normalized release less than 10^{-6} EPA units, the smallest release displayed in CCDF construction (Stockman 1996). The largest normalized release would be 9.98×10^{-7} EPA units, corresponding to 10^{-7} kg of ^{241}Am if the release was entirely ^{241}Am.

PA-4.3.5 NUTS Transport Calculations

For BRAGFLO realizations with greater than 10^{-7} kg reaching the boundaries in the tracer calculations, NUTS models the transport of five different radionuclide species (^{241}Am, ^{239}Pu, ^{238}Pu, ^{234}U, and ^{230}Th). These radionuclides represent a larger number of radionuclides: as discussed in Section PA-4.3.3, radionuclides were grouped together based on similarities, such as isotopes of the same element and those with similar half-lives, to simplify the calculations. For transport purposes, solubilities are lumped to represent both dissolved and colloidal forms. These groupings simplify and expedite calculations.

PA-4.3.6 Numerical Solution

Equation (PA.95) and Equation (PA.96) are numerically solved by the NUTS program (WIPP Performance Assessment 1997a) on the same computational grid (Figure PA-15) used by BRAGFLO for the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30). In the solution procedure, Equation (PA.95) and Equation (PA.96) are numerically solved with $S_l = 0$ for each time step, with the instantaneous updating of concentrations indicated in Equation (PA.97) and the appropriate modification to C_{sl} in Equation (PA.96) taking place after the time step. The solution is carried out for the five radionuclides indicated in Equation (PA.113).

The initial value and boundary value conditions used with Equation (PA.95) and Equation (PA.96) are given in Table PA-14. At time $t = 0$ (corresponding to the year 2033), the total inventory of each radionuclide is assumed to be in brine; the solubility constraints associated with Equation (PA.97) then immediately adjust the values for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$ for consistency with the constraints imposed by $S_T(Br, Ox, El)$ and available radionuclide inventory.

The n_R PDEs in Equation (PA.95) and Equation (PA.96) are discretized in two dimensions and then developed into a linear system of algebraic equations for numerical implementation. The following conventions are used in the representation of each discretized equation:

- The subscript b is dropped from C_{bl}, so that the unknown function is represented by C_l.
- A superscript n denotes time t_n, with the assumption that the solution C_l is known at time t_n and is to be propagated to time t_{n+1}.
- The grid indices are i in the x-direction and j in the y-direction, and are the same as the BRAGFLO grid indices.

Table PA-14. Initial and Boundary Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$

Initial Conditions for $C_{bl}(x, y, t)$ and $C_{sl}(x, y, t)$
$C_{bl}(x,y,t)$ = $A_l(0)/V_b(0)$ if (x, y) is a point in the repository (i.e., areas Waste Panel, South RoR and North RoR, in Figure PA-15), where $A_l(0)$ is the amount (kg) of radionuclide l present at time $t = 0$ (Table PA-13) and $V_b(0)$ is the amount (m^3) of brine in repository at time $t = 0$ (from solution of Equation (PA.24) through Equation (PA.30) with BRAGFLO) for all (x, y). = 0 otherwise.
$C_{sl}(x,y,t)$ = 0 if (x, y) is a point in the repository.
Boundary Conditions for $C_{bl}(x, y, t)$
$f_l(B,t)$ = $\int_B \boldsymbol{v}_b(x,y,t)\, C_{bl}(x,y,t)\, \alpha(x,y)\cdot n(x,y)\, ds$, where B is any subset of the outer boundary of the computational grid in Figure PA-15, $f_l(B,t)$ is the flux (kg/s) at time t of radionuclide l across B, $\boldsymbol{v}_b(x, y, t)$ is the Darcy velocity ($m^3/m^2/s$) of brine at (x, y) on B and is obtained from the solution of Equation (PA.24) through Equation (PA.30) by BRAGFLO, $\boldsymbol{n}(x, y)$ denotes an outward-pointing unit normal vector, and $\int_B ds$ denotes a line integral along B.

- Fractional indices refer to quantities evaluated at grid block interfaces.
- Each time step by NUTS is equal to 20 BRAGFLO time steps because BRAGFLO stores results (here, v_b, ϕ, and S_b) every 20 time steps.

The following finite-difference discretization is used for the l^{th} equation in each grid block (i, j):

$$q^{n+1}_{b,i+1/2,j}C^{n+1}_{l,i+1/2,j} - q^{n+1}_{b,i-1/2,j}C^{n+1}_{l,i-1/2,j} + q^{n+1}_{b,i,j+1/2}C^{n+1}_{l,i,j+1/2} - q^{n+1}_{b,i,j-1/2}C^{n+1}_{l,i,j-1/2} =$$

$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n+1} - \left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n}\right] \qquad \text{(PA.114)}$$

$$+V_{R,i,j}\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n+1}\lambda_l - V_{R,i,j}\left(\phi_{i,j}S_{b_{i,j}}\right)^{n+1}\sum_{p\in P(l)}C^{n+1}_{p,i,j}\lambda_p$$

where q_b is the grid block interfacial brine flow rate (m^3/s) and V_R is the grid block volume (m^3). The quantity q_b is based on v_b and α in Equation (PA.95) and Equation (PA.96), and the quantity V_R is based on grid block dimensions (Figure PA-15) and α.

The interfacial values of concentration in Equation (PA.114) are discretized using the one-point upstream weighting method (Aziz and Settari 1979), which results in

$$q^{n+1}_{b,i+1/2,j}\left(\omega_{i+1}C^{n+1}_{l,i,j}+\left(1-\omega_{i+1}\right)C^{n+1}_{l,i+1,j}\right)-q^{n+1}_{b,i-1/2,j}\left(\omega_i C^{n+1}_{l,i-1,j}+\left(1-\omega_i\right)C^{n+1}_{l,i,j}\right)$$
$$+q^{n+1}_{b,i,j+1/2}\left(\omega_{j+1}C^{n+1}_{l,i,j}+\left(1-\omega_{j+1}\right)C^{n+1}_{l,i,j+1}\right)-q^{n+1}_{b,i,j-1/2}\left(\omega_j C^{n+1}_{b,i,j-1}+\left(1-\omega_j\right)C^{n+1}_{l,i,j}\right)=$$
$$\frac{V_{R,i,j}}{\Delta t}\left[\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n+1}-\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n}\right]+V_{R,i,j}\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n+1}\lambda_l$$
$$-V_{R,i,j}\left(\phi_{i,j}S_{b_{i,j}}\right)^{n+1}\sum_{p\in P(l)}C^{n+1}_{p,i,j}\lambda_p \qquad \text{(PA.115)}$$

where ω derives from the upstream weighting for flow between adjacent grid blocks and is defined by

$$\omega_i=\begin{cases}1 & \text{if flow is from grid block } (i-1,j) \text{ to grid block } (i,j)\\ 0 & \text{otherwise}\end{cases}$$

$$\omega_j=\begin{cases}1 & \text{if flow is from grid block } (i,j-1) \text{ to grid block } (i,j)\\ 0 & \text{otherwise}\end{cases}$$

By collecting similar terms, Equation (PA.115) can be represented by the linear equation

$$AC^{n+1}_{l,i,j-1}+BC^{n+1}_{l,i-1,j}+DC^{n+1}_{l,i,j}+EC^{n+1}_{l,i+1,j}+FC^{n+1}_{l,i,j+1}=R_{l,i,j} \qquad \text{(PA.116)}$$

where

$$A=-\omega_j q^{n+1}_{b,i,j-1/2} \qquad B=-\omega_j q^{n+1}_{b,i-1/2,j}$$
$$E=\left(1-\omega_{i+1}\right)q^{n+1}_{b,i+1/2,j} \qquad F=\left(1-\omega_{j+1}\right)q^{n+1}_{b,i,j+1/2}$$

$$D=-\left(1-\omega_j\right)q^{n+1}_{b,i,j-1/2}-\left(1-\omega_i\right)q^{n+1}_{b,i-1/2,j}+\omega_{j+1}q^{n+1}_{b,i,j+1/2}+\omega_{i+1}q^{n+1}_{b,i+1/2,j}$$
$$-\left(\frac{V_{R,i,j}}{\Delta t}-V_{R,i,j}\lambda_l\right)\left\{\phi_{i,j}S_{b_{i,j}}\right\}^{n+1}$$

$$R_{l,i,j}=-\frac{V_{R,i,j}}{\Delta t}\left\{\phi_{i,j}S_{b_{i,j}}C_{l,i,j}\right\}^{n}-V_{R,i,j}\left(\phi_{i,j}S_{b_{i,j}}\right)^{n+1}\sum_{p\in P(l)}C^{n+1}_{p,i,j}\lambda_p$$

Given the form of Equation (PA.116), the solution of Equation (PA.95) and Equation (PA.96) has now been reduced to the solution of $n_R \times n_G$ linear algebraic equations in $n_R \times n_G$ unknowns, where n_R is the number of equations for each grid block (i.e., the number of radionuclides) and n_G is the number of grid blocks into which the spatial domain is discretized (Figure PA-15).

The system of PDEs in Equation (PA.95) and Equation (PA.96) is strongly coupled because of the contribution from parental decay to the equation governing the immediate daughter.

Consequently, a sequential method is used to solve for the radionuclide concentrations by starting at the top of a decay chain and working down from parent to daughter. This implies that when solving Equation (PA.116) for the l^{th} isotope concentration, all parent concentrations occurring in the right-hand-side term R are known. The system of equations is then linear in the concentrations of the l^{th} isotope. As a result, solving Equation (PA.95) and Equation (PA.96) is reduced from the solution of one algebraic equation at each time step with $n_R \times n_G$ unknowns to the solution of n_R algebraic equations each with n_G unknowns at each time step, which can result in a significant computational savings.

The matrix resulting from one-point upstream weighting has the following structural form for a 3×3 system of grid blocks, and a similar structure for a larger number of grid blocks:

	1	2	3	4	5	6	7	8	9
1	X	X	0	X					
2	X	X	X	0	X				
3	0	X	X	0	0	X			
4	X	0	0	X	X	0	X		
5		X	0	X	X	X	0	X	
6			X	0	X	X	0	0	X
7				X	0	0	X	X	0
8					X	0	X	X	X
9						X	0	X	X

where X designates possible nonzero matrix entries, and 0 designates zero entries within the banded structure. All entries outside of the banded structure are zero. Because of this structure, a banded direct elimination solver (Aziz and Settari 1979, Section 8.2.1) is used to solve the linear system for each radionuclide. The bandwidth is minimized by first indexing equations in the coordinate direction with the minimum number of grid blocks. The coefficient matrix is stored in this banded structure, and all infill coefficients calculated during the elimination procedure are contained within the band structure. Therefore, for the matrix system in two dimensions, a pentadiagonal matrix of dimension $I_{BW} \times n_G$ is inverted instead of a full $n_G \times n_G$ matrix, where I_{BW} is the bandwidth.

The numerical implementation of Equation (PA.96) enters the solution process through updates to the radionuclide concentrations in Equation (PA.115) between each time step, as indicated in Equation (PA.97). The numerical solution of Equation (PA.95) and Equation (PA.96) also generates the concentrations required to integrate numerically evaluating the integral that defines $C_l(t, B)$ in Equation (PA.101).

PA-4.3.7 Additional Information

Additional information on NUTS and its use in WIPP PA can be found in the NUTS users manual (WIPP Performance Assessment 1997a) and in the analysis package of Salado transport

calculations for the CRA-2009 PA (Ismail and Garner 2008). Furthermore, additional information on dissolved and colloidal actinides is given in Appendix SOTERM-2009.

PA-4.4 Radionuclide Transport in the Salado: PANEL

This section describes the model used to compute radionuclide transport in the Salado for the E1E2 scenario. The model for transport in E0, E1, and E2 scenarios is described in Section PA-4.3.

PA-4.4.1 Mathematical Description

A relatively simple mixed-cell model is used for radionuclide transport in the vicinity of the repository after an E1E2 intrusion, when connecting flow between two drilling intrusions into the same waste panel is assumed to take place. With this model, the amount of radionuclide l contained in a waste panel is represented by

$$\frac{dA_l}{dt} = -r_b C_{bl} - \lambda_l A_l + \sum_{p \in P(l)} \lambda_p A_p \qquad \text{(PA.117)}$$

where

$A_l(t)$ = amount (mol) of radionuclide l in waste panel at time t

$C_{bl}(t)$ = concentration (mol/m^3) of radionuclide l in brine in waste panel at time t (Equation (PA.118) and Equation (PA.119))

$r_b(t)$ = rate (m^3/s) at which brine flows out of the repository at time t (supplied by BRAGFLO from solution of Equation (PA.93))

and λ_l and $P(l)$ are defined in conjunction with Equation (PA.95) and Equation (PA.96).

The brine concentration C_{bl} in Equation (PA.117) is defined by

$$C_{bl}(t) = S_T[Br, Ox, El]\, MF_l(t) \quad \text{if} \quad S_T[Br(t), Ox, El] \le \sum_{k \in El(l)} A_k(t)/V_b(t) \qquad \text{(PA.118)}$$

$$= A_l(t)/V_b(t) \quad \text{if} \sum_{k \in El(l)} A_k(t)/V_b(t) < S_T[Br, Ox, El] \qquad \text{(PA.119)}$$

where

$MF_l(t)$ = mole fraction of radionuclide l in waste panel at time t

$$= \frac{A_l(t)}{\sum_{k \in El(l)} A_k(t)} \quad \text{(PA.120)}$$

$V_b(t)$ = volume (m^3) of brine in waste panel at time t (supplied by BRAGFLO from solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30))

and $S_T[Br, Ox, El]$ is supplied by Equation (PA.102).

For Equation (PA.118) and Equation (PA.119), $S_T[Br, Ox, El]$ must be expressed in units of mol/L. In other words, $C_{bl}(t)$ is defined to be the maximum concentration (S_T in Equation (PA.102)) if there is sufficient radionuclide inventory in the waste panel to generate this concentration (Equation (PA.118)); otherwise, $C_{bl}(t)$ is defined by the concentration that results when all the relevant element in the waste panel is placed in solution (Equation (PA.119)). The dissolved and colloidal An equilibrate instantly for each element.

Given r_b and C_{bl}, evaluation of the integral

$$R_l(t) = \int_0^t C_{bl}(\tau) r_b(\tau) d\tau \quad \text{(PA.121)}$$

provides the cumulative release $R_l(t)$ of radionuclide l from the waste panel through time t.

PA-4.4.2 Numerical Solution

Equation (PA.117) is numerically evaluated by the PANEL model (WIPP Performance Assessment 1998b) using a discretization based on time steps of 50 years or less. Specifically, Equation (PA.117) is evaluated with the approximation

$$A_l(t_{n+1}) = A_l(t_n) - \left[\int_{t_n}^{t_{n+1}} r_b(\tau) d\tau\right] C_{bl}(t_n) - A_l(t_n) \exp(-\lambda_l \Delta t) + G_l(t_n, t_{n+1}) \quad \text{(PA.122)}$$

where

$G_l(t_n, t_{n+1})$ = gain in radionuclide l due to the decay of precursor radionuclides between t_n and t_{n+1} (see Equation (PA.123)), $\Delta t = t_{n+1} - t_n = 50\ yr$.

As the solution progresses, values for $C_{bl}(t_n)$ are updated in consistency with Equation (PA.118) and Equation (PA.119), and the products $r_b(t_n)C_{bl}(t_n)$ are accumulated to provide an approximation to R_l in Equation (PA.121).

The term $G_l(t_n, t_{n+1})$ in Equation (PA.122) is evaluated with the Bateman equations (Bateman 1910), with PANEL programmed to handle decay chains of up to five (four decay daughters for a given radionuclide). As a single example, if radionuclide l is the third radionuclide in a decay chain (i.e., $l = 3$) and the two preceding radionuclides in the decay chain are designated by $l = 1$ and $l = 2$, then

$$G_3(t_n, t_{n+1}) = \frac{\lambda_2 A_2(t_n)}{(\lambda_3 - \lambda_2)}\left[\exp(-\lambda_2 \Delta t) - \exp(-\lambda_3 \Delta t)\right] + \lambda_1 \lambda_2 A_1(t_n)\left\{\frac{\exp(-\lambda_1 \Delta t)}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} + \frac{\exp(-\lambda_2 \Delta t)}{(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)} + \frac{\exp(-\lambda_3 \Delta t)}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)}\right\} \quad \text{(PA.123)}$$

in Equation (PA.122).

PA-4.4.3 Implementation in PA

The preceding model is used in two ways in PA. First, Equation (PA.121) estimates releases to the Culebra associated with E1E2 intrusion scenarios (see Section PA-6.7.3). Second, the radionuclide concentrations are computed using the minimum brine volume for a significant release to estimate DBRs (see Section PA-6.8.2.3). The calculation of the minimum brine volume used in the CRA-2009 PA is found in Stein (2005). The calculated concentrations are the S_l term indicated in Equation (PA.97) which are used in the NUTS calculations discussed in Section PA-4.3.

For E1E2 intrusions, the initial amount A_l of radionuclide l is the inventory of the decayed isotope at the time of the E1 intrusion. PANEL calculates the inventory of each of the 29 radioisotopes throughout the regulatory period. The initial concentration C_{bl} of radionuclide l is computed by Equation (PA.117), Equation (PA.118), and Equation (PA.119). For the DBR calculations, the initial amount A_l of radionuclide l is the inventory of the isotope at the time of repository closure.

PA-4.4.4 Additional Information

Additional information on PANEL and its use in the CRA-2009 PA calculations can be found in the PANEL user's manual (WIPP Performance Assessment 2003b), the analysis package for PANEL calculations (Garner and Leigh 2005), and the analysis package for Salado transport calculations in the CRA-2009 PA (Ismail and Garner 2008).

PA-4.5 Cuttings and Cavings to Surface: CUTTINGS_S

Cuttings are waste solids contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste, while cavings are additional waste solids eroded from the borehole by the upward-flowing drilling fluid within the borehole. The releases associated with these processes are computed within the CUTTINGS_S code (WIPP Performance Assessment 2003c). The mathematical representations used for cuttings and cavings are described in this section.

PA-4.5.1 Cuttings

The uncompacted volume of cuttings removed and transported to the surface in the drilling fluid, V_{cut}, is given by

$$V_{cut} = AH_i = \pi D^2 H_i / 4 \quad \text{(PA.124)}$$

where A is the drill bit area (m^2), H_i is the initial (or uncompacted) repository height (3.96 m), and D is the drill-bit diameter (0.31115 m) (Fox 2008, Table 13). For drilling intrusions through RH-TRU waste, H_i = 0.509 m is used (Fox 2008, Table 45).

PA-4.5.2 Cavings

The cavings component of the direct surface release is caused by the shearing action of the drilling fluid on the waste as it flows up the borehole annulus. Like the cuttings release, the cavings release is assumed to be independent of the conditions that exist in the repository during a drilling intrusion.

The final diameter of the borehole depends on the diameter of the drillbit and on the extent to which the actual borehole diameter exceeds the drill-bit diameter. Although a number of factors affect erosion within a borehole (Chambre Syndicale de la Recherche et de la Production du Petrole et du Gaz Naturel 1982), the most important is the fluid shear stress on the borehole wall (i.e., the shearing force per unit area, N/m^2) resulting from circulating drilling fluids (Darley 1969, Walker and Holman 1971). As a result, PA estimates cavings removal with a model based on the effect of shear stress on the borehole diameter. In particular, the borehole diameter is assumed to grow until the shear stress on the borehole wall is equal to the shear strength of the waste, which is the limit below which waste erosion ceases.

The final eroded diameter D_f (m) of the borehole through the waste determines the total volume V (m^3) of uncompacted waste removed to the surface by circulating drilling fluid. Specifically,

$$V = V_{cut} + V_{cav} = \pi D_f^2 H_i / 4 \quad \text{(PA.125)}$$

where V_{cav} is the volume (m^3) of waste removed as cavings.

Most borehole erosion is believed to occur in the vicinity of the drill collar (Figure PA-22) because of decreased flow area and consequent increased mud velocity (Rechard, Iuzzolino, and Sandha 1990, Letters 1a and 1b, App. A). An important determinant of the extent of this erosion is whether the flow of the drilling fluid in the vicinity of the collar is laminar or turbulent. PA uses Reynolds numbers to distinguish between the occurrence of laminar flow and turbulent flow. The Reynolds number is the ratio between inertial and viscous (or shear) forces in a fluid, and can be expressed as (Fox and McDonald 1985)

$$\mathrm{Re} = \frac{\rho_f D_e v}{\eta} \quad \text{(PA.126)}$$

where Re is the Reynolds number (dimensionless), ρ_f is the fluid density (kg/m^3), D_e is the equivalent diameter (m), $v = \|\mathbf{v}\|$ is the fluid speed (m s^{-1}), and η is the fluid viscosity (kg m^{-1} s^{-1}).

Typically, ρ_f, v, and η are averages over a control volume with an equivalent diameter of D_e, where $\rho_f = 1.21 \times 10^3$ kg/m^3 (Fox 2008, Table 13), $v = 0.7089$ m s^{-1} (based on 40 gal/min/in of drill diameter) (Berglund 1992), and $D_e = 2\,(R - R_i)$, as shown in Figure PA-22. The diameter of the drill collar (i.e., $2R_i$ in Figure PA-22) is 8.0 in = 0.2032 m (Ismail 2008). The determination of η is discussed below. PA assumes that Reynolds numbers less than 2100 are associated with laminar flow, while Reynolds numbers greater than 2100 are associated with turbulent flow (Walker 1976).

Drilling fluids are modeled as non-Newtonian, which means that the viscosity η is a function of the shear rate within the fluid (i.e., the rate at which the fluid velocity changes normal to the flow direction, m/s/m). PA uses a model proposed by Oldroyd (1958) to estimate the viscosity of drilling fluids. As discussed in the *Drilling Mud and Cement Slurry Rheology Manual* (Chambre Syndicale de la Recherche et de la Production du Petrole et du Gaz Naturel 1982), the Oldroyd model leads to the following expression for the Reynolds number associated with the helical flow of a drilling fluid within an annulus:

$$\mathrm{Re} = \frac{0.8165\,\rho_f D_e v}{\eta_\infty} \qquad \text{(PA.127)}$$

where ρ_f, D_e, and v are defined as in Equation (PA.126), and η_∞ is the asymptotic value for the derivative of the shear stress (τ, kg m^{-1} s^{-2}) with respect to the shear rate (Γ, s^{-1}) obtained as the shear rate increases (i.e., $\eta_\infty = d\tau / d\Gamma$ as $\Gamma \to \infty$). PA uses Equation (PA.127) to determine whether drilling fluids in the area of the drill collar are undergoing laminar or turbulent flow.

The Oldroyd model assumes that the shear stress τ is related to the shear rate Γ through the relationship

$$\tau = \eta_0 \left(\frac{1 + \sigma_2 \Gamma^2}{1 + \sigma_1 \Gamma^2} \right) \Gamma \qquad \text{(PA.128)}$$

where η_0 is the asymptotic value of the viscosity (kg m^{-1} s^{-1}) that results as the shear rate Γ approaches zero, and σ_1 and σ_2 are constants (s^2). The expression leads to

$$\eta_\infty = \eta_0 \left(\frac{\sigma_2}{\sigma_1} \right) \qquad \text{(PA.129)}$$

PA uses values of $\eta_0 = 1.834 \times 10^{-2}$ kg m^{-1} s^{-1}, $\sigma_1 = 1.082 \times 10^{-6}$ s^2, and $\sigma_2 = 5.410 \times 10^{-7}$ s^2 (Berglund 1996), from which viscosity in the limit of infinite shear rate is found to be $\eta_\infty =$

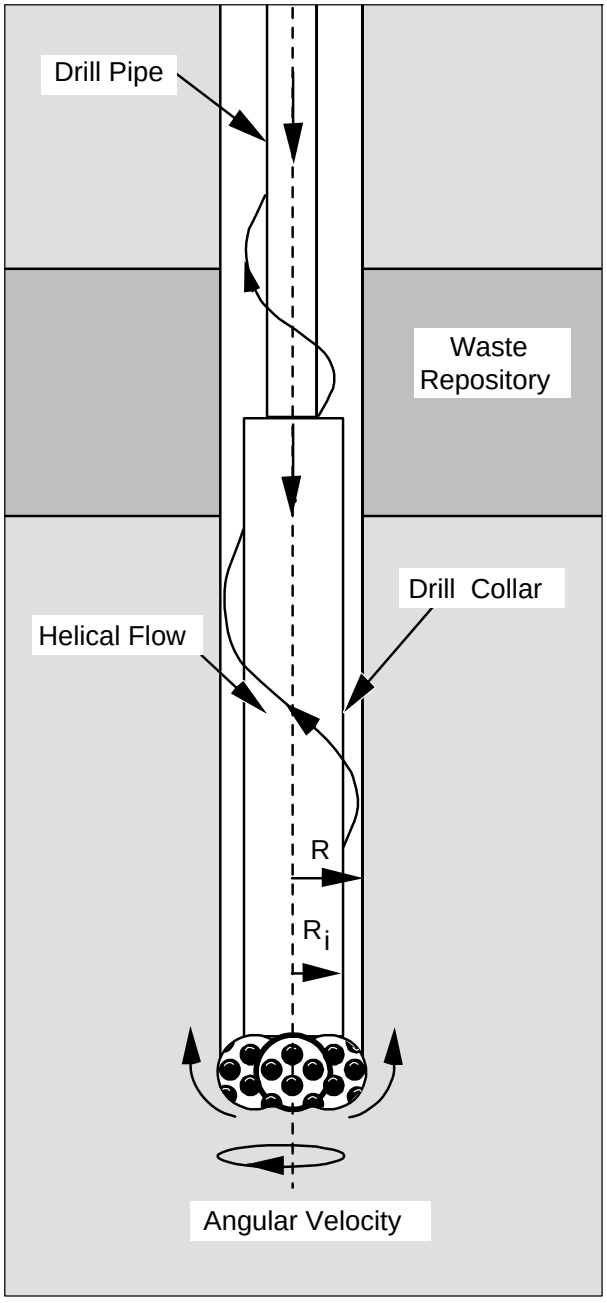


Figure PA-22. Detail of Rotary Drill String Adjacent to Drill Bit

9.17×10^{-3} kg m^{-1} s^{-1}. The quantity η_∞ is comparable to the plastic viscosity of the fluid (Chambre Syndicale de la Recherche et de la Production du Petrole et du Gaz Naturel 1982).

As previously indicated, different models are used to determine the eroded diameter D_f of a borehole depending on whether flow in the vicinity of the drill collar is laminar or turbulent. The model for borehole erosion in the presence of laminar flow is described next, and then the model for borehole erosion in the presence of turbulent flow is described.

PA-4.5.2.1 Laminar Flow Model

As shown by Savins and Wallick (1966), the shear stresses associated with the laminar helical flow of a non-Newtonian fluid, as a function of the normalized radius, r, can be expressed as

$$\tau(R,r)=\sqrt{\left(\frac{C}{r^2}\right)^2+\left[\frac{RJ}{2r}\left(r^2-\lambda^2\right)\right]^2} \qquad \text{(PA.130)}$$

for $R_i/R \le r \le 1$, where R_i and R are the inner and outer radii within which the flow occurs, as indicated in Figure PA-22; $\tau(R,\rho)$ is the shear stress (kg m^{-1} s^{-2}) at a radial distance ΔR beyond the inner boundary (i.e., at $r = (R_i + \Delta R)/R$); and the variables C, J, and λ depend on R and satisfy conditions Equation (PA.132) through Equation (PA.134) indicated below. The shear stress at the outer radius R is given by

$$\tau(R,1)=\sqrt{C^2+\left[\frac{RJ}{2}\left(1-\lambda^2\right)\right]^2} \qquad \text{(PA.131)}$$

As previously indicated, the borehole radius R is assumed to increase as a result of erosional processes until a value of R is reached at which $\tau(R, 1)$ is equal to the shear strength of the waste. In PA, the shear strength of the waste is treated as an uncertain parameter (see WTAUFAIL in Table PA-19). Computationally, determining the eroded borehole diameter R associated with a particular value of the waste shear strength requires repeated evaluation of $\tau(R, 1)$, as indicated in Equation (PA.131), until a value of R is determined for which $\tau(R, 1)$ equals the shear strength.

The quantities C, J, and λ must satisfy the following three conditions (Savins and Wallick 1966) for Equation (PA.131) to be valid:

$$\int_{R_i/R}^{1}\left(\frac{x^2-\lambda^2}{\eta x}\right)dx=0 \qquad \text{(PA.132)}$$

$$C\int_{R_i/R}^{1}\frac{dx}{\eta x^3}=\Delta\Omega \qquad \text{(PA.133)}$$

$$J\int_{R_i/R}^{1}\left(\frac{\left(R_i/R\right)^2-x^2}{\eta x}\right)\left(\frac{x^2-\lambda^2}{\eta x}\right)dx=-\frac{2Q}{\pi R^4} \qquad \text{(PA.134)}$$

where η, the drilling fluid viscosity (kg m^{-1} s^{-1}), is a function of R and ρ; $\Delta\Omega$ is the drill string angular velocity (rad s^{-1}); and Q is the drilling fluid flow rate (m^3 s^{-1}).

The viscosity η in Equation (PA.132) through Equation (PA.134) is introduced into the analysis by assuming that the drilling fluid follows the Oldroyd model for shear stress in Equation (PA.128). By definition of the viscosity η,

$$\tau = \eta\Gamma \tag{PA.135}$$

and from Equation (PA.128)

$$\Gamma^2 = \frac{\eta - \eta_0}{\eta_0\sigma_2 - \eta\sigma_1} \tag{PA.136}$$

thus the expression in Equation (PA.130) can be reformulated as

$$\frac{\eta^2(\eta - \eta_0)^2}{(\eta_0\sigma_2 - \eta\sigma_1)^2} = \left(\frac{C}{r^2}\right)^2 + \left[\frac{RJ}{2r}\left(r^2 - \lambda^2\right)\right]^2 \tag{PA.137}$$

As discussed by Savins and Wallick (1966) and Berglund (1992), the expressions in Equation (PA.132) through Equation (PA.134) and Equation (PA.136) can be numerically evaluated to obtain C, J, and λ for use in Equation (PA.130) and Equation (PA.131). In PA, the drill string angular velocity $\Delta\Omega$ is treated as an uncertain parameter (see DOMEGA in Table PA-19), and

$$Q = v\left(\pi R^2 - \pi R_i^2\right) \tag{PA.138}$$

where $v = 0.7089$ m s^{-1} as used in Equation (PA.126), and η_0, σ_1, and σ_2 are defined as in Equation (PA.128) and Equation (PA.129).

PA-4.5.2.2 Turbulent Flow Model

The model for borehole erosion in the presence of turbulent flow is now described. Unlike the theoretically derived relationship for erosion in the presence of laminar flow, the model for borehole erosion in the presence of turbulent flow is empirical. In particular, pressure loss for axial flow in an annulus under turbulent flow conditions can be approximated by (Chambre Syndicale de la Recherche et de la Production du Petrole et du Gaz Naturel 1982)

$$\Delta P = \frac{2fL\rho_f v^2}{0.8165D_e} \tag{PA.139}$$

where ΔP is the pressure change (Pa), f is the Fanning friction factor (dimensionless), L is the distance (m) over which pressure change ΔP occurs, and ρ_f, v, and D_e are defined in Equation (PA.126).

For turbulent pipe flow, f is empirically related to the Reynolds number Re defined in Equation (PA.126) by (Whittaker 1985)

$$\frac{1}{\sqrt{f}} = -4\log_{10}\left(\frac{\varepsilon}{3.72D} + \frac{1.255}{\mathrm{Re}\sqrt{f}}\right) \quad \text{(PA.140)}$$

where D is the inside diameter (m) of the pipe and ε is a "roughness term" equal to the average depth (m) of pipe wall irregularities. In the absence of a similar equation for flow in an annulus, Equation (PA.140) is used in PA to define f for use in Equation (PA.139), with D replaced by the effective diameter $D_e = 2(R - R_i)$ and ε equal to the average depth of irregularities in the waste-borehole interface. In the present analysis, ε = 0.025 m (Fox 2008, Table 34), which exceeds the value often selected in calculations involving very rough concrete or riveted steel piping (Streeter 1958).

The pressure change ΔP in Equation (PA.139) and the corresponding shear stress τ at the walls of the annulus are approximately related by

$$(\Delta P)\pi\left(R^2 - R_i^2\right) = 2\pi L\tau\left(R + R_i\right) \quad \text{(PA.141)}$$

where $\pi\left(R^2 - R_i^2\right)$ is the cross-sectional area of the annulus (see Figure PA-22) and $2\pi L(R + R_i)$ is the total surface area of the annulus. Rearranging Equation (PA.139) and using the relationship in Equation (PA.135) yields

$$\tau(R) = \frac{f\rho_f v^2}{2(0.8165)} \quad \text{(PA.142)}$$

which was used in the 1991 and 1992 WIPP PAs to define the shear stress at the surface of a borehole of radius R. The radius R enters into Equation (PA.132) through Equation (PA.134) through the use of $D = 2(R - R_i)$ in the definition of f in Equation (PA.140). As with laminar flow, the borehole radius R is assumed to increase until a value of $\tau(R)$ is reached that equals the sample value for the shear strength of the waste (i.e., the uncertain parameter WTAUFAIL in Table PA-19). Computationally, the eroded borehole diameter is determined by solving Equation (PA.142) for R under the assumption that $\tau(R)$ equals the assumed shear strength of the waste.

For the CRA-2004 PA, a slight modification to the definition of τ in Equation (PA.142) was made to account for drill string rotation when fluid flow in the vicinity of the drill collars is turbulent (Abdul Khader and Rao 1974; Bilgen, Boulos, and Akgungor 1973). Specifically, an axial flow velocity correction factor (i.e., a rotation factor), F_r, was introduced into the definition of τ. The correction factor F_r is defined by

$$F_r = v_{2100} / v \quad \text{(PA.143)}$$

where v_{2100} is the norm of the flow velocity required for the eroded diameters to be the same for turbulent and laminar flow at a Reynolds number of Re = 2100, and is obtained by solving

$$\tau_{fail} = \frac{f\rho_f v_{2100}^2}{2(0.8165)} \quad \text{(PA.144)}$$

for v_{2100} with D in the definition of f in Equation (PA.140) assigned the final diameter value that results for laminar flow at a Reynolds number of Re = 2100 (that is, the D in $D_e = 2(R - R_i) = D - 2R_i$ obtained from Equation (PA.127) with Re = 2100). The modified definition of τ is

$$\tau(R) = \frac{f\rho_f (F_r v)^2}{2(0.8165)} \quad \text{(PA.145)}$$

and results in turbulent and laminar flow with the same eroded diameter at a Reynolds number of 2100, where PA assumes that the transition between turbulent and laminar flow takes place.

PA-4.5.2.3 Calculation of R_f

The following algorithm was used to determine the final eroded radius R_f of a borehole and incorporates a possible transition from turbulent to laminar fluid flow within a borehole:

Step 1. Use Equation (PA.127) to determine an initial Reynolds number Re, with R initially set to the drill-bit radius, R_0 = 0.31115 m (Fox 2008, Table 13).

Step 2. If Re < 2100, the flow is laminar and the procedure in Section PA-4.5.2.1 is used to determine R_f. Because any increase in the borehole diameter will cause the Reynolds number to decrease, the flow will remain laminar and there is no need to consider the possibility of turbulent flow as the borehole diameter increases, with the result that R_f determined in this step is the final eroded radius of the borehole.

Step 3. If Re ≥ 2100, then the flow is turbulent, and the procedure discussed in Section PA-4.5.2.2 is used to determine R_f. Once R_f is determined, the associated Reynolds number Re is recalculated using Equation (PA.127) and $R = R_f$. If the recalculated Re > 2100, a transition from turbulent to laminar flow cannot take place, and the final eroded radius is R_f determined in this step. If not, go to Step 4.

Step 4. If the Reynolds number Re with the new R_f in Step 3 satisfies the inequality Re ≤ 2100, a transition from turbulent to laminar flow is assumed to have taken place. In this case, R_f is recalculated assuming laminar flow, with the outer borehole radius R initially defined to be the radius associated with Re = 2100. In particular, the initial value for R is given by the radius at which the transition from laminar to turbulent flow takes place:

$$R = R_i + \frac{2100\eta_\infty}{2(0.8165)v\rho} \quad \text{(PA.146)}$$

which is obtained from Equation (PA.127) by solving for R with Re = 2100. A new value for R_f is then calculated with the procedure discussed in Section PA-4.5.2.1 for

laminar flow, with this value of R_f replacing the value from Step 3 as the final eroded diameter of the borehole.

Step 5. Once R_f is known, the amount of waste removed to the surface is determined using Equation (PA.125) with $D_f = 2R_f$.

PA-4.5.3 Additional Information

Additional information on CUTTINGS_S and its use in the CRA-2004 PA to determine cuttings and cavings releases can be found in the CUTTINGS_S user's manual (WIPP Performance Assessment 2003c) and in the analysis package for cuttings and cavings releases (Ismail 2008).

PA-4.6 Spallings to Surface: DRSPALL and CUTTINGS_S

Spallings are waste solids introduced into a borehole by the movement of waste-generated gas towards the lower-pressure borehole. In engineering literature, the term "spalling" describes the dynamic fracture of a solid material, such as rock or metal (Antoun et al. 2003). In WIPP PA, the spallings model describes a series of processes, including tensile failure of solid waste, fluidization of failed material, entrainment into the wellbore flow, and transport up the wellbore to the land surface. Spallings releases could occur when pressure differences between the repository and the wellbore cause solid stresses in the waste exceeding the waste material strength and gas velocities sufficient to mobilize failed waste material.

The spallings model is described in the following sections. Presented first are the primary modeling assumptions used to build the conceptual model. Next, the mathematical model and its numerical implementation in the computer code DRSPALL are described. Finally, implementation of the spallings model in WIPP PA by means of the code CUTTINGS_S is discussed.

PA-4.6.1 Summary of Assumptions

Assumptions underlying the spallings model include the future state of the waste, specifications of drilling equipment, and the driller's actions at the time of intrusion. Consistent with the other PA models, the spallings model assumes massive degradation of the emplaced waste through mechanical compaction, corrosion, and biodegradation. Waste is modeled as a homogeneous, isotropic, weakly consolidated material with uniform particle size and shape. The rationale for selecting the spallings model material properties is addressed in detail by Hansen et al. (1997) and Hansen, Pfeifle, and Lord (2003).

Drilling equipment specifications, such as bit diameter and drilling mud density, are based on surveys of drillers in the Delaware Basin (Hansen, Pfeifle, and Lord 2003). Assumptions about the driller's actions during the intrusion are conservative. Typically, the drilling mud density is controlled to maintain a slightly "overbalanced" condition so that the mud pressure is always slightly higher than the fluid pressures in the formation. If the borehole suddenly passes through a high-pressure zone, the well can quickly become "underbalanced," with a resulting fluid pressure gradient driving formation fluids into the wellbore. This situation is known as a *kick* and is of great concern to drillers because a violent kick can lead to a blowout of mud, gas, and

oil from the wellbore, leading to equipment damage and worker injury. Standard drilling practice is to watch diligently for kicks. The first indicator of a kick is typically an increase in mud return rate, leading to an increase in mud pit volume (Frigaard and Humphries 1997). Downhole monitors detect whether the kick is air, H_2S, or brine. If the kick fluid is air, the standard procedure is to stop drilling and continue pumping mud in order to circulate the air pocket out. If the mud return rate continues to grow after drilling has stopped and the driller believes that the kick is sufficiently large to cause damage, the well may be shut in by closing the blowout preventer. Once shut in, the well pressure may be bled off slowly and mud weight eventually increased and circulated to offset the higher formation pressure before drilling continues. The spallings model simulates an underbalanced system in which a gas kick is assured, and the kick proceeds with no intervention from the drill operation. Therefore, drilling and pumping continue during the entire blowout event.

PA-4.6.2 Conceptual Model

The spallings model calculates transient repository and wellbore fluid flow before, during, and after a drilling intrusion. To simplify the calculations, both the wellbore and the repository are modeled by one-dimensional geometries. The wellbore assumes a compressible Newtonian fluid consisting of a mixture of mud, gas, salt, and waste solids; viscosity of the mixture varies with the fraction of waste solids in the flow. In the repository, flow is viscous, isothermal, compressible single-phase (gas) flow in a porous medium.

The wellbore and repository flows are coupled by a cylinder of porous media before penetration, and by a cavity representing the bottom of the borehole after penetration. Schematic diagrams of the flow geometry prior to and after penetration are shown in Figure PA-23 and Figure PA-24, respectively. The drill bit moves downward as a function of time, removing salt or waste material. After penetration, waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream at the cavity forming the repository-wellbore boundary.

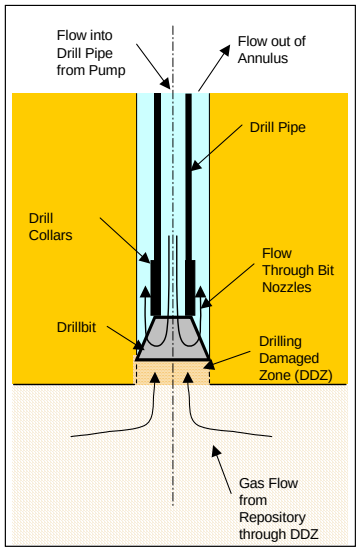


Figure PA-23. Schematic Diagram of the Flow Geometry Prior to Repository Penetration

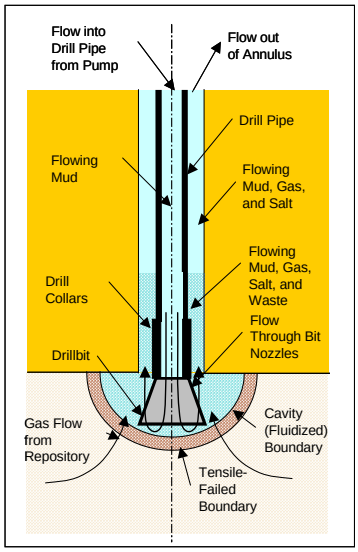


Figure PA-24. Schematic Diagram of the Flow Geometry After Repository Penetration

PA-4.6.2.1 Wellbore Flow Model

Flow in the well is modeled as a one-dimensional pipe flow with cross-sectional areas corresponding to the appropriate flow area at a given position in the well, as shown in Figure PA-25 and Figure PA-26. This model is conceptually similar to that proposed by Podio and Yang (1986) for use in the oil and gas industry. Drilling mud is added at the wellbore entrance by the pump. Flow through the drill bit is treated as a choke with cross-sectional area appropriate for the bit nozzle area. At the annulus output to the surface, the mixture is ejected at a constant atmospheric pressure. The gravitational body force acts in its appropriate direction based on position before or after the bit.

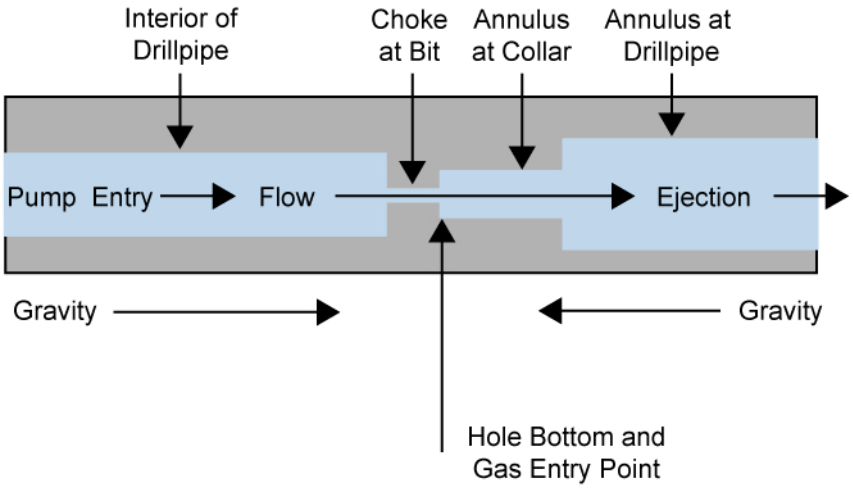


Figure PA-25. Effective Wellbore Flow Geometry Before Bit Penetration

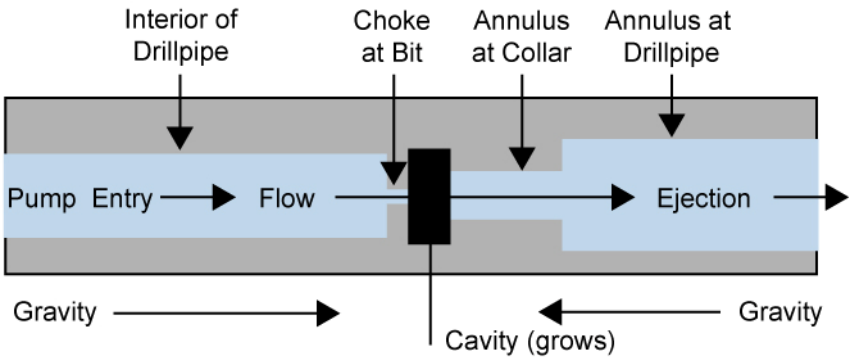


Figure PA-26. Effective Wellbore Flow Geometry After Bit Penetration

Prior to drill bit penetration into the repository, gas from the repository can flow through drilling-damaged salt into the well. After penetration, the cavity at the bottom of the wellbore couples the wellbore flow and the repository flow models; gas and waste material can exit the repository domain into the cavity. The cavity radius increases as waste materials are moved into the wellbore.

The system of equations representing flow in the wellbore consists of four equations for mass conservation, one for each phase (salt, waste, mud, and gas); one equation for conservation of total momentum; two equations relating gas and mud density to pressure; the definition of density for the fluid mixture; and one constraint imposed by the fixed volume of the wellbore. The conservation of mass and momentum is described by

$$\frac{\partial}{\partial t}\left(\rho_q V_q\right)+\frac{\partial}{\partial z}\left(\rho_q V_q u\right)=S_q \qquad \text{(PA.147)}$$

$$\frac{\partial}{\partial t}\left(\rho V u\right)+\frac{\partial}{\partial z}\left(\rho V u^2\right)=-V\left(\frac{\partial P}{\partial z}-\rho g+F\right)+S_{mom} \qquad \text{(PA.148)}$$

where

q = phase (w for waste, s for salt, m for mud, and g for gas)
V_q = volume (m^3) of phase q
V = total volume (m^3)
ρ_q = density (kg/m^3) of phase q, constant for salt and waste (2,180 and 2,650 kg/m^3, respectively) and pressure-dependent for gas and mud (see Equation (PA.149) and Equation (PA.150))
ρ = density of fluid mixture (kg/m^3) determined by Equation (PA.151)
u = velocity (m/s) of fluid mixture in wellbore
t = time (s)
z = distance (m) from inlet at top of well
S_q = rate of mass (kg/s) in phase q entering and exiting wellbore domain at position z (Equation (PA.162))

S_{mom} = rate of momentum (kg m/s^2) entering and exiting wellbore domain at position z (Equation (PA.165))
P = pressure (Pa) at position z
g = standard gravity (9.8067 kg/m/s^2)
F = friction loss using pipe flow model (kg/m^2/s^2) determined by Equation (PA.153)

Gas is treated as isothermal and ideal, so the pressure and density are related by Boyle's law:

$$\frac{\rho}{\rho_{g,0}} = \frac{P}{P_{atm}} \tag{PA.149}$$

where $\rho_{g,0}$ is the density of H_2 gas at atmospheric pressure and 298 K (8.24182×10^{-2} kg/m^3).

The mud is assumed to be a compressible fluid, so

$$\rho_m = \rho_{m,0}\left[1 + c_m\left(P - P_{atm}\right)\right] \tag{PA.150}$$

where $\rho_{m,0}$ is the density of the mud at atmospheric pressure (1,210 kg/m^3) and c_m is the compressibility of the mud (3.1×10^{-10} Pa^{-1}).

The density of the fluid mixture is determined from the densities and volumes occupied by the phases:

$$\rho = \frac{\rho_g V_g + \rho_m V_m + \rho_s V_s + \rho_w V_w}{V} \tag{PA.151}$$

The volume of each phase is constrained by the fixed total volume of the wellbore:

$$V = V_g + V_m + V_s + V_w \tag{PA.152}$$

The friction loss is a standard formulation for pipe flow (Fox and McDonald 1985), where the head loss per unit length is given as

$$F = \frac{\Delta P}{L} = \frac{f \rho u^2}{2 d_h} \tag{PA.153}$$

where the hydraulic diameter d_h is given by

$$d_h = \frac{4A}{\pi\left(D_i + D_o\right)} \tag{PA.154}$$

In PA, D_o = 0.31115 m throughout the domain. From the bit to the top of the collar, D_i = 0.2032 m; above the collar, D_i = 0.1143 m. The area A is calculated as the area of the annulus between the outer and inner radii:

$$A = \frac{\pi}{4}\left(D_o^2 - D_i^2\right) \tag{PA.155}$$

Thus, $d_h = 0.108$ m from the bit to the top of the collar, and $d_h = 0.197$ m above the collar.

The Darcy friction factor f in Equation (PA.153) is determined by the method of Colebrook (Fox and MacDonald 1985). In the laminar regime, which is assumed to be characterized by Reynolds numbers below 2100 (Walker 1976),

$$f = \frac{64}{\mathrm{Re}} \tag{PA.156}$$

and in the turbulent regime (Re > 2100)

$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left(\frac{\varepsilon}{3.72 d_h} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \tag{PA.157}$$

where $\mathrm{Re} = \frac{u\rho d_h}{\eta}$ is the Reynolds number of the mixture, and η is the viscosity calculated in Equation (PA.158), below. As the wellbore mixture becomes particle-laden, the viscosity of the mixture is determined from an empirical relationship developed for proppant slurry flows in channels for the oil and gas industry (Barree and Conway 1995). Viscosity is computed by an approximate slurry formula based on the volume fraction of waste solids:

$$\eta = \eta_0\left(1 - \frac{w}{w_{\max}}\right)^s \tag{PA.158}$$

where η_0 is a base mixture viscosity (9.17×10^{-3} Pa s), $w = V_w/V$ is the current volume fraction of waste solids, w_{max} is an empirically determined maximal volume fraction above which flow is choked (0.615), and s is an empirically determined constant (−1.5) (Hansen, Pfeifle, and Lord 2003).

PA-4.6.2.1.1 Wellbore Initial Conditions

Initial conditions in the wellbore approximate mixture flow conditions just prior to waste penetration. The wellbore is assumed to contain only mud and salt. Initial conditions for the pressure, fluid density, volume fractions of mud and salt, and the mixture velocity are set by the following algorithm:

Step 1. Set pressure in the wellbore to hydrostatic: $P(z) = P_{atm} - \rho_{m,0} g z$.

Step 2. Set mud density using Equation (PA.150).

Step 3. Set mixture velocity: $u(z) = R_m/A(z)$, where R_m is the volume flow rate of the pump (0.0202 m^3/s), and $A(z)$ is the cross-sectional area of the wellbore.

Step 4. Set volume of salt in each cell: $V_{s,i} = R_{drill}A_{bit}\Delta z_i/u_i$, where R_{drill} is the rate of drilling (0.004445 m/s), $A_{bit} = \pi d_{bit}^2 / 4$ is the area of the bottom of the wellbore, and d_{bit} is the diameter of the bit (0.31115 m).

Step 5. Set volume fraction of mud in each cell: $V_{m,i} = V_i - V_{s,i}$.

Step 6. Recalculate mixture density using Equation (PA.151), assuming no waste or gas in the wellbore.

The initial conditions set by this algorithm approximate a solution to the wellbore flow (Equation (PA.147) and Equation (PA.148)) for constant flow of mud and salt in the well. The approximation rapidly converges to a solution for wellbore flow if steady-state conditions are maintained (WIPP Performance Assessment 2003d).

PA-4.6.2.1.2 Wellbore Boundary Conditions

For simplicity, DRSPALL does not model flow of mud down the pipe to the bit. Mass can enter the wellbore below the drill bit and exit at the wellbore outlet. Below the bit, mud, salt, gas, and waste can enter the wellbore. PA assumes a constant volume of mud flow down the drilling pipe; therefore, the source term for mud, $S_{m,in}$, is set by the volumetric flow rate of the pump R_m (0.0202 m^3/s) and the density of the mud at the bottom of the wellbore:

$$S_{m,in} = \rho_m R_m \tag{PA.159}$$

Until the drill bit penetrates the repository, salt enters the wellbore at a constant rate:

$$S_{s,in} = \rho_s R_{drill} A_{bit} \tag{PA.160}$$

Additional mass enters the wellbore by gas flow from the repository ($S_{gas,in}$) and spalling of waste material ($S_{w,in}$); these mass sources are discussed in Section PA-4.6.2.3. The outlet of the wellbore is set to atmospheric pressure. Mass exiting the wellbore is determined from the mixture velocity, the area of the outlet A_{out} (0.066 m^2), and the density and volume fraction of each phase at the outlet of the wellbore:

$$S_{q,out} = \rho u_{out} A_{out} \frac{V_q}{V} \tag{PA.161}$$

Finally, the net change in mass and momentum for phase q is

$$S_q = S_{q,in} - S_{q,out} \tag{PA.162}$$

$$S_{mom,in} = \frac{\rho_{0,m}}{A_p} R_{mudpump} \quad \text{(PA.163)}$$

The outlet of the wellbore is set to atmospheric pressure. Momentum exiting the wellbore is determined from the fluid velocity and the area of the outlet A_{out} (0.066 m^2):

$$S_{mom,out} = -\rho A_{out} u_{out}^2 \quad \text{(PA.164)}$$

No momentum is added by mass flow into the wellbore from the repository; thus

$$S_{mom} = S_{mom,in} - S_{mom,out} \quad \text{(PA.165)}$$

PA-4.6.2.2 Repository Flow Model

The repository is modeled as a radially symmetric domain. A spherical coordinate system is used for this presentation and for most DRSPALL calculations. In a few circumstances, cylindrical coordinates are used in PA calculations, where spall volumes are large enough that spherical coordinates are not representative of the physical process (Lord, Rudeen, and Hansen 2003). Cylindrical coordinates are also available; the design document for DRSPALL (WIPP Performance Assessment 2003e) provides details on implementing the repository flow model in cylindrical coordinates.

Flow in the repository is transient, compressible, viscous, and single-phase (gas) flow in a porous medium. Gas is treated as isothermal and ideal. The equations governing flow in the repository are the equation of state for ideal gases (written in the form of Boyle's law for an ideal gas at constant temperature), conservation of mass, and Darcy's law with the Forchheimer correction (Aronson 1986, Whitaker 1996):

$$\frac{\rho_g}{\rho_{g,0}} = \frac{P}{P_{atm}} \quad \text{(PA.166)}$$

$$\phi \frac{\partial \rho_g}{\partial t} + \nabla \cdot \left(\rho_g u \right) = 0 \quad \text{(PA.167)}$$

$$\nabla P = -\frac{\eta_g}{k} \left(1 + F \right) u \quad \text{(PA.168)}$$

where

P = pressure in pore space (Pa)
ρ_g = density of gas (kg/m^3)
u = velocity of gas in pore space (m/s)
ϕ = porosity of the solid (unitless)
η_g = gas viscosity (8.934×10^{-6} Pa s)

k = permeability of waste solid (m^2)
F = Forchheimer correction (unitless)

The Forchheimer correction is included in Equation (PA.168) to account for inertia in the flowing gas, which becomes important at high gas velocities (Ruth and Ma 1992). When the Forchheimer coefficient is zero, Equation (PA.168) reduces to Darcy's law. A derivation of Equation (PA.168) from the Navier-Stokes equations is given by Whitaker (1996); the derivation suggests that F is a linear function of gas velocity for a wide range of Reynolds numbers.

In PA, the Forchheimer correction takes the form

$$F = \beta_{nd} \rho u \tag{PA.169}$$

where β_{nd} is the non-Darcy coefficient, which depends on material properties such as the tortuosity and area of internal flow channels, and is empirically determined (Belhaj et al. 2003). DRSPALL uses a value from Li et al. (2001) that measured high-velocity nitrogen flow through porous sandstone wafers, giving the result

$$\beta_{nd} = \frac{1.15 \times 10^{-6}}{k\phi} \tag{PA.170}$$

Equation (PA.166) through Equation (PA.168) combines into a single equation for pressure in the porous solid:

$$\frac{\partial P}{\partial t} = \frac{k'}{2\phi\eta_g} \nabla^2 P^2 + \frac{1}{2\phi\eta_g} \nabla P^2 \cdot \nabla k' \tag{PA.171}$$

where

$$k' = \frac{k}{1+F} = \frac{k}{1+\beta_{nd}\rho u} \tag{PA.172}$$

and the Laplacian operator in a radially symmetric coordinate system is given by

$$\nabla^2 = \frac{1}{r^{n-1}} \frac{\partial}{\partial r} \left(r^{n-1} \frac{\partial}{\partial r} \right) \tag{PA.173}$$

where $n = 2$ and $n = 3$ for polar and spherical coordinates, respectively.

In DRSPALL, the permeability of the waste solid is a subjectively uncertain parameter that is constant for waste material that has not failed and fluidized. In a region of waste that has failed, the permeability increases as the waste fluidizes by a factor of $1 + F_f$, where F_f is the fraction of failed material that has fluidized and is based on the fluidization relaxation time. This approximately accounts for the material bulking as it fluidizes.

Initial pressure in the repository is set to a constant value P_{ff}. A no-flow boundary condition is imposed at the outer boundary ($r = R$):

$$\nabla P(R) = 0 \qquad \text{(PA.174)}$$

At the inner boundary ($r = r_{cav}$), the pressure is specified as $P(r_{cav},t) = P_{cav}(t)$, where $P_{cav}(t)$ is defined in the next section. The cavity radius r_{cav} increases as drilling progresses and waste material fails and moves into the wellbore; calculation of r_{cav} is described in Section PA-4.6.2.3.3.

PA-4.6.2.3 Wellbore to Repository Coupling

Prior to penetration, a cylinder of altered-permeability salt material with diameter equal to the drill bit is assumed to connect the bottom of the wellbore to the repository. At the junction of the repository and this cylinder of salt, a small, artificial cavity is used to determine the boundary pressure for repository flow. After penetration, the cavity merges with the bottom of the wellbore to connect the wellbore to the repository.

PA-4.6.2.3.1 Flow Prior to Penetration

The cylinder of salt connecting the wellbore to the repository is referred to as the DDZ in Figure PA-23. The permeability of the DDZ, k_{DDZ}, is 1×10^{-14} m^2. The spallings model starts with the bit 0.15 m above the repository; the bit advances at a rate of $R_{drill} = 0.004445$ m/s.

To couple the repository to the DDZ, the model uses an artificial pseudo-cavity in the small hemispherical region of the repository below the wellbore with the same surface area as the bottom of the wellbore (Figure PA-26). The pseudo-cavity is a numerical device that smoothes the discontinuities in pressure and flow that would otherwise occur upon bit penetration of the repository. The pseudo-cavity contains only gas, and is initially at repository pressure. The mass of gas in the cavity m_{cav} is given by

$$\frac{dm_{cav}}{dt} = S_{rep} - S_{g,in} \qquad \text{(PA.175)}$$

where

S_{rep} = gas flow from repository into pseudo-cavity (kg/s); see Equation (PA.176)
$S_{g,\,in}$ = gas flow from pseudo-cavity through DDZ into wellbore (kg/s); see Equation (PA.177)

Flow from the repository into the pseudo-cavity is given by

$$S_{rep} = \rho_{g,rep} u_{rep} \phi A_{cav} \qquad \text{(PA.176)}$$

where

$\rho_{g,rep}$ = gas density in repository at cavity surface (kg/m^3) = $\rho_g\left(r_{cav}\right)$
u_{rep} = gas velocity (m/s) in repository at cavity surface = $u\left(r_{cav}\right)$
ϕ = porosity of waste (unitless)
A_{cav} = surface area of hemispherical part of the cavity (m^2)
= $\pi d_{bit}^2 / 4$, where d_{bit} is the diameter of the bit (m)

Flow out of the pseudo-cavity through the DDZ and into the wellbore is modeled as steady-state using Darcy's Law:

$$S_{g,in} = \frac{k_{DDZ}\pi M_w}{2\eta_g RTL}\left(\frac{d_{bit}}{2}\right)^2\left(P_{cav}^2 - P_{BH}^2\right) \qquad \text{(PA.177)}$$

where

η_g = viscosity of H_2 gas (8.934×10^{-6} Pa s)
M_w = molecular weight of H_2 gas (0.00202 kg / mol)
R = ideal gas constant (8.314 J/mol K)
T = repository temperature (constant at 300 K (27 ºC; 80 ºF))
L = length (m) of DDZ (from bottom of borehole to top of repository)
P_{cav} = pressure in pseudo-cavity (Pa)
P_{BH} = pressure at bottom of wellbore (Pa)

A justification for using this steady-state equation is provided in the design document for DRSPALL (WIPP Performance Assessment 2003e). The pseudo-cavity is initially filled with gas at a pressure of P_{ff}. The boundary pressure on the well side (P_{BH}) is the pressure immediately below the bit, determined by Equation (PA.147) and Equation (PA.148). The pressure in the pseudo-cavity (P_{cav}) is determined by the ideal gas law:

$$P_{cav} = \frac{m_{cav}R_0T}{V_{cav}} \qquad \text{(PA.178)}$$

where m_{cav} is the number of moles of gas in the cavity and the cavity volume V_{cav} is given by

$$V_{cav} = \frac{\pi d_{bit}^3}{24\sqrt{2}} \qquad \text{(PA.179)}$$

In PA, the drilling rate into the ground is assumed constant at 0.004445 m/s; thus $L = L_i - 0.004445t$ until $L = 0$, at which time the bit penetrates the waste. The term L_i is the distance from the bit to the waste at the start of calculation (0.15 m).

PA-4.6.2.3.2 Flow After Penetration

After waste penetration, the bottom of the wellbore is modeled as a hemispherical cavity in the repository, the radius of which grows as drilling progresses and as material fails and moves into the cavity. Gas, drilling mud, and waste are assumed to thoroughly mix in this cavity; the resulting mixture flows around the drill collars and then up the annulus between the wellbore and the drill string. Gas flow from the repository into the cavity is given by Equation (PA.176); however, A_{cav} is now dependent on the increasing radius of the cavity (see Section PA-4.6.2.3.3). Mudflow into the cavity from the wellbore is given by Equation (PA.159). Waste flow into the cavity is possible if the waste fails and fluidizes; these mechanisms are discussed in Section PA-4.6.2.3.4 and Section PA-4.6.2.3.5. Pressure in the cavity is equal to that at the bottom of the wellbore, and is computed by Equation (PA.178).

PA-4.6.2.3.3 Cavity Volume After Penetration

The cylindrical cavity of increasing depth created by drilling is mapped to a hemispherical volume at the bottom of the wellbore to form the cavity. This mapping maintains equal surface areas in order to preserve the gas flux from the repository to the wellbore. The cavity radius from drilling is thus

$$r_{drill} = \sqrt{\frac{d_{bit}^2 + 4 d_{bit} \Delta H}{8}} \qquad \text{(PA.180)}$$

where ΔH is the depth of the drilled cylinder. In PA, the drilling rate into the ground is assumed constant at 0.004445 m/s; thus $\Delta H = 0.004445t$ until $\Delta H = H$, the height of compacted waste (m). Since the initial height of the repository is 3.96 m, H is computed from the porosity ϕ by $H = 3.96(1-\phi_0)/(1-\phi)$, where ϕ_0 is the initial porosity of a waste-filled room.

The cavity radius r_{cav} is increased by the radius of failed and fluidized material r_{fluid}, which is the depth to which fluidization has occurred beyond the drilled radius. That is,

$$r_{cav} = r_{drill} + r_{fluid} \qquad \text{(PA.181)}$$

PA-4.6.2.3.4 Waste Failure

Gas flow from the waste creates a pressure gradient within the waste, which induces elastic stresses in addition to the far-field confining stress. These stresses may lead to tensile failure of the waste material, an assumed prerequisite to spallings releases. While the fluid calculations using Equation (PA.166) through Equation (PA.168) are fully transient, the elastic stress calculations are assumed to be quasi-static (i.e., sound-speed phenomena in the solid are ignored). Elastic effective stresses are (Timoshenko and Goodier 1970)

$$\sigma_r(r) = \sigma_{sr}(r) + \sigma_{ff}\left(1 - \left(\frac{r_{cav}}{r}\right)^3\right) + P(r_{cav})\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r) \qquad \text{(PA.182)}$$

$$\sigma_\theta(r) = \sigma_{s\theta}(r) + \sigma_{ff}\left[1 + \frac{1}{2}\left(\frac{r_{cav}}{r}\right)^2\right] - \frac{P(r_{cav})}{2}\left(\frac{r_{cav}}{r}\right)^3 - \beta P(r) \qquad \text{(PA.183)}$$

where β is Biot's constant (assumed here to be 1.0) and σ_{ff} is the confining far-field stress (assumed constant at 14.8 MPa).

The flow-related radial and tangential stresses (σ_{sr} and $\sigma_{s\theta}$, respectively) are computed by equations analogous to differential thermal expansion (Timoshenko and Goodier 1970):

$$\sigma_{sr}(r) = \frac{2\beta}{r^3}\left(\frac{1-2\upsilon}{1-\upsilon}\right)\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds \qquad \text{(PA.184)}$$

$$\sigma_{s\theta}(r) = -\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\left(\frac{1}{r^3}\int_{r_{cav}}^{r}\left(P(s) - P_{ff}\right)s^2 ds - \left(P(r) - P_{ff}\right)\right) \qquad \text{(PA.185)}$$

where P_{ff} is the initial repository pressure and υ is Poisson's ratio (0.38).

Since stresses are calculated as quasi-static, an initial stress reduction caused by an instantaneous pressure drop at the cavity face propagates instantaneously through the waste. The result of calculating Equation (PA.182) can be an instantaneous early-time tensile failure of the entire repository if the boundary pressure is allowed to change suddenly. This is nonphysical and merely a result of the quasi-static stress assumption, combined with the true transient pore pressure and flow-related stress equations. To prevent this nonphysical behavior, tensile failure propagation is limited by a tensile failure velocity (1000 m/s; see Hansen et al. 1997). This limit has no quantitative effect on results, other than to prevent nonphysical tensile failure.

At the cavity face, Equation (PA.182) and Equation (PA.184) evaluate to zero, consistent with the quasi-static stress assumption. This implies that the waste immediately at the cavity face cannot experience tensile failure; however, tensile failure may occur at some distance into the waste material. Consequently, the radial effective stress σ_r is averaged from the cavity boundary into the waste over a characteristic length L_t (0.02 m). If this average radial stress $\bar{\sigma}_r$ is tensile and its magnitude exceeds the material tensile strength ($|\bar{\sigma}_r|$ > TENSLSTR), the waste is no longer capable of supporting radial stress and fails, permitting fluidization. The waste tensile strength is an uncertain parameter in the analysis (see TENSLSTR in Table PA-15).

Equation (PA.183) and Equation (PA.185) evaluate shear stresses in the waste. DRSPALL does not use the waste shear stresses to calculate waste failure for spall releases. These stresses are included in this discussion for completeness.

PA-4.6.2.3.5 Waste Fluidization

Failed waste material is assumed to be disaggregated, but not in motion; it remains as a porous, bedded material lining the cavity face, and is treated as a continuous part of the repository from the perspective of the porous flow calculations. The bedded material may be mobilized and enter the wellbore if the gas velocity in the failed material (see Equation (PA.168)) exceeds a

minimum fluidization velocity, U_f. The minimum fluidization velocity is determined by solving the following quadratic equation (Cherimisinoff and Cherimisinoff 1984, Ergun 1952)

$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho_g}{\eta_g}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho_g}{\eta_g}\right) = \frac{d_p^3 \rho_g \left(\rho_w - \rho_g\right) g}{\eta_g^2} \qquad \text{(PA.186)}$$

where

a = particle shape factor (unitless)
d_p = particle diameter (m)

Fluidization occurs in the failed material to the depth at which gas velocity does not exceed the fluidization velocity; this depth is denoted by r_{fluid} and is used to determine cavity radius (Section PA-4.6.2.3.3). If fluidization occurs, the gas and waste particles mix into the cavity at the bottom of the wellbore. Because this mixing cannot be instantaneous, which would be nonphysical (much as allowing instantaneous tensile failure propagation would be nonphysical), a small artificial relaxation time, equal to the cavity radius r_{cav} divided by the superficial gas velocity $u(r_{cav})$, is imposed upon the mixing phenomenon. The fluidized material is released into the cavity uniformly over the relaxation time.

PA-4.6.3 Numerical Model

The numerical model implements the conceptual and mathematical models described above (Section PA-4.6.2). Both the wellbore and the repository domain calculations use time-marching finite differences. These are part of a single computational loop and therefore use the same time step. The differencing schemes for the wellbore and repository calculations are similar, but not identical.

PA-4.6.3.1 Numerical Method—Wellbore

The wellbore is zoned for finite differencing, as illustrated in Figure PA-27, which shows zones, zone indices, grid boundaries, volumes, and interface areas. The method is Eulerian: zone boundaries are fixed, and fluid flows across the interfaces by advection. Quantities are zone-centered and integration is explicit in time.

To reduce computation time, an iterative scheme is employed to update the wellbore flow solution. The finite-difference scheme first solves Equation (PA.147) and Equation (PA.148) for the mass of each phase in each grid cell and the momentum in each grid cell.

The updated solution to Equation (PA.147) and Equation (PA.148) is then used to compute the volume of each phase, the pressure, and the mixture velocity in each grid cell.

All of the materials (mud, salt, gas, and waste) are assumed to move together as a mixture. Because fluid moves through the cell boundaries, the calculation requires a value for the flow through each cell boundary during a time step. These values are obtained by averaging the fluid velocities at the zone centers, given by

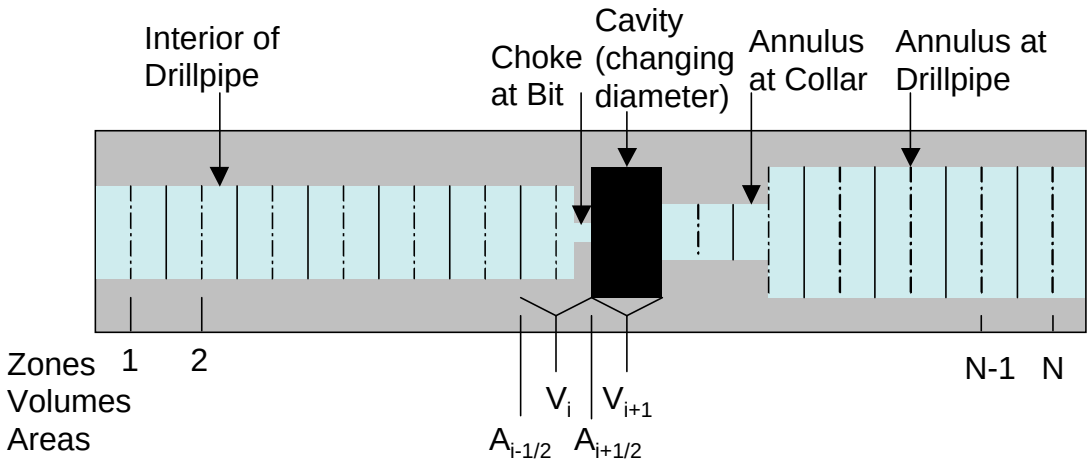


Figure PA-27. Finite-Difference Zoning for Wellbore

$$u_{i+1/2} = \frac{1}{2}\left(u_{i+1}^{n-1} + u_i^{n-1}\right) \qquad \text{(PA.187)}$$

The mass transport equation, prior to any volume change, becomes

$$V_i\ \rho_i^* = V_i \rho_i^{n-1} - \left(A_{i+1/2}\rho_{i+1/2}^{n-1}u_{i+1/2} - A_{i-1/2}\rho_{i-1/2}^{n-1}u_{i-1/2}\right)\Delta t + S_{m,i}\Delta t \qquad \text{(PA.188)}$$

Here, the source terms $S_{m,i}$ correspond to material entering or exiting at the pump, cavity, and surface. The "upwind" zone-centered densities are used for the interfaces values, $\rho_{i+1/2}^{n-1}$ and $\rho_{i-1/2}^{n-1}$.

Finally, any changed volumes are incorporated and numerical mass diffusion is added for stability:

$$V_i\rho_i^n = V_i\rho_i^* + \Delta z_i s \sum_{q\in\{w,m,s,g\}} \zeta_q D_{i,q} \qquad \text{(PA.189)}$$

where

$$D_{i,q} = \left[A_{i+1/2}\left(\left(\rho f_q\right)_{i+1}^{n-1} - \left(\rho f_q\right)_i^{n-1}\right) - A_{i-1/2}\left(\left(\rho f_q\right)_i^{n-1} - \left(\rho f_q\right)_{i-1}^{n-1}\right)\right]$$

and ζ_q is the diffusion coefficient for phase q. The density ρf_q for phase q being diffused is calculated from the mixture density, ρ, and the mass fraction, f_q, of phase q in the referenced cell ($f_q = \rho V_{q,i}/\rho V_i$). The numerical diffusion coefficient ζ_q is chosen empirically for stability. Separate diffusion coefficients could be used for the different materials (mud, gas, etc.); however, sufficient stability is obtained by diffusing only mud and salt using the same coefficient ($\zeta_m = \zeta_s = 0.0001$ and $\zeta_w = \zeta_g = 0$).

Momentum is differenced as

$$V_i\left(\rho u\right)_i^* = V_i\left(\rho u\right)_i^{n-1} - \Delta t\left(A_{i+1/2}\left(\rho u\right)_{i+1/2}^{n-1} u_{i+1/2} - A_{i-1/2}\left(\rho u\right)_{i-1/2}^{n-1} u_{i-1/2}\right) - V_i \Delta t\left(\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g + F_i^{n-1}\right) + S_{mom,i}\Delta t \quad \text{(PA.190)}$$

where the dissipation term F_i^{n-1} is obtained from Equation (PA.153) and is constrained by

$$\left|F_i^{n-1}\right| \le \left|\frac{P_{i+1}^{n-1} - P_{i-1}^{n-1}}{2\Delta z} - \rho_i^{n-1} g\right| \quad \text{(PA.191)}$$

and the sign of F_i^{n-1} is chosen to oppose flow. Finally, numerical momentum diffusion is added without distinguishing between phases in the mixture (ρ is the mixture density):

$$V_i\ \left(\rho u\right)_i^n = V_i\ \left(\rho u\right)_i^* - \zeta_p \Delta x_i\left[A_{i+1/2}\left(\left(\rho u\right)_{i+1}^{n-1} - \left(\rho u\right)_i^{n-1}\right) - A_{i-1/2}\left(\left(\rho u\right)_i^{n-1} - \left(\rho u\right)_{i-1}^{n-1}\right)\right] \quad \text{(PA.192)}$$

In PA, $\zeta_p = 0.01$.

Equation (PA.150), Equation (PA.151), and Equation (PA.152) comprise a simultaneous system of equations for the volumes of gas and mud and the pressure in the wellbore. The volumes of salt and waste are known, since they are considered incompressible. Equation (PA.150) and Equation (PA.151) combine into a quadratic equation for gas volume:

$$aV_g^2 + bV_g - c = 0 \quad \text{(PA.193)}$$

where

$$a = 1 - c_m P_{atm},$$
$$b = c_m P_{atm} V_{g,0} - aV^* + V_{m,0},$$
$$c = V^* c_m P_{atm} V_{g,0},$$
$$V_{g,0} = m_g / \rho_{g,0},$$
$$V_{m,0} = m_m / \rho_{m,0},$$
$$V^* = V_m + V_g = V - V_s - V_w$$

The volume of the mud phase follows from Equation (PA.150) and the pressure from Equation (PA.149). Once the mixture density in each cell (ρ_i) is updated by Equation (PA.151), the mixture velocity in each cell (u_i) is computed by

$$u_i = \frac{(\rho u)_i}{\rho_i} \tag{PA.194}$$

where the quantity ρu is determined by Equation (PA.192).

PA-4.6.3.2 Numerical Method—Repository

The time integration method for the repository flow is implicit, with spatial derivatives determined after the time increment. This method requires the inversion of a matrix for the entire repository, which is usually straightforward. The implicit scheme is unconditionally stable. However, it is still necessary to use small time steps to ensure gradient accuracy.

The numerical method follows Press et al. (1989). For simplicity, the equations are presented for constant zone size, although DRSPALL implements difference equations that allow for a variable zone size. Near the cavity, a small, constant zone size is used, and then zones are allowed to grow geometrically as the outer boundary is approached. This procedure greatly increases computational efficiency without sacrificing accuracy in the region of interest.

For an isothermal ideal gas, the pseudopressure ψ is defined as

$$\psi = \frac{P^2}{\eta} \tag{PA.195}$$

Using Equation (PA.195), Equation (PA.171) is expanded to

$$\frac{\partial \psi}{\partial t} = D(\psi)\left[\frac{\partial^2 \psi}{\partial r^2} + \frac{(m-1)}{r}\frac{\partial \psi}{\partial r} + \frac{1}{k'}\frac{\partial k'}{\partial r}\frac{\partial \psi}{\partial r}\right] \tag{PA.196}$$

where $D(\psi) = \frac{k'}{\phi}\sqrt{\frac{\psi}{\eta}} = \frac{k'P}{\phi\eta}$; Equation (PA.196) is then converted to a difference equation by treating $D(\psi)$ as constant over a zone, using its zone-centered value at the current time D_j^n:

$$\frac{\psi_j^{n+1} - \psi_j^n}{\Delta t} = \frac{D_j^n}{\Delta r}\left[\frac{\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}}{\Delta r} + \frac{(m-1)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{2r_j} + \frac{\left(k'^{n+1}_{j+1} - k'^{n+1}_{j-1}\right)\left(\psi_{j+1}^{n+1} - \psi_{j-1}^{n+1}\right)}{4k'\Delta r}\right] \tag{PA.197}$$

Collecting similar terms in ψ leads to a tridiagonal system:

$$-\alpha_1 \psi_{j-1}^{n+1} + (1+2\alpha)\psi_j^{n+1} - \alpha_2 \psi_{j+1}^{n+1} = \psi_j^n, \text{ j} = 1,2\ldots. \tag{PA.198}$$

where

$$\alpha = \frac{D_j^n \Delta t}{(\Delta r)^2}$$

$$\alpha_1 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} - \frac{(m-1)}{2r_j} - \frac{k_{i+1}'^{n+1} - k_{i-1}'^{n+1}}{4k'\Delta r}\right)\Delta t$$

$$\alpha_2 = \left(\frac{D_j^n}{\Delta r}\right)\left(\frac{1}{\Delta r} + \frac{(m-1)}{2r_j} + \frac{k_{i+1}'^{n+1} - k_{i-1}'^{n+1}}{4k'\Delta r}\right)\Delta t$$

Equation (PA.198) may be solved by simplified LU decomposition, as presented in Press et al. (1989).

The boundary condition at the inner radius is implemented by noting that for $i = 1$ (the first intact or nonfluidized cell), ψ_{i-1} is the cavity pseudopressure, which is known, and therefore can be moved to the right-hand side of Equation (PA.198):

$$(1+2\alpha)\psi_1^{n+1} - \alpha_2\psi_2^{n+1} = \psi_1^n + \alpha_1\psi_{cav}^{n+1} \qquad \text{(PA.199)}$$

The far-field boundary condition is a zero gradient, which is implemented by setting $\psi_{j+1}^{n+1} = \psi_j^{n+1}$ in Equation (PA.199), recognizing that $1+2\alpha = 1+\alpha_1+\alpha_2$ and rearranging, which gives

$$-\alpha_1\psi_{j-1}^{n+1} + (1+\alpha_1)\psi_j^{n+1} = \psi_j^n \qquad \text{(PA.200)}$$

where j is the index of the last computational cell.

PA-4.6.3.3 Numerical Method—Wellbore to Repository Coupling

The term u_{rep}, appearing in Equation (PA.176), is the gas velocity in the repository at the waste-cavity interface and is determined from the pressure gradient inside the waste. DRSPALL uses the pressure (P_1) at the center of the first numerical zone in the waste to determine u_{rep}:

$$u_{rep} = \frac{k(P_1 - P_{cav})}{\eta_g \phi \Delta r} \qquad \text{(PA.201)}$$

PA-4.6.4 Implementation

During development of the spallings model, a total of five parameters were determined to be both uncertain and potentially significant to model results (Hansen, Pfeifle, and Lord 2003; Lord and Rudeen 2003). All five parameters relate to the repository conditions or the state of the waste at the time of intrusion. Table PA-15 lists the uncertain parameters in the DRSPALL calculations; these parameters are also listed in Table PA-19.

Table PA-15. Uncertain Parameters in the DRSPALL Calculations

Parameter	Variable	Implementation
Repository Pressure	REPIPRES	Initial repository pressure (Pa); spall calculated for values of 10, 12, 14, and 14.8 MPa. Defines initial repository pressure in Equation (PA.171) (see Section PA-4.6.2.2) and P_{ff} in Equation (PA.184).
Repository Permeability	REPIPERM	Permeability (m^2) of waste, implemented by parameter SPALLMOD/REPIPERM. Log-uniform distribution from 2.4×10 to 2.4×10^{-12}. Defines k in Equation (PA.168).
Repository Porosity	REPIPOR	Porosity (dimensionless) of waste, implemented by parameter SPALLMOD/REPIPOR. Uniform distribution from 0.35 to 0.66. Defines ϕ in Equation (PA.167).
Particle Diameter	PARTDIAM	Particle diameter of waste (m) after tensile failure, implemented by parameter SPALLMOD/PARTDIAM. Log-uniform distribution from 0.001 to 0.1 (m). Defines d_p in Equation (PA.186).
Tensile Strength	TENSLSTR	Tensile strength of waste (Pa), implemented by parameter SPALLMOD/TENSLSTR. Uniform distribution from 0.12 MPa to 0.17 MPa. Defines maximum $\bar{\sigma}_r$ for Section PA-4.6.2.3.4.

The computational requirements of DRSPALL prohibit calculation of spall volumes for all possible combinations of initial conditions and parameter values. Since repository pressure is a time-dependent value computed by the BRAGFLO model (see Section PA-4.2), DRSPALL calculations were performed for a small number of pressures. Sensitivity studies showed that spall does not occur at pressures below 10 MPa; this value was used as the lower bound on pressure. In DRSPALL, the repository pressure cannot exceed the far-field confining stress (14.8 MPa); consequently, 14.8 MPa was used as the upper bound on pressure. Computations were also performed for intermediate pressures of 12 and 14 MPa. The remaining four parameters listed in Table PA-15 are treated as subjectively uncertain. The uncertainty represented by these parameters pertains to the future state of the waste, which is modeled in PA as a homogeneous material with uncertain properties (see Section PA-5.0).

Spall volumes are computed for each combination of initial pressure and sample element, for a total of $4 \times 300 = 1{,}200$ model runs. Although repository porosity could be treated as an initial condition (using the time-dependent value computed by BRAGFLO), to reduce the number of computational cases and ensure that extreme porosity values were represented, repository porosity was included as a sampled parameter.

The spallings submodel of the code CUTTINGS_S uses the DRSPALL results to compute the spall volume for a given initial pressure *P*. If $P < 10$ MPa or $P > 14.8$ MPa, the spall volume is the value computed for REPIPRESS = 10 MPa or REPIPRESS = 14.8 MPa, respectively. If *P* falls between 10 and 14.8 MPa, the spall volume is constructed by linear interpolation between the DRSPALL results for pressures that bracket *P*.

PA-4.6.5 Additional Information

Additional information on DRSPALL and its use in PA to determine spallings releases can be found in the DRSPALL user's manual (WIPP Performance Assessment 2003f) and in the analysis package for spallings releases (Ismail 2008). Additional information on the construction of spall volumes by the code CUTTINGS_S can be found in the CUTTINGS_S design document (WIPP Performance Assessment 2003g).

PA-4.7 DBR to Surface: BRAGFLO

This section describes the model for DBR volumes, which are volumes of brine released to the surface at the time of a drilling intrusion. DBR volumes are calculated by the code BRAGFLO, the same code used to compute two-phase flow in and around the repository (see Section PA-4.2).

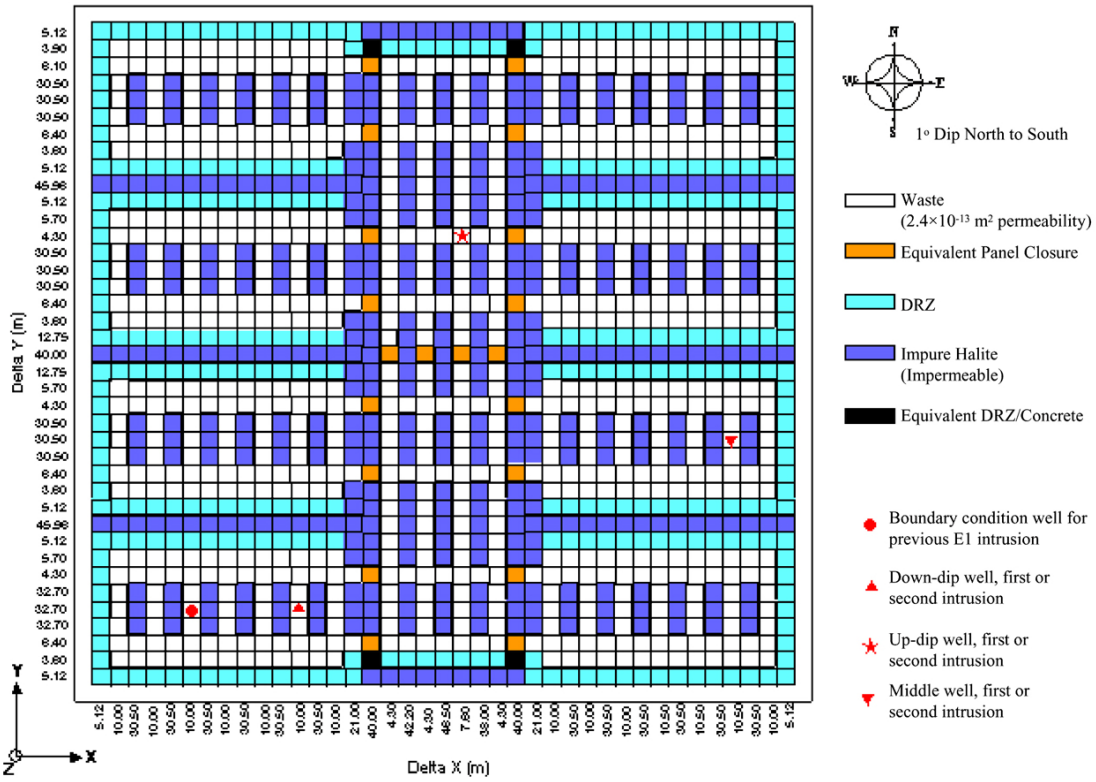
PA-4.7.1 Overview of Conceptual Model

DBRs could occur if the pressure in the repository at the time of a drilling intrusion exceeds 8 MPa, which is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and O'Brien 1996). For repository pressures less than 8 MPa, no DBRs are assumed to occur. However, even if the repository pressure exceeds 8 MPa at the time of a drilling intrusion, a DBR is not assured, as there might not be sufficient mobile brine in the repository to result in movement towards the borehole.

DBRs are estimated for the following cases: (1) an initial intrusion into the repository into either a lower (down-dip), middle, or upper (up-dip) panel; (2) an intrusion into a waste panel preceded by an E1 intrusion into either the same waste panel, an adjacent panel, or a nonadjacent panel; and (3) an intrusion into a waste panel preceded by an E2 intrusion into either the same waste panel, an adjacent panel, or a nonadjacent panel (see Section PA-6.7). To determine releases for the above cases, the DBR calculations use a computational grid that explicitly includes all 10 waste panels (Figure PA-28).

For perspective, the following list provides a comparison of the BRAGFLO mesh for the Salado flow calculations (Figure PA-15) and the DBR mesh used for the DBR calculations (Figure PA-28):

1. The DBR mesh is defined in the areal plane with the z dimension (height) one element thick; the BRAGFLO mesh is defined as a cross section, with multiple layers in height and the thickness (y dimension) one element thick.



Note: Model cells are not to scale. The actual dimensions of the grid blocks are indicated along the edge of the diagram.

Figure PA-28. DBR Grid Used in PA

2. The DBR mesh uses constant thickness, while the BRAGFLO mesh uses rectangular flaring to account for three-dimensional volumes in a two-dimensional grid (Figure PA-16).

3. The DBR mesh represents flow only in the waste area. The BRAGFLO model includes the surrounding geology as well as the entire WIPP excavation (including operations, experimental, and shaft regions).

4. Local scale heterogeneities are included in the DBR mesh, including the salt pillars, rooms, panel closures, and passageways that contain waste. These are not fully represented in the BRAGFLO mesh.

5. The DRZ is included in both models, but exists above and below the excavated regions in the BRAGFLO model, whereas the DRZ surrounds the waste rooms on the sides of the DBR mesh.

6. Both models include a one-degree formation dip through the excavated regions (Equation (PA.33)).

The DBRs are assumed to take place over a relatively short period of time (i.e., 3 to 4.5 days; see Section PA-4.7.8) following the drilling intrusion. The initial value conditions for determining DBR volumes are obtained by mapping solutions of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30)

obtained from BRAGFLO with the computational grid in Figure PA-15 onto the grid in Figure PA-28.

In concept, the DBR for a drilling intrusion has the form

$$DBR = \int_0^{t_e} rDBR(t)\,dt \qquad \text{(PA.202)}$$

where

DBR = DBR volume (m^3) for drilling intrusion
$rDBR(t)$ = rate (m^3) at time t at which brine flows up intruding borehole
t = elapsed time (s) since drilling intrusion
t_e = time (s) at which DBR ends

The definition of $rDBR(t)$ is discussed in the following sections. It is based on the two-phase flow relationships in Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) and use of the Poettmann-Carpenter correlation (Poettmann and Carpenter 1952) to determine a boundary pressure at the connection between the intruding borehole and the repository. The time t_e is based on current drilling practices in the Delaware Basin (Section PA-4.7.8).

PA-4.7.2 Linkage to Two-Phase Flow Calculation

The mesh in Figure PA-28 was linked to the mesh in Figure PA-15 by subdividing the waste disposal area in the mesh in Figure PA-15 into three regions (Figure PA-29). The upper region represents the northern rest of repository (North RoR) area in Figure PA-15. The middle region represents the southern rest of repository (South RoR) area in Figure PA-15. The lower region represents the farthest down-dip repository area (Waste Panel) in Figure PA-15 that contained waste and thus corresponds to the single down-dip waste panel. The linkage between the solutions to Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) and the DBR calculations was made by assigning quantities calculated by BRAGFLO for each region in Figure PA-15 to the corresponding waste region in Figure PA-28.

The height of the grid in Figure PA-28 was assigned a value that corresponded to the crushed height, h (m), of the waste as predicted by the solution of Equation (PA.24) through Equation (PA.30). Specifically,

$$h = h_i \frac{1-\phi_i}{1-\phi} \qquad \text{(PA.203)}$$

where h_i and ϕ_i are the initial height (m) and porosity of the waste and ϕ is the volume-averaged porosity of the waste at the particular time under consideration (Section PA-4.2.3). The areas designated equivalent panel closures, DRZ, and impure halite in Figure PA-28 were assigned the

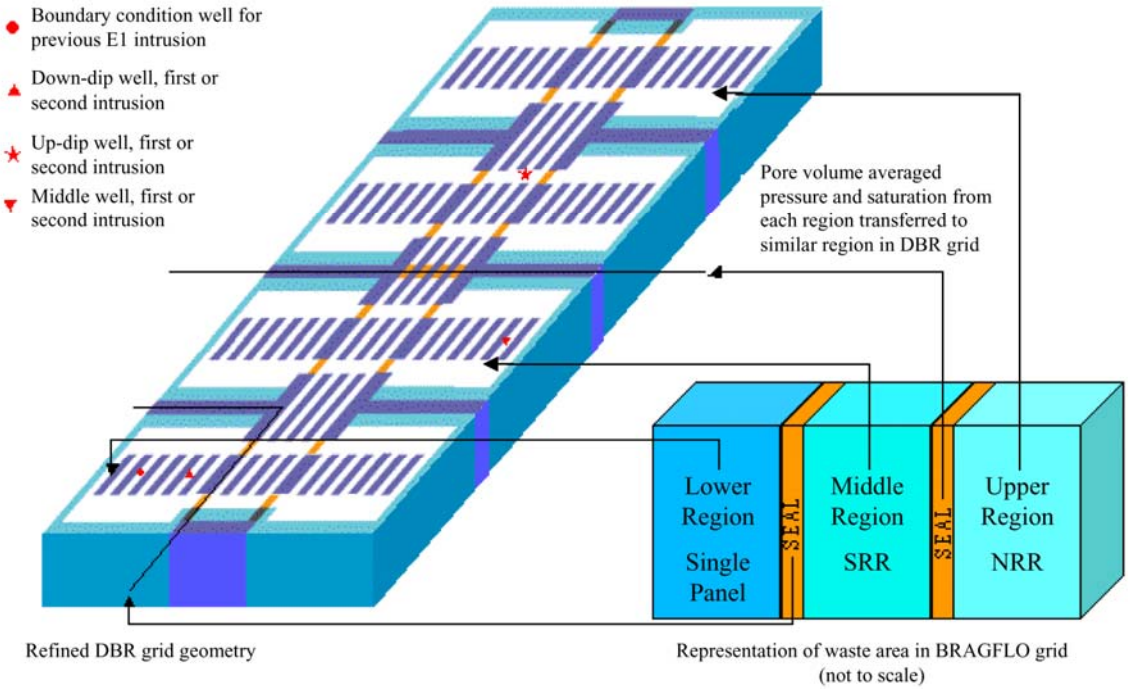


Figure PA-29. Assignment of Initial Conditions for DBR Calculation

same pressures and saturations as the corresponding grid blocks in the 10,000-year BRAGFLO calculations. The area designated equivalent DRZ/concrete (Figure PA-28) was assigned the same pressures and saturations as the DRZ. These areas were assigned porosities that resulted in a conservation of the initial pore volumes used in the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) on the grid in Figure PA-15. Specifically, the pore volumes associated with the panel closures, DRZ, and impure halite do not change with time the constant values being given by the definitions of $\phi(x, y, 0)$ in Table PA-16.

The initial brine pressure $p_b(x, y, 0)$ and gas saturation $S_g(x, y, 0)$ in the grid in Figure PA-28 are assigned by

$$p_b\left(x,y,0\right)=\frac{\int_R \tilde{p}_b\left(\tilde{x},\tilde{y},t_{int}\right)dV}{\int_R dV} \tag{PA.204}$$

$$S_g\left(x,y,0\right)=\frac{\int_R \tilde{S}_g\left(\tilde{x},\tilde{y},t_{int}\right)dV}{\int_R dV} \tag{PA.205}$$

where $\left(x,y\right)$ designates a point in the grid in Figure PA-28, $\tilde{p}_b$ and $\tilde{S}_g$ denote solutions to Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30), $\tilde{x}$ and $\tilde{y}$ denote the variables of integration, t_{int} is the time at which the drilling intrusion occurs, and R corresponds to the region in the BRAGFLO computational grid (Figure PA-15) that is mapped into the region in the DBR computational grid

(Figure PA-28) that contains the point (x, y) (Figure PA-29). Note that t_{int} defines a time in the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30); $t = 0$ defines the start time for the DBR calculation and corresponds to t_{int} in the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30).

The initial porosity $\phi(x, y, 0)$ in the grid in Figure PA-28 is set by the equations listed in Table PA-15. In Table PA-16, h_i is the initial height of the waste panels (3.96 m), $\phi_{WP,i}$ is the initial porosity of the waste panels (0.848), $h(t_{int})$ is the height of the repository at the time of intrusion (typically 1 to 1.5 m; corresponds to h in Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30)), $h_{DRZ,i}$ is the initial DRZ height (43.60 m) that results in the DRZ in Figure PA-28 having the same pore volume as the initial pore volume of the DRZ in Figure PA-15, A_{DRZ} is the area associated with DRZ in Figure PA-28, and $\phi_{DRZ,i}$ is the initial porosity of DRZ (see Table PA-3). The quantity $h_{DRZ,i} \times A_{DRZ} \times \phi_{DRZ,i}$ is equal to the pore volume of DRZ above and below the waste filled regions in Figure PA-15. In Table PA-16, the term ϕ_C is the porosity of the panel closure concrete material (CONC_PCS; see Table PA-3), d_1 is the length of the drift/explosion wall portion of the panel closure (32.1 m; see Figure PA-20), and d_2 is the length of the concrete portion of the panel closure (7.9 m; see Figure PA-20). The porosity of the panel closure and the equivalent DRZ/concrete materials are defined as the volume-weighted mean porosity of the component materials; this definition results in the same brine volume within the pore space in each set of panel closures in Figure PA-15 and Figure PA-28. In Table PA-16, $h_{H,i}$ is the initial height of undisturbed halite in Figure PA-28, which is arbitrarily taken to be 8.98 m. However, this value is unimportant because of the extremely low permeability of the undisturbed halite ($\sim 3.16 \times 10^{-23}$ m^2); any brine in the halite could not flow into the waste over the short time period of the DBR calculation, so no effort was made to preserve halite pore volume when mapping from the computational grid in Figure PA-15 to the computational grid in Figure PA-28. The quantity $\phi_{H,i}$ is the initial porosity of halite (HALPOR, see Table PA-19).

PA-4.7.3 Conceptual Representation for Flow Rate *rDBR*(*t*)

The driving force that would give rise to the DBR is a difference between waste panel pressure, p_w (Pa), and the flowing bottomhole pressure in the borehole, p_{wf} (Pa), at the time of the intrusion. The flowing bottomhole pressure p_{wf}, defined as the dynamic pressure at the inlet of the intruding borehole to the waste panel, is less than the static pressure p_w due to friction and acceleration effects. The rate at which brine and gas are transported up the intruding borehole is determined by the difference $p_w - p_{wf}$ and a productivity index J_p for the intruded waste panel (Mattax and Dalton 1990, p. 79):

$$q_p(t) = J_p\left[p_w(t) - p_{wf}\right] \tag{PA.206}$$

where

Table PA-16. Initial Porosity in the DBR Calculation

Grid Region	Initial Porosity
Waste (ϕ_W)	$1-h_i\dfrac{1-\phi_{WP,i}}{h\left(t_{\text{int}}\right)}$
Panel Closures	$\dfrac{d_1\phi_W+d_2\phi_C}{d_1+d_2}$
DRZ	$\phi_{DRZ,i}\dfrac{h_{DRZ,i}}{h\left(t_{\text{int}}\right)}$
Impure Halite	$\phi_{H,i}\dfrac{h_{H,i}}{h\left(t_{\text{int}}\right)}$
Equivalent DRZ/Concrete	$\dfrac{d_1\phi_C+d_2\phi_{DRZ,i}}{d_1+d_2}$

$q_p(t)$ = flow rate (m^3/s) at time t for phase p ($p = b \sim$ brine, $p = g \sim$ gas)

J_p = productivity index ($m^3/Pa{\cdot}s$) for phase p

and p_w and p_{wf} are defined above. As indicated by the inclusion/exclusion of a dependence on t, the terms J_p and p_{wf} are constant during the determination of $q_p(t)$ for a particular drilling intrusion in the present analysis, and $p_w(t)$ changes as a function of time. In concept, the DBR is given by

$$DBR=\int_0^{t_e} rDBR(t)\,dt=\int_0^{t_e} J_b\left[p_w(t)-p_{wf}\right]dt \qquad \text{(PA.207)}$$

once J_b (brine), p_w, and p_{wf} are determined. Section PA-4.7.4 discusses the determination of J_p (for both gas and brine), Section PA-4.7.5 presents the numerical determination of p_w and DBR, and the determination of p_{wf} is discussed in Section PA-4.7.6. The associated gas release is given by the corresponding integral with J_g (gas) rather than J_b (brine). In the computational implementation of the analysis, DBR is determined as part of the numerical solution of the system of PDEs that defines p_w (Section PA-4.7.5).

PA-4.7.4 Determination of Productivity Index J_p

In a radial drainage area with uniform saturation, which is assumed to be valid throughout the DBR, the following representation for J_p can be determined from Darcy's law (Mattax and Dalton 1990, p. 79; Williamson and Chappelear 1981; Chappelear and Williamson 1981):

$$J_p = \frac{2\pi k k_{rp} h}{\mu_p \left[\ln\left(\frac{r_e}{r_w}\right) + s + c \right]} \quad \text{(PA.208)}$$

where

k = absolute permeability (assumed to be constant through time at 2.4×10^{-13} m^2)
k_{rp} = relative permeability to phase p (calculated with modified Brooks-Corey model in Equation (PA.139), Equation (PA.140), and Equation (PA.141) and brine and gas saturations, S_b and S_g, obtained by mapping solutions of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) obtained with the grid in Figure PA-15 onto the grid in Figure PA-28)
h = crushed panel height (Equation (PA.203))
μ_p = viscosity of fluid phase (assumed to be constant through time with $\mu_b = 1.8 \times 10^{-3}$ Pa·s, and $\mu_g = 8.92 \times 10^{-6}$ Pa·s [Kaufmann 1960])
r_e = external drainage radius (for use with the rectangular grid blocks in Figure PA-28, r_e is taken to be the equivalent areal radius; see Equation (PA.209))
r_w = wellbore radius (assumed to be constant through time at 0.1556 m (Gatlin 1960, Table 14.7)
c = –0.50 for pseudo-steady-state flow
s = skin factor, which is used to incorporate flow stimulation caused by cavings and spallings release (see Equation (PA.210))

In the present analysis,

$$r_e = \sqrt{(\Delta x)(\Delta y)/\pi} \quad \text{(PA.209)}$$

where Δx is the x dimension (m) and Δy is the y dimension (m) of the grid block containing the down-dip well in Figure PA-28 (Δx = 10 m and Δy = 32.7 m).

The skin factor s is derived from the cavings and spallings release. Due to the uncertainty in the cavings and spallings parameters, the calculated solid release volume can vary for each realization. The skin factor is calculated for each realization, based on the calculated solid release volume, through the following petroleum engineering well testing relationship (Lee 1982, pp. 5–7):

$$s = \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_s}{r_w}\right) \quad \text{(PA.210)}$$

where

k_s = permeability (m^2) of an open channel as a result of spallings releases (assumed to be infinite)
r_s = effective radius (m) of the wellbore with the cuttings, cavings, and spallings volume removed

The effective radius r_s is obtained by converting the cuttings, cavings, and spallings volume removed into a cylinder of equal volume with the initial height of the waste (h_i), and then computing the radius of the cylinder:

$$r_s = \sqrt{\frac{V_i}{h_i \pi}} \tag{PA.211}$$

and substitution of r_s into Equation (PA.210) with $k_s = \infty$ yields

$$s = (-1) \ln \left(\frac{\sqrt{\frac{V_i}{h_i \pi}}}{r_w} \right) \tag{PA.212}$$

PA-4.7.5 Determination of Waste Panel Pressure $p_w(t)$ and DBR

The repository pressure $p_w(t)$ in Equation (PA.207) after a drilling intrusion is determined with the same system of nonlinear PDEs discussed in Section PA-4.2. These equations are solved numerically by the code BRAGFLO used with the computational grid in Figure PA-28 and assumptions (i.e., parameter values, initial value conditions, and boundary value conditions) appropriate for representing brine flow to an intruding borehole over a relatively short time period immediately after the intrusion (e.g., 3 to 4.5 days). Due to the short time periods under consideration, the model for DBR does not include gas generation due to either corrosion or microbial action or changes in repository height due to creep closure. Furthermore, to stabilize the calculation and thus allow longer time steps in the numerical solution, the capillary pressure was assigned a value of 0 Pa in all modeled regions (Figure PA-28); in the analysis of the full system in Section PA-4.2, capillary pressure had a value of 0 Pa in the waste regions and the DRZ, but a nonzero value in the panel closures (Table PA-4). Use of a capillary pressure of 0 Pa results in the brine pressure $p_b(x, y, t)$ and the gas pressure $p_g(x, y, t)$ being equal, with the pressure $p_w(t)$ in Equation (PA.207) given by

$$p_w(t) = p_b(x, y, t) \tag{PA.213}$$

Although the determination of DBR can be conceptually represented by the integral in Equation (PA.202), in the numerical implementation of the analysis, DBR is determined within the numerical solution of the system of PDEs that defines $p_b(x, y, t)$.

With the specific assumptions for DBR, Equation (PA.24) , Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) become

Gas Conservation $$\nabla\cdot\left[\frac{\alpha\rho_g K_g k_{rg}}{\mu_g}\left(\nabla p_g+\rho_g g\nabla h\right)\right]=\alpha\frac{\partial\left(\phi\rho_g S_g\right)}{\partial t} \quad \text{(PA.214)}$$

Brine Conservation $$\nabla\cdot\left[\frac{\alpha\rho_b K_b k_{rb}}{\mu_b}\left(\nabla p_b+\rho_b g\nabla h\right)\right]=\alpha\frac{\partial\left(\phi\rho_b S_b\right)}{\partial t} \quad \text{(PA.215)}$$

Saturation Constraint $$S_g+S_b=1 \quad \text{(PA.216)}$$

Capillary Pressure Constraint $$p_g-p_b=0 \quad \text{(PA.217)}$$

Gas Density ρ_g determined by RKS equation of state (Equation (PA.54)) (PA.218)

Brine Density $$\rho_b=\rho_0\exp\left[c_b\left(p_b-p_{b0}\right)\right] \quad \text{(PA.219)}$$

Formation Porosity $$\phi=\phi_0\exp\left[c_\phi\left(p_b-p_{b0}\right)\right] \quad \text{(PA.220)}$$

with all symbols having the same definitions as in Equation (PA.24), Equation (PA.25), Equation (PA.26) Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30).

The primary differences between the BRAGFLO calculations described in Section PA-4.2 and the BRAGFLO calculations described in this section are in the computational meshes (Figure PA-28 and Figure PA-15), initial values (Table PA-3 and Section PA-4.7.2), and boundary conditions (Table PA-17). In particular, brine and gas flow associated with intruding boreholes in the DBR calculations are incorporated by the assignment of appropriate boundary conditions. Specifically, brine flow up an intruding borehole is incorporated into Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) by using the Poettmann-Carpenter wellbore model to determine the pressure at the outflow point in a waste panel (Figure PA-28), with this pressure entering the calculation as a boundary value condition (Table PA-17). The details of this determination are discussed in Section PA-4.7.6. Furthermore, for calculations that assume a prior E1 intrusion, the effects of this intrusion are also incorporated into the analysis by specifying a pressure as a boundary condition (Table PA-17). The determination of this pressure is discussed in Section PA-4.7.6.

PA-4.7.6 Boundary Value Pressure p_{wf}

The boundary value pressure p_{wf} at the inlet of the intruding borehole is defined by a system of equations of the following form:

Table PA-17. Boundary Conditions for p_b and S_g in DBR Calculations

(x, y) on Upper (Northern) or Lower (Southern) Boundary in Figure PA-28, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{j} = 0\ Pa/m$	No gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{j} = 0\ Pa/m$	No brine flow condition
(x, y) on Right (Eastern) or Left (Western) Boundary in Figure PA-28, $0 \le t$	
$\left(\nabla p_g + \rho_g g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{i} = 0\ Pa/m$	No gas flow condition
$\left(\nabla p_b + \rho_b g \nabla h\right)\Big\|_{(x,y,t)} \cdot \mathbf{i} = 0\ Pa/m$	No brine flow condition
(x, y) at Location of Drilling Intrusion under Consideration (see indicated points in Figure PA-28), $0 \le t$	
$p_b(x, y, t) = p_{wf}$ (see Section PA-4.7.6)	Constant pressure condition
(x, y) at Location of Prior Drilling Intrusion into Pressurized Brine (see indicated point in Figure PA-28), $0 \le t$	
$p_b(x, y, t) = p_{wE1}$ (see Section PA-4.7.7)	Constant pressure condition

$$\frac{dp}{dh} = G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right), \quad 0 \le h \le 655m \tag{PA.221}$$

$$p(655) = 1.013 \times 10^5\ Pa \tag{PA.222}$$

$$q_b\left[p(0)\right] = J_b\left[p_w - p(0)\right] \tag{PA.223}$$

$$q_g\left[p(0)\right] = J_g\left[p_w - p(0)\right] \tag{PA.224}$$

where $p(h)$ is pressure (Pa) at elevation h in the borehole, with $h = 0$ m corresponding to the entry point of the borehole into the waste panel and $h = 655$ m corresponding to the land surface (Figure PA-30); G is a function (Pa/m) characterizing the change of pressure with elevation in the borehole; $p(655)$ is an initial value condition requiring that pressure at the land surface (i.e., the outlet point of the borehole) be equal to atmospheric pressure; $q_b[p(0)]$ and $q_g[p(0)]$ define brine and gas flow rates (m^3/s) into the borehole; J_b and J_g are productivity indexes ($m^3/Pa\ s$) (see Equation (PA.208); and p_w is the pressure (Pa) in the repository at the time of the drilling intrusion.

The boundary value pressure p_{wf} is defined by

$$p_{wf} = p(0) \tag{PA.225}$$

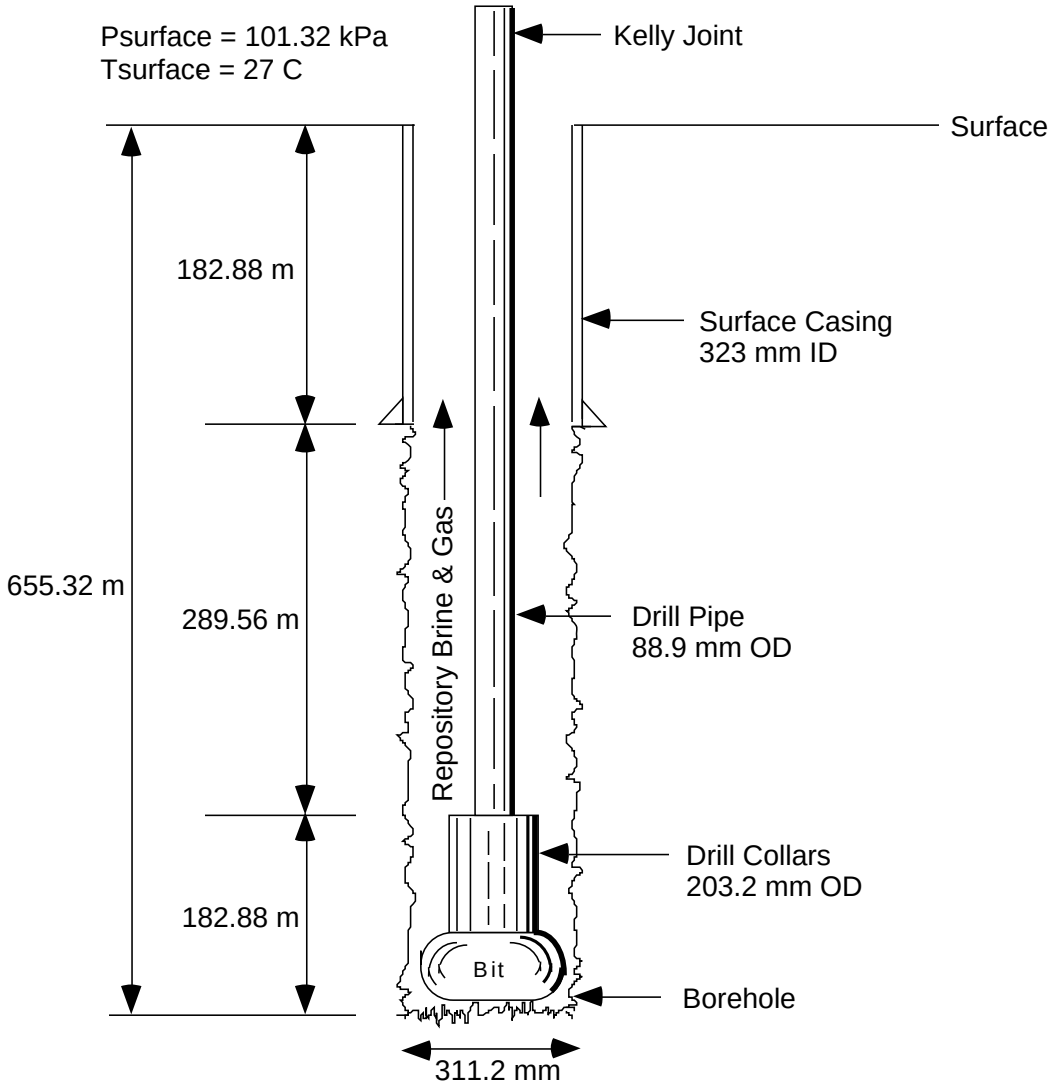


Figure PA-30. Borehole Representation Used for Poettmann-Carpenter Correlation

Thus, p_{wf} is determined by the numerical solution of Equation (PA.221) for $p(0)$ subject to the constraints in Equation (PA.222), Equation (PA.223), and Equation (PA.224).

The pressure p_w corresponds to the pressure $p_w(0)$ in Equation (PA.213) and is obtained from the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) with the computational grid in Figure PA-15 (see Section PA-4.7.2). The production indexes J_b and J_g are defined in Equation (PA.208). Thus, the only quantity remaining to be specified in Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224) is the function G.

Brine and gas flow up a borehole is governed by complex physics dependent on frictional effects and two-phase fluid properties. This phenomenon has been widely studied in the petroleum industry and many modeling procedures have been developed to predict flow rates and pressures in vertical two-phase pipe flow (i.e., to define G in Equation (PA.221)) (Brill and Beggs 1986).

For this analysis, the Poettmann-Carpenter model (Poettmann and Carpenter 1952; Welchon, Bertuzzi, and Poettmann 1962) was used to define G because it accounts for multiphase frictional effects based on empirical (i.e., field) data from flowing wells, is one of the few modeling approaches that included annular flow data in its development, and is relatively easy to implement. Specifically, the Poettmann-Carpenter model defines G by

$$G\left(q_b\left[p(0)\right], q_g\left[p(0)\right], p(h), h\right) = gm(h) + f'\left(m(h), D(h), q_b\left[p(0)\right]\right) gm(h) F^2(h) / D^5(h) \quad \text{(PA.226)}$$

where

g = acceleration due to gravity (9.8 m/s^2)

$m(h)$ = density (kg/m^3) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: $m(h)$ is a function of $q_b[p(0)]$ and $q_g[p(0)]$; see Equation (PA.227) below)

$f'\left\{m(h), D(h) q_b\left[p(0)\right]\right\}$ = empirically defined scale factor (m/s^2) (Note: f' is the scale factor in the Poettmann-Carpenter model for fluid flow in a wellbore [Poettmann and Carpenter 1952]; see discussion below)

$F(h)$ = flow rate (m^3/s) of fluids (i.e., gas and brine) in wellbore at elevation h (Note: $F(h)$ is a function of $q_b[p(0)]$ and $q_g[p(0)]$; see Equation (PA.228))

$D(h)$ = effective diameter (m) of wellbore (see Equation (PA.231))

The first term, $gm(h)$, in Equation (PA.226) results from the contribution of elevation to pressure; the second term results from frictional effects (Poettmann and Carpenter 1952). The fluid density $m(h)$ at elevation h is given by

$$m(h) = \frac{q_b\left[p(0)\right]\rho_b\left[p(0)\right] + q_g\left[p(0)\right]\rho_g\left[p(0)\right]}{F(h)} \quad \text{(PA.227)}$$

where

$$F(h) = q_b\left[p(0)\right] + \frac{z(h)\,p(h)}{p(0)} q_g\left[p(0)\right] \quad \text{(PA.228)}$$

and

$\rho_b\left[p(0)\right]$ = density (kg/m^3) of brine at pressure $p(0)$ and temperature 300.1 K, which is fixed at 1230 kg/m^3

$\rho_g\left[p(0)\right]$ = density (kg/m^3) of H_2 at pressure $p(0)$ and temperature 300.1 K (see Equation (PA.229), below)

$z(h)$ = z-factor for compressibility of H_2 at elevation h (Note: $z(h)$ is a function of $p(h)$; see Equation (PA.230), below), and $q_b[p(0)]$ and $q_g[p(0)]$ are defined in Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224)

The gas density in Equation (PA.227) is obtained from the universal gas law, $PV = nRT$, by

$$\rho_g\left[p(0)\right] = C_{m,kg}\frac{n}{V} = C_{m,kg}\frac{P}{RT} \qquad \text{(PA.229)}$$

where n is the amount of gas (mol) in a volume V, $C_{m,kg}$ is the conversion factor from moles to kilograms for H_2 (i.e., 2.02×10^{-3} kg/mol), $P = p(0)$, $R = 8.3145$ J/mol K, and $T = 300.1$ K. The z-factor is given by

$$z(h) = 1 + \left(8.54 \times 10^{-8}\ \text{Pa}^{-1}\right) p(h) \qquad \text{(PA.230)}$$

and was obtained from calculations performed with the SUPERTRAPP program (Ely and Huber 1992) for pure H_2 and a temperature of 300.1 K (Stoelzel and O'Brien 1996, Figure 4.7.4). The preceding approximation to $z(h)$ was obtained by fitting a straight line between the results for pressures of 0 psi and 3000 psi and a H_2 mole fraction of 1 in Stoelzel and O'Brien (1996, Figure 4.7.4); the actual calculations used the more complex, but numerically similar, regression model given in Stoelzel and O'Brien (1996, Figure 4.7.4). The numerator and denominator in Equation (PA.227) involve rates, with the time units canceling to give $m(h)$ in units of kg/m^3.

The effective diameter $D(h)$ in Equation (PA.226) is defined with the hydraulic radius concept. Specifically,

$$D^5(h) = \left[D_o(h) + D_i(h)\right]^2 \left[D_o(h) - D_i(h)\right]^3 \qquad \text{(PA.231)}$$

where $D_i(h)$ and $D_o(h)$ are the inner and outer diameters (m) of the wellbore at elevation $h(m)$ (see Figure PA-30). The factor f' in Equation (PA.226) is a function of $m(h)$, $D(h)$, and $q_b[p(0)]$.

Subsequent to submittal of the CCA PA, it was discovered that the factor of 2π was omitted from Equation (PA.208). This error was determined to be of no consequence to the CCA PA conclusions (Hadgu et al. 1999) and was corrected in the CRA-2004 PA. As a consequence of the error correction, the regression models used to determine the boundary pressure p_{wf} were recalculated (Hadgu et al. 1999). The corrected regression models are reported in this appendix.

The following iterative procedure based on the bisection method was used to approximate solutions to Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224).

Step 1. Estimate $p(0)$ using a bisection algorithm:

The initial guess for $p(0)$ is the midpoint $\frac{1}{2} p_w$ of interval $[0, p_w]$, where p_w is the pressure in the repository at the time of the drilling intrusion used in Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224).

The next guess for $p(0)$ is at the midpoint of either $\left[0, \frac{1}{2} p_w\right]$ or $\left[\frac{1}{2} p_w, p_w\right]$, depending on whether the resultant approximation to $p(655)$ is above or below atmospheric pressure.

Subsequent guesses for $p(0)$ are made in a similar manner.

Step 2. Use $p(0)$, known values for J_b, J_g, and p_w, and Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224) to determine $q_b[p(0)]$ and $q_g[p(0)]$.

Step 3. Use the bisection method with Δh = 25 ft = 7.62 m and appropriate changes in annular diameter (Figure PA-30) to determine $p(655)$ (i.e., $p(h + \Delta h) = p(h) + G(q_b[p(0)], q_g[p(0)], p(h), h), \Delta h)$).

Step 4. Stop if $p(655)$ is within 0.07% of atmospheric pressure (i.e., if $|1.013 \times 10^5 \, Pa - p(655)| \leq 70 \, Pa$)). Otherwise, return to Step 1 and repeat process.

The preceding procedure is continued until the specified error tolerance (i.e., 0.07%) has been met. The computational design of the PA has the potential to require more than 23,000 separate DBR calculations (3 replicates × 5 scenarios × 3 drilling locations × 100 vectors × 5 to 6 intrusion times per scenario). In concept, each of these cases requires the solution of Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224) with the iterative procedure just presented to obtain the boundary value condition $p_{wf} = p(0)$ (Table PA-17). To help hold computational costs down, $p(0)$ was calculated for approximately 2,000 randomly generated vectors of the form

$$\mathbf{v} = \left[p_w, h, S_{br}, S_{gr}, S_b, A_i \right] \qquad \text{(PA.232)}$$

where p_w is the repository pressure (used in definition of $q_b[p(0)]$ and $q_g[p(0)]$ in Equation (PA.221), Equation (PA.222), Equation (PA.223), and Equation (PA.224)), h is the crushed height of the repository (used in definition of J_p in Equation (PA.208)), S_{br} and S_{gr} are the residual saturations for gas and brine in the repository (used in definition of k_{rp} in Equation (PA.208)), S_b is the saturation of brine in the repository (used in definition of k_{rp} in Equation (PA.208)), and A_i is the equivalent area of material removed by cuttings, cavings, and spallings (used in definition of skin factor s in Equation (PA.212)). The outcomes of these calculations were divided into three cases:

1. Mobile brine only (i.e., $k_{rg} = 0$ in Equation (PA.214))

2. Brine-dominated flow (i.e., $k_{rb} > k_{rg}$)

3. Gas-dominated flow (i.e., $k_{rg} > k_{rb}$)

Regression procedures were then used to fit algebraic models that can be used to estimate $p(0)$. These regression models were then used to determine $p(0)$, and hence, p_{wf}. The resulting three regression models (or curve fit equations) for flowing bottomhole pressure (p_{wf}) are as follows:

1. For a system with only mobile brine ($k_{rg} = 0$)

$$p_{wf} = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y \qquad \text{(PA.233)}$$

where $x = \log(j_b)$ and $y = p_w$ (= repository pressure), the coefficients in Equation (PA.233) were determined to be

$a = 3.2279346 \times 10^{11}$
$b = 9.4816648 \times 10^{10}$
$c = -6.2002715 \times 10^{3}$
$d = 9.2450601 \times 10^{9}$
$e = 4.1464475 \times 10^{-6}$
$f = -1.2886068 \times 10^{3}$
$g = 2.9905582 \times 10^{8}$
$h = 1.0857041 \times 10^{-14}$
$i = 4.7119798 \times 10^{-7}$
$j = -6.690712 \times 10^{-1}$

with a resulting coefficient of determination R2 = 0.974.

2. For brine-dominated flow ($k_{rb} > k_{rg}$)

$$p_{wf} = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy} \qquad \text{(PA.234)}$$

where $x = \log\left(\frac{k_{rg}}{k_{rb}}\right)$ and $y = p_w$ (= repository pressure), the coefficients in Equation (PA.234) were determined to be

$a = 1.6065077 \times 10^{6}$
$b = 2.6243397 \times 10^{6}$
$c = 2.4768899 \times 10^{6}$
$d = -5.3635476 \times 10^{-2}$
$e = 7.0815693 \times 10^{-1}$
$f = 3.8012696 \times 10^{-1}$

$g = 4.1916956 \times 10^{-3}$
$h = -2.4887085 \times 10^{-8}$

with a resulting coefficient of determination $R^2 = 0.997$.

3. For gas-dominated flow ($k_{rg} > k_{rb}$)

$$p_{wf} = a + b\frac{1}{x} + cy + d\frac{1}{x^2} + ey^2 + f\frac{x}{y} + g\frac{1}{x^3} + hy^3 + i\frac{y^2}{x} + j\frac{y}{x^2} \qquad \text{(PA.235)}$$

where $x = \log(j_g)$ and $y = p_w$ (= repository pressure), the coefficients in Equation (PA.235) were determined to be

$a = -1.0098405 \times 10^{9}$
$b = -2.3044622 \times 10^{10}$
$c = 9.8039146$
$d = -1.7426466 \times 10^{11}$
$e = 1.8309137 \times 10^{-7}$
$f = 1.7497064 \times 10^{2}$
$g = -4.3698224 \times 10^{11}$
$h = -1.4891198 \times 10^{-16}$
$i = 1.3006196 \times 10^{-6}$
$j = 7.5744833 \times 10^{2}$

with a resulting coefficient of determination $R^2 = 0.949$.

PA-4.7.7 Boundary Value Pressure p_{wE1}

Some of the DBR calculations are for a drilling intrusion that has been preceded by an E1 intrusion in either the same waste panel, an adjacent waste panel, or a nonadjacent waste panel (Section PA-6.7.6). The effects of these prior E1 intrusions are incorporated into the solution of Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220), and hence into the DBR, by specifying a boundary pressure p_{wE1} at the location of the E1 intrusion into the repository (Table PA-17).

Two cases are considered for the definition of p_{wE1}: (1) an open borehole between the brine pocket and the repository and (2) a borehole filled with silty-sand-like material between the brine pocket and the repository. The first case corresponds to the situation in which the drilling intrusion occurs within 200 years of a prior drilling intrusion that penetrated the pressurized brine pocket, and the second case corresponds to the situation in which the drilling intrusion occurs more than 200 years after a prior drilling intrusion that penetrated the pressurized brine pocket.

PA-4.7.7.1 Solution for Open Borehole

In this case, p_{wE1} is set equal to the flowing well pressure p_{wfBP} of an open borehole between the brine pocket and the repository, and is given by

$$Q = f_1\left(p_{BP}, p_{wfBP}\right) \tag{PA.236}$$

$$Q = f_2\left(p_{wfBP}, p_{wfBI}\right) \tag{PA.237}$$

$$Q = f_3\left(p_{wfBI}, p_{wfBO}\right) \tag{PA.238}$$

where

p_{BP} = pressure (Pa) in brine pocket

p_{wfBP} = flowing well pressure (Pa) at outlet from brine pocket

p_{wfBI} = flowing well pressure (Pa) at inlet to repository from brine pocket

p_{wfBO} = flowing well pressure (Pa) at outlet from repository due to intruding borehole (Note: The boreholes associated with p_{wfBI} and p_{wfBO} arise from different drilling intrusions and hence are at different locations; see Figure PA-28)

Q = brine flow rate (m^3/s) from brine pocket to repository, through repository, and then to surface

and f_1, f_2, and f_3 are linear functions of their arguments. In the development, p_{BP} and p_{wfBO} are assumed to be known, with the result that Equation (PA.236), Equation (PA.237), and Equation (PA.238) constitutes a system of three linear equations in three unknowns (i.e., p_{wfBP}, p_{wbFI} and Q) that can be solved to obtain p_{wfBI}. In the determination of p_{wfBI} for use in a particular solution of Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219),and Equation (PA.220), p_{BP} is the pressure in the brine pocket at the time of the intrusion obtained from the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) with BRAGFLO, and p_{wfBO} is the flowing well pressure obtained from conditions at the time of the intrusion (from the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30)) and the solutions of the Poettmann-Carpenter model embodied in Equation (PA.233), Equation (PA.234), and Equation (PA.235) (i.e., given pressure, k_{rg} and k_{rb} at the time of the intrusion, and J_p, p_{wfBO} is determined from the regression models indicated in Equation (PA.233), Equation (PA.234), and Equation (PA.235)).

The definition of Equation (PA.236), Equation (PA.237), and Equation (PA.238) is now discussed. Equation (PA.236) characterizes flow out of the brine pocket into an open borehole and has the form (Williamson and Chappelear 1981, Chappelear and Williamson 1981)

$$Q = \left(\frac{2\pi k_{BP} h_{BP}}{\mu \left[\ln\left(r_{eBP} / r_w \right) - 0.5 \right]} \right) \left(p_{BP} - p_{wfBP} \right) \qquad \text{(PA.239)}$$

where

k_{BP} = brine pocket permeability (m^2)
h_{BP} = effective brine pocket height (m)
r_{eBP} = effective brine pocket radius (m)
r_w = wellbore radius (m)
μ = brine viscosity (Pa s)

In the present analysis, k_{BP} is an uncertain analysis input (see BHPRM in Table PA-19); h_{BP} = 125.83 m; r_{eBP} = 114 m (Stoelzel and O'Brien 1996), which corresponds to the size of the largest brine pocket that could fit under one waste panel; r_w = (8.921 in.)/2 = 0.1133 m, which is the inside radius of a 9 5/8 in. outside diameter casing (Gatlin 1960, Table 14.7); $\mu = 1.8 \times 10^{-3}$ Pa s; and p_{BP} is determined from the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30), as previously indicated.

Equation (PA.237) characterizes flow up an open borehole from the brine pocket to the repository and is based on Poiseuille's Law (Prasuhn 1980, Eqs. 7-21, 7-22). Specifically, Equation (PA.237) has the form

$$Q = \left[\frac{\pi D^4}{128 \mu \left(y_{BP} - y_{rep} \right)} \right] \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \left(y_{rep} - y_{BP} \right) \right] \qquad \text{(PA.240)}$$

where

D = wellbore diameter (m)
y_{rep} = elevation of repository (m) measured from surface
y_{BP} = elevation of brine pocket (m) measured from surface
g = acceleration due to gravity (9.8 m/s^2)
ρ = density of brine (kg/m^3)

and the remaining symbols have already been defined.

In the present analysis, $D = 2r_w$ = 0.2266 m, ρ = 1230 kg/m^3, and $y_{BP} - y_{rep}$ = 247 m. With the preceding values,

$$128\mu \left(y_{BP} - y_{rep} \right) \Big/ \pi D^4 = 6.87 \times 10^3 \text{ Pa s} / m^3 \qquad \text{(PA.241)}$$

$$g\rho\left(y_{rep} - y_{BP}\right) = 2.98\times10^{6}\ \text{Pa} \tag{PA.242}$$

Thus,

$$p_{wfBI} = p_{wfBP} - 2.98\times10^{6}\ \text{Pa} \tag{PA.243}$$

when Q is small ($\leq 0.1\ m^3/s$). When appropriate, this approximation can be used to simplify the construction of solutions to Equation (PA.236), Equation (PA.237), and Equation (PA.238).

Equation (PA.238) characterizes flow through the repository from the lower borehole to the bottom of the borehole associated with the drilling intrusion under consideration and has the same form as Equation (PA.239). Specifically,

$$Q = \left(\frac{2\pi k_{rep} h_{rep}}{\mu\left[\ln\left(r_{e,rep}/r_w\right) - 0.5\right]}\right)\left(p_{wfBI} - p_{wfBO}\right) \tag{PA.244}$$

where

k_{rep} = repository permeability (m^2)

h_{rep} = repository height (m)

$r_{e,rep}$ = effective repository radius (m)

and the remaining symbols have already been defined. In the present analysis, $k_{rep} = 2.4 \times 10^{-13}$ m^2; h_{rep} at the time of the drilling intrusion under consideration is obtained from the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30) (see Equation (PA.203)); and $r_{e,rep}$ is the same as the radius r_e defined in Equation (PA.209). As previously indicated, p_{wfBO} is obtained from the solutions to the Poettmann-Carpenter model summarized in Equation (PA.233), Equation (PA.234), and Equation (PA.235).

Three equations (i.e., Equation (PA.239), Equation (PA.240), and Equation (PA.244)) with three unknowns (i.e., p_{wfBP}, p_{wfBI} and Q) have now been developed. The solution for p_{wfBI} defines the initial value p_{wE1} in Table PA-17. When the simplification in Equation (PA.243) is used, the resultant solution for p_{wfBI} is

$$p_{wfBI} = \frac{p_{wfBO} + \left(p_{BP} - 2.98\times10^{6}\right)K_1}{1 + K_1} \tag{PA.245}$$

where

$$K_1 = \frac{k_{BP} h_{BP} \left[\ln\left(\frac{r_{e,rep}}{r_w} \right) - \frac{1}{2} \right]}{k_{rep} h_{rep} \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]} \qquad \text{(PA.246)}$$

and -2.98×10^6 comes from Equation (PA.242). The expression in Equation (PA.246) was used to define p_{wE1} in the CCA for the determination of DBRs resulting from a drilling intrusion that occurred within 200 years of a preceding E1 intrusion (see Table PA-7). The same approach was used for the CRA-2004 and the CRA-2009.

PA-4.7.7.2 Solution for Sand-Filled Borehole

The determination of the pressure p_{wfBI}, with the assumption that a borehole filled with silty-sand-like material connects the brine pocket and the repository, is now considered. The approach is similar to that used for the open borehole, except that Equation (PA.236) and Equation (PA.237) are replaced by a single equation based on Darcy's Law. Specifically, flow from the brine pocket to the repository is represented by

$$Q = \frac{k_{BH} A_{BH} \left[\left(p_{wfBP} - p_{wfBI} \right) + g\rho \right]}{\mu \left(y_{BP} - y_{rep} \right)} \qquad \text{(PA.247)}$$

where

k_{BH} = borehole permeability (m^2)

A_{BH} = borehole cross-sectional area (m^2)

and the remaining symbols have been previously defined. In the present analysis, k_{BH} is an uncertain input (see BHPRM in Table PA-19) and A_{BH} is defined by the assumption that the borehole diameter is the same as the drill bit diameter (i.e., 12.25 in. = 0.31115 m).

The representation for flow from the brine pocket inlet point through the repository to the outlet point associated with the drilling intrusion under consideration remains as defined in Equation (PA.244). Thus, two equations (i.e., Equation (PA.244) and Equation (PA.247)) and two unknowns (i.e., p_{wfBI} and Q) are under consideration. Solution for p_{wfBI} yields

$$p_{wfBI} = \frac{p_{wfBO} + K_2 p_{BP} - 2.98 \times 10^6 K_2}{1 + K_2} \qquad \text{(PA.248)}$$

where

$$K_2 = \frac{\pi k_{BH} r_w^2 \left[\ln\left(\frac{r_{eBP}}{r_w} \right) - \frac{1}{2} \right]}{2\pi h_{rep} k_{rep} \left(y_{BP} - y_{rep} \right)} \qquad \text{(PA.249)}$$

and -2.98×10^6 comes from Equation (PA.242). The expression in Equation (PA.249) was used to define p_{wE1} in the determination of DBRs for a drilling intrusion that occurred more than 200 years after a preceding E1 intrusion (see Table PA-7).

PA-4.7.8 End of DBR

The CRA-2009 PA has 23,400 cases that potentially require solution of Equation (PA.214) through Equation (PA.220) to obtain the DBR volume (See Section PA-6.7.6). However, the DBR was set to zero without solution of Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) when there was no possibility of a release (i.e., at the time of the intrusion, the intruded waste panel had either a pressure less than 8 MPa or a brine saturation below the residual brine saturation S_{br}).

For the remaining cases, Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) were solved for a time period of 50 days, although the value used for t_e was always less than 50 days. The minimum value used for t_e was three days, which is an estimate of the time required to drill from the repository through the Castile Formation and then cement the intermediate casing. If there is little or no gas flow associated with brine inflow into the borehole during drilling in the Salado Formation, the current industry practice is to allow the brine to "seep" into the drilling mud and be discharged to the mud pits until the salt section is cased.

If there is a significant amount of gas flow, it is possible that the driller will lose control of the well. In such cases, DBRs will take place until the gas flow is brought under control. Two possibilities exist: (1) the driller will regain control of the well when the gas flow drops to a manageable level, and (2) aggressive measures will be taken to shut off the gas flow before it drops to a manageable level. In the CCA PA, the driller was assumed to regain control of the well when the gas flow dropped to a "cut-off" rate of 1×10^5 standard cubic feet per day (SCF/d in commonly used oil field units). Experience at the South Culebra Bluff Unit #1, which blew out in January 1978, suggests that approximately 11 days may be needed to bring a well under control before the gas flow drops to a manageable level (i.e., 1×10^5 SCF/d) (the CCA, Appendix MASS, Attachment MASS 16-2). In particular, it took 11 days to assemble the equipment and personnel needed to bring that well under control.

A reevaluation of the current drilling practices, including a review of the historic information and interviews with current drilling personnel in the WIPP area, was conducted (Kirkes 2007). This analysis found

1. The South Culebra Bluff #1 is not a suitable analogue for a hypothetical WIPP blowout.

2. Basing the WIPP maximum DBR parameter on the single most catastrophic blowout event in the region's history does not reasonably represent "current drilling practice" as directed by regulations.

3. Well-known drilling procedures are sufficient to stop or *kill* a WIPP blowout under the most extreme anticipated pressures in hours, not days.

4. Using 4.5 days for a maximum DBR duration is still quite conservative, in that it assumes flow into the wellbore continues throughout the kill procedure and casing/cementing procedures, even though this assumption is not consistent with current practice.

Therefore, for the CRA-2009 PA, a value of 4.5 days was used for the maximum value used for t_e.

Given the preceding, t_e is defined by

$$t_e = \begin{cases} \max\left\{3 \text{ d}, t_f\right\} & \text{if } t_f \le 4.5 \text{ d} \\ 4.5 \text{ d} & \text{if } t_f > 4.5 \text{ d} \end{cases} \qquad \text{(PA.250)}$$

in PA, where t_f is the time at which the gas flow out of the well drops below 1×10^5 SCF/d. As a reminder, gas flow out of the repository in the intruding borehole, and hence t_e, is determined as part of the solution to Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220).

PA-4.7.9 Numerical Solution

As previously indicated, the BRAGFLO program is used to solve Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) with the computational grid in Figure PA-28, the initial value conditions in Section PA-4.7.2, the boundary value conditions in Table PA-17, and parameter values appropriate for modeling DBRs. Thus, the numerical procedures in use for Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) are the same as those described in Section PA-4.2.11 for the solution of Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30).

In this solution, the boundary value conditions associated with drilling intrusions (i.e., p_{wf} and p_{wE1} in Table PA-17) are implemented through the specification of fluid withdrawal terms (i.e., q_g and q_b in Equation (PA.24), Equation (PA.25), Equation (PA.26), Equation (PA.27), Equation (PA.28), Equation (PA.29), and Equation (PA.30)), rather than as predetermined boundary value conditions. With this implementation, the representations in Equation (PA.214) and Equation (PA.215) for gas and brine conservation become

$$\nabla\cdot\left[\frac{\alpha\rho_g K_g k_{rg}}{\mu_g}\left(\nabla p_g+\rho_g g\nabla h\right)\right]+\alpha q_g=\alpha\frac{\partial\left(\phi\rho_g S_g\right)}{\partial t} \qquad \text{(PA.251)}$$

$$\nabla\cdot\left[\frac{\alpha\rho_b K_b k_{rb}}{\mu_b}\left(\nabla p_b+\rho_b g\nabla h\right)\right]+\alpha q_b=\alpha\frac{\partial\left(\phi\rho_b S_b\right)}{\partial t} \qquad \text{(PA.252)}$$

and the constraints in Equation (PA.214), Equation (PA.215), Equation (PA.216), Equation (PA.217), Equation (PA.218), Equation (PA.219), and Equation (PA.220) remain unchanged. As used in Equation (PA.251) and Equation (PA.252), q_g and q_b are independent of the computational grid in use (Figure PA-28). In practice, q_g and q_b are defined with a productivity index (see Equation (PA.208)) that is a function of the specific computational grid in use, with the result that these definitions are only meaningful in the context of the computational grid that they are intended to be used with. This specificity results because q_g and q_b as used in Equation (PA.251) and Equation (PA.252) are defined on a much smaller scale than can typically be implemented with a reasonably sized computational grid. As a result, the values used for q_g and q_b in the numerical solution of Equation (PA.251) and Equation (PA.252) must incorporate the actual size of the grid in use.

In the solution of Equation (PA.251) and Equation (PA.252) with the computational grid in Figure PA-28, q_g is used to incorporate gas flow out of the repository, and q_b is used to incorporate both brine inflow to the repository from a pressurized brine pocket and brine flow out of the repository. For gas flow out of the repository,

$$q_g(x,y,t)=\frac{kk_{rg}(x,y,t)[p_g(x,y,t)-p_{wf}]}{\mu_g[\ln(r_e/r_w)+s+c]} \qquad \text{(PA.253)}$$

if (x, y) is at the center of the grid cell containing the drilling intrusion (Figure PA-28), and $q_g(x, y, t) = 0$ (kg/m^3)/s otherwise, where k, k_{rg}, μ_g, r_e, r_w, s, and c are defined in conjunction with Equation (PA.208), p_g is gas pressure, and p_{wf} is the flowing well pressure at the outlet borehole (i.e., the boundary value condition in Table PA-17). The factor h in Equation (PA.208) is the crushed height of the repository as indicated in Equation (PA.208) and defines the factor α in Equation (PA.251) and Equation (PA.252). In the numerical solution, $q_g(x, y, t)$ defines $q_{g_{i,j}}^{n+1}$ in Equation (PA.91), with $q_{g_{i,j}}^{n+1}$ having a nonzero value only when i, j correspond to the grid cell containing the borehole through which gas outflow is taking place (i.e., the grid cells containing the down-dip, middle, and up-dip wells in Figure PA-28).

For brine flow,

$$q_b(x,y,t)=\frac{kk_{rb}(x,y,t)[p_b(x,y,t)-p_{wf}]}{\mu_b[\ln(r_e/r_w)+s+c]} \qquad \text{(PA.254)}$$

if (x, y) is at the center of the grid cell containing the drilling intrusion through which brine outflow from the repository is taking place (Figure PA-28);

$$q_b(x,y,t) = \frac{kk_{rb}(x,y,t)[p_{wE1} - p_b(x,y,t)]}{\mu_b[\ln(r_e / r_w) + c]} \quad \text{(PA.255)}$$

if (x, y) is at the center of the grid cell containing a prior drilling intrusion into a pressurized brine pocket (Figure PA-28), where p_{wE1} is the boundary value condition defined in Table PA-17; and $q_b(x, y, t) = 0$ otherwise. In the numerical solution of Equation (PA.251), $q_g(x, y, t)$ defines $q_{b_{i,j}}^{n+1}$ in a discretization for Equation (PA.252) that is equivalent to the discretization for Equation (PA.251) shown in Equation (PA.91), with $q_{b_{i,j}}^{n+1}$ having a nonzero value only when *i, j* correspond to the grid cell containing the borehole through which brine outflow is taking place (i.e., the grid cells containing the down-dip, middle, and up-dip wells in Figure PA-28), in which case, Equation (PA.254) defines $q_{b_{i,j}}^{n+1}$, or when *i, j* corresponds to the grid cell containing the borehole through which brine inflow to the repository from a pressurized brine pocket is taking place (i.e., the grid cell containing the E1 intrusion in Figure PA-28), in which case Equation (PA.255) defines $q_{b_{i,j}}^{n+1}$.

PA-4.7.10 Additional Information

Additional information on BRAGFLO and its use in the CRA-2009 PA to determine DBRs can be found in the analysis package for DBR (Clayton 2008b) and in the BRAGFLO user's manual (Nemer 2007c).

PA-4.8 Groundwater Flow in the Culebra Dolomite

Extensive site characterization and modeling activities conducted in the WIPP vicinity have confirmed that the Culebra Dolomite Member of the Rustler Formation is the most transmissive geologic unit above the Salado. Thus, the Culebra is the unit into which actinides are most likely to be introduced from long-term flow up a hypothetical abandoned borehole.

The Culebra's regional variation in groundwater flow direction is influenced by the distribution of rock types in the groundwater basin where the WIPP is located. Site characterization activities have shown that the direction of groundwater flow in the Culebra varies somewhat regionally, but in the area that overlies the site, flow is generally southward. Site characterization activities have also demonstrated that there is no evidence of karst groundwater systems in the controlled area, although groundwater flow in the Culebra is affected by the presence of fractures, fracture fillings, and vuggy pore features.

Basin-scale regional modeling of three-dimensional groundwater flow in the units above the Salado demonstrates that it is appropriate, for the purposes of estimating radionuclide transport, to conceptualize the Culebra as a two-dimensional confined aquifer. Groundwater flow in the Culebra is modeled as a steady-state process, but uncertainty in the flow field is incorporated in

the analysis by using 100 different geostatistically based T fields. The T fields are initially constructed to be consistent with available head, transmissivity, and well testing data. Each T field is subsequently modified to incorporate impacts of uncertain future processes (potash mining and climate change), as described below.

Potash mining in the McNutt Potash Zone (hereafter referred to as the McNutt) of the Salado, which occurs now in the Delaware Basin outside the controlled area and may continue in the future, could affect flow in the Culebra if subsidence over mined areas causes fracturing or other changes in rock properties. Consistent with regulatory criteria, mining outside the controlled area is assumed to occur in the near future, and mining within the controlled area is assumed to occur with a probability of 1 in 100 per century (adjusted for the effectiveness of AICs during the first 100 years following closure). Consistent with regulatory guidance, the effects of mine subsidence are incorporated in the PA by increasing the transmissivity of the Culebra over the areas identified as mineable by a factor sampled from a uniform distribution between 1 and 1000. T fields used in the PA are therefore adjusted to account for this and steady-state flow fields calculated accordingly, once for mining that occurs only outside the controlled area, and once for mining that occurs both inside and outside the controlled area. Mining outside the controlled area is considered in both undisturbed and disturbed performance.

Climatic changes during the next 10,000 years may also affect groundwater flow by altering recharge to the Culebra. The extent to which the climate will change during the next 10,000 years and how such a change will affect groundwater flow in the Culebra are uncertain. However, regional three-dimensional modeling of groundwater flow in the units above the Salado indicates that flow velocities in the Culebra may increase by a factor of 1 to 2.25 for reasonably possible future climates (Corbet and Swift 1996a and 1996b). This uncertainty is incorporated in the PA by scaling the calculated steady-state specific discharge within the Culebra by a sampled parameter within this range.

PA-4.8.1 Mathematical Description

Groundwater flow in the Culebra is represented by the PDE

$$S = \left(\frac{\partial h}{\partial t} \right) = \nabla \cdot \left(b \mathbf{K} \nabla h \right) - Q \qquad \text{(PA.256)}$$

where

S = medium storativity (dimensionless),
h = hydraulic head (m),
t = time (s),
b = aquifer thickness (m),
$\mathbf{K}$ = hydraulic conductivity tensor (m/s),
Q = source/sink term expressed as the volumetric flux per unit area ((m^3/m^2)/s = m/s).

Further, the Culebra is assumed to be two-dimensional with isotropic hydraulic conductivity. As a result, $\mathbf{K}$ is defined by

$$\mathbf{K}(x,y) = k(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{(PA.257)}$$

where $k(x, y)$ is the hydraulic conductivity (m/s) at the point (x, y). The following simplifying assumptions are also made: fluid flow in the Culebra is at steady state (i.e., $\partial h/\partial t = 0$), and source and sink effects arising from borehole intrusions and infiltration are negligible (i.e., $Q = 0$). Given these assumptions, Equation (PA.256) simplifies to

$$\nabla \cdot \left(b\mathbf{K}\nabla h\right) = 0 \quad \text{(PA.258)}$$

which is the equation actually solved to obtain fluid flow in the Culebra. In PA, $b = 7.75$ m, and $k(x, y)$ in Equation (PA.257) is a function of an imprecisely known T field, as discussed in Section PA-4.8.2.

PA-4.8.2 Implementation

This section describes the salient features of the Culebra flow field calculation implementation. One should note, however, that this implementation has not been changed for the CRA-2009 PA. Instead, the flow fields generated for the CRA-2004 PABC have been reused for the CRA-2009 PA (Lowry and Kanney 2005).

The first step in the analysis of fluid flow in the Culebra is to generate T fields $T(x, y)$ (m^2/s) for the Culebra and to characterize the uncertainty in these fields. This was accomplished by generating a large number of plausible T fields. A description of the method used to construct these T fields is included in Appendix TFIELD-2009. A brief outline of the method is presented below.

The T fields used for PA are based on several types of information, including a regression model developed on WIPP-site geologic data, measured head levels in the Culebra for the year 2000, and well drawdown test results. The process that led to the final T fields used in the PA is discussed below.

Geologic data, including (1) depth to the top of the Culebra, (2) reduction in thickness of the upper Salado by dissolution, and (3) the spatial distribution of halite in the Rustler below and above the Culebra, were used to define a geologic regression model that relates transmissivity at any location to a set of geologically defined parameters.

Base T fields are defined for a modeling domain measuring 22.4 km (19 miles) east-west by 30.7 km north-south using a method of stochastic simulation. The base T fields were constructed from information on the depth to the Culebra, indicator functions defining the location of Salado dissolution, halite occurrence, and high transmissivity zones.

Seed T fields are defined by conditioning base T fields to measured values of transmissivity. This conditioning is performed with a Gaussian geostatistical simulation algorithm.

The seed T fields are calibrated to transient water-level data from the year 2000 in 37 wells across the region using the parameter estimation program PEST (Doherty 2002). The PEST program iteratively changes the seed T field values to minimize an objective function, using MODFLOW 2000 (Harbaugh et al. 2000) to compute the flow solution for each iteration. The objective function minimized by PEST is a combination of the weighted sum of the squared residuals between the measured and modeled heads and a second weighted sum of the squared differences in the estimated transmissivity between pairs of pilot points. The second weighted sum is designed to keep the T field as homogeneous as possible and provide numerical stability when estimating more parameters than there are data.

The calibrated T fields produced by PEST and MODFLOW are screened according to specific acceptance criteria (Beauheim 2003). Calibrated T fields that meet the acceptance criteria are modified for the partial and full mining scenarios. This modification increases transmissivity by a random factor between 1 and 1000 in areas identified as containing potash reserves, as described below. Steady-state flow simulations are then run using the mining-modified T fields.

Because radionuclide transport calculations are performed using a grid with uniform cells of 50 × 50 m, the final step in the flow simulation is to run MODFLOW with a 50 × 50 m grid to calculate the flow fields required for the transport code. The hydraulic conductivities for the finer grid are obtained by dividing each 100 × 100 m cell used in the T field calculations into four 50 × 50 m cells. The conductivity assigned to each of the four cells is equal to the conductivity of the larger cell (Leigh, Beauheim, and Kanney 2003).

The hydraulic conductivity $k(x, y)$ in Equation (PA.257) is defined in terms of the T fields $T(x, y)$ by

$$k(x, y) = T(x, y) / b \tag{PA.259}$$

Fluid flow is determined (using MODFLOW to solve Equation (PA.258)) for two different cases: (1) a partial mining case (mining of potash deposits outside the LWB), and (2) a full mining case (mining of potash deposits inside and outside the LWB) (Figure PA-31; see Lowry and Kanney 2005, Section 3.2.5 for more details). As specified by guidance in 40 CFR Part 194, potash mining increases the Culebra's hydraulic conductivity in the vicinity of such mining by an uncertain factor with a value between 1 and 1000. As specified in section 194.32 and described in Section PA-3.9, economic potash reserves outside the LWB are assumed to have been fully mined by the end of the 100-year period of AICs, after which the occurrence of potash mining within the LWB follows a Poisson process with a rate constant of $\lambda_m = 1 \times 10^{-4}$ yr^{-1}.

In the partial mining case, the hydraulic conductivity $k_{PM}(x, y)$ is defined by Equation (PA.259) inside the WIPP boundary and by $k_{PM}(x, y) = k(x, y) \times MF$ outside the WIPP boundary, where MF is determined by the uncertain parameter CTRANSFM (see Table PA-19). In the full mining case, the hydraulic conductivity is defined by $k_{FM}(x, y) = k(x, y) \times MF$ in all areas of the modeling domain.

In turn, $k_{PM}(x, y)$ and $k_{FM}(x, y)$ result in the following definition for the hydraulic conductivity tensor $\mathbf{K}$:

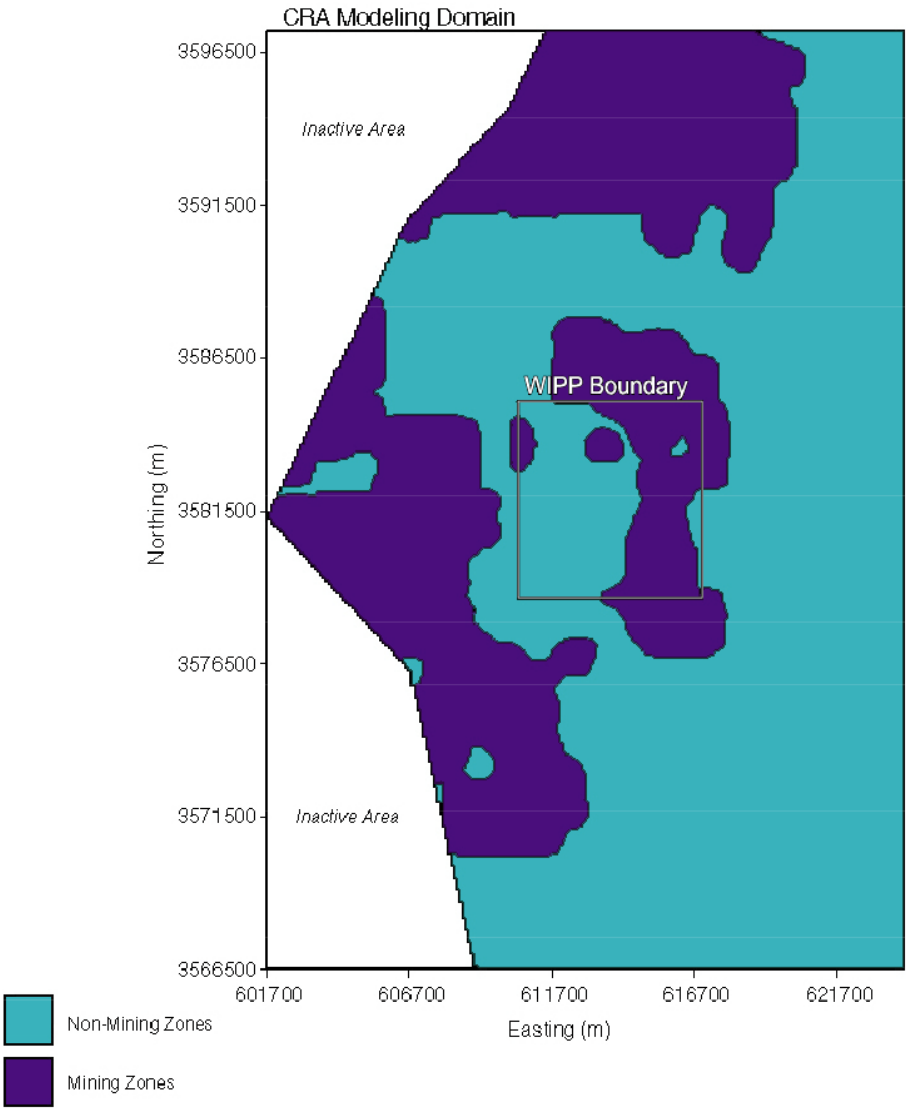


Figure PA-31. Areas of Potash Mining in the McNutt Potash Zone

$$\mathbf{K}_i(x,y) = k_i(x,y)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad i = PM, FM \tag{PA.260}$$

In the analysis, Equation (PA.258) is solved with each of the preceding definitions of $\mathbf{K}_i$ to obtain characterizations of fluid flow in the Culebra for partially-mined conditions and fully mined conditions.

The determination of fluid flow in the Culebra through the solution of Equation (PA.258) does not incorporate the potential effects of climate change on fluid flow. Such effects are incorporated into the analysis by an uncertain scale factor to introduce the potential effects of climate change into the analysis (Corbet and Swift 1996a and 1996b). Specifically, the Darcy fluid velocity $v_i(x, y)$ actually used in the radionuclide transport calculations is given by

$$\mathbf{v}_i(x,y) = \left[u_i(x,y), v_i(x,y)\right] = SFC\left[\mathbf{K}_i(x,y)\nabla h_i(x,y)\right]^T,\ i = PM, FM \quad \text{(PA.261)}$$

where $u_i(x, y)$ and $v_i(x, y)$ represent Darcy fluid velocities (m/s) at the point (x, y) in the x and y directions, respectively; $\nabla h_i(x, y)$ is obtained from Equation (PA.258) with $\mathbf{K} = \mathbf{K}_i$; and *SFC* is a scale factor used to incorporate the uncertainty that results from possible climate changes. The scale factor *SFC* is determined by the uncertain parameter CCLIMSF (see Table PA-19).

PA-4.8.3 Computational Grids and Boundary Value Conditions

The representation for fluid flow in the Culebra in Equation (PA.258) is evaluated on a numerical grid 22.4 km (13 miles) east-west by 30.7 km (19 miles) north-south, aligned with the compass directions (Figure PA-32). The modeling domain is discretized into 68,768 uniform 100 × 100 m cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km (7.4 mi) north of the northern WIPP site boundary, and about 1 km (0.62 miles) north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-transmissivity region that contributes little flow to the modeling domain. The southern boundary

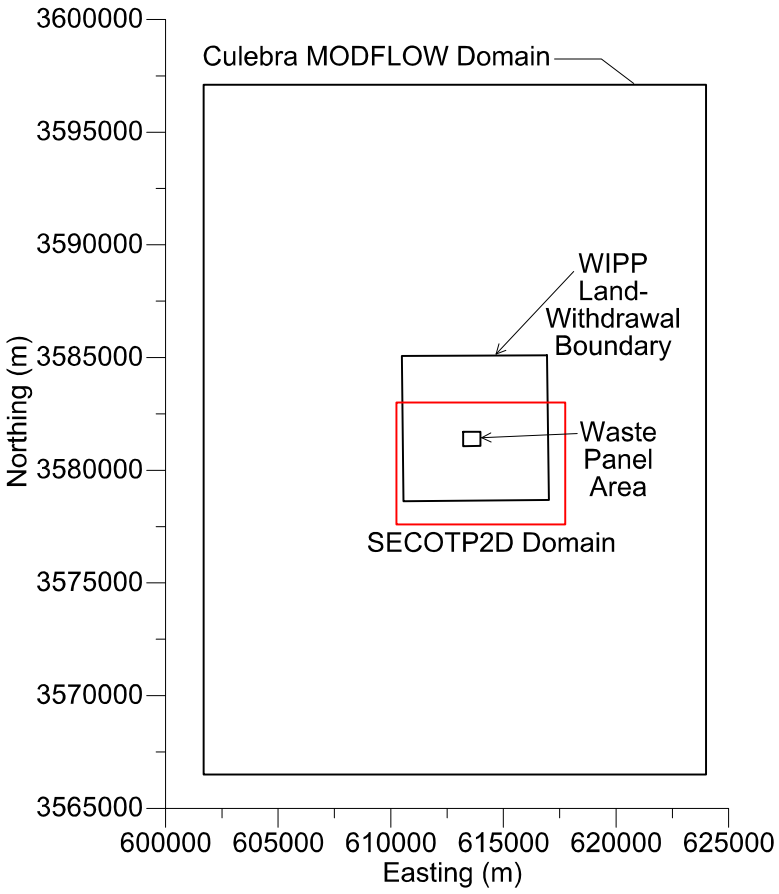


Figure PA-32. Modeling Domain for Groundwater Flow (MODFLOW) and Radionuclide Transport (SECOTP2D) in the Culebra

lies 12.2 km (7.5 miles) south of the southern WIPP site boundary, far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the Mosaic (formerly International Minerals and Chemicals) tailings pond (Laguna Uno; see Hunter [1985]) due west of the WIPP site in Nash Draw.

Two types of boundary conditions are specified: constant-head and no-flow (Figure PA-33). Constant-head conditions are assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads are obtained from a kriged initial head field. The western model boundary passes through the Mosaic tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996).

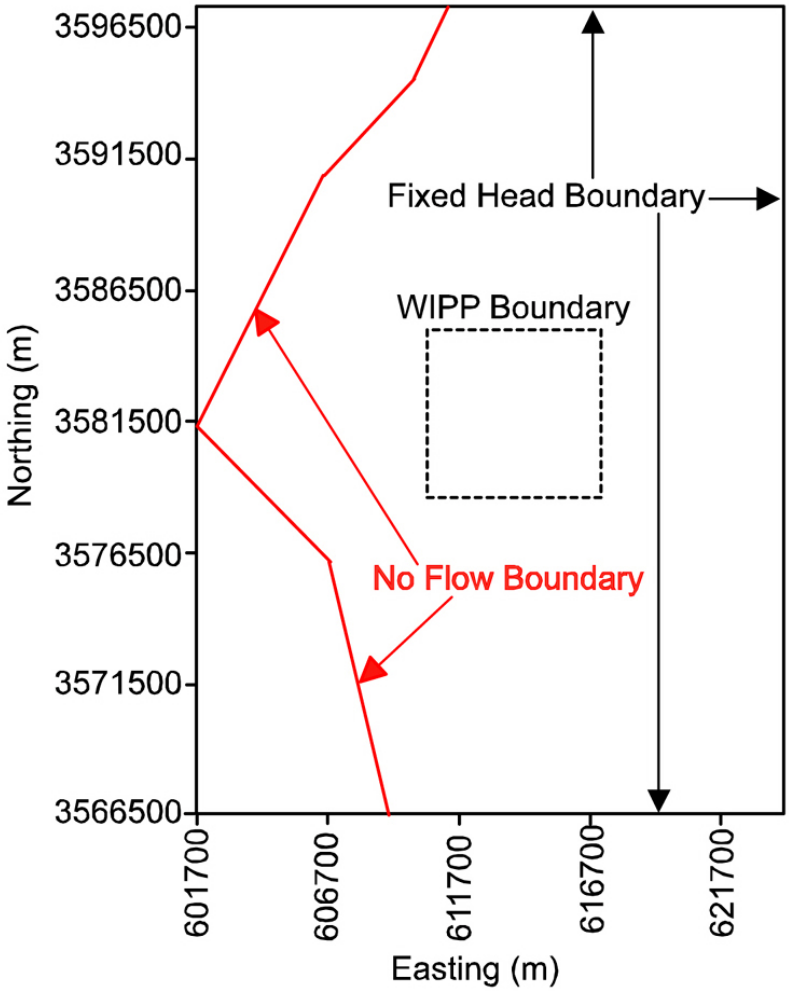


Figure PA-33. Boundary Conditions Used for Simulations of Brine Flow in the Culebra

Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW.

PA-4.8.4 Numerical Solution

The flow model in Equation (PA.258) is evaluated on the computational grid described in Section PA-4.8.3 using MODFLOW 2000 (Harbaaugh et al. 2000). MODLFOW discretizes the flow equation with a second-order difference procedure (McDonald and Harbaugh 1988, p. 126). Specifically, the discretized form of Equation (PA.258) is

$$0 = CR_{i,j-1/2}\left(h_{i,j-1} - h_{i,j}\right) + CR_{i,j+1/2}\left(h_{i,j+1} - h_{i,j}\right)$$

$$+ CC_{i-1/2,j}\left(h_{i-1,j} - h_{i,j}\right) + CC_{i+1/2,j}\left(h_{i+1,j} - h_{i,j}\right) \qquad \text{(PA.262)}$$

where CR and CC are the row and column hydraulic conductances at the cell interface between node i, j and a neighboring node (m^2/s). Since the grid is uniform, the hydraulic conductance is simply the harmonic mean of the hydraulic conductivity in the two neighboring cells multiplied by the aquifer thickness. For example, the hydraulic conductance between cells (i, j) and $(i, j - 1)$ is given by $CR_{i,j-1/2}$, and the hydraulic conductance between cells (i, j) and $(i + 1, j)$ is given by $CC_{i+1/2, j}$:

$$CR_{i,j-1/2} = \frac{2k_{i,j}k_{i,j-1}}{k_{i,j} + k_{i,j-1}} \times b \quad \text{and} \quad CC_{i+1/2,j} = \frac{2k_{i,j}k_{i+1,j}}{k_{i,j} + k_{i+1,j}} \times b$$

where $k_{i, j}$ is the hydraulic conductivity in cell i, j (m/s) and b is the aquifer thickness (m).

Figure PA-34 illustrates the cell numbering convention used in the finite-difference grid for MODFLOW. The determination of h is then completed by the solution of the linear system of equations in Equation (PA.262) for the unknown heads $h_{i,j}$. Fluxes at cell interfaces are calculated from the values for $h_{i,j}$ internally in MODFLOW.

PA-4.8.5 Additional Information

Additional information on MODFLOW and its use in WIPP PA to determine fluid flow in the Culebra can be found in the MODFLOW-2000 user's manual (Harbaugh et al. 2000) and in McKenna and Hart (2003), Lowry (2003), and Lowry and Kanney (2005). Calculation of the flow fields used in the CRA-2009 PA is presented in Lowry and Kanney (2005).

PA-4.9 Radionuclide Transport in the Culebra Dolomite

Extensive laboratory and field investigations have focused on the physical mechanisms influencing transport in the Culebra, as well as the behavior of dissolved and colloidal actinides in the Culebra. Field tests have shown that the Culebra is best characterized as a double-porosity

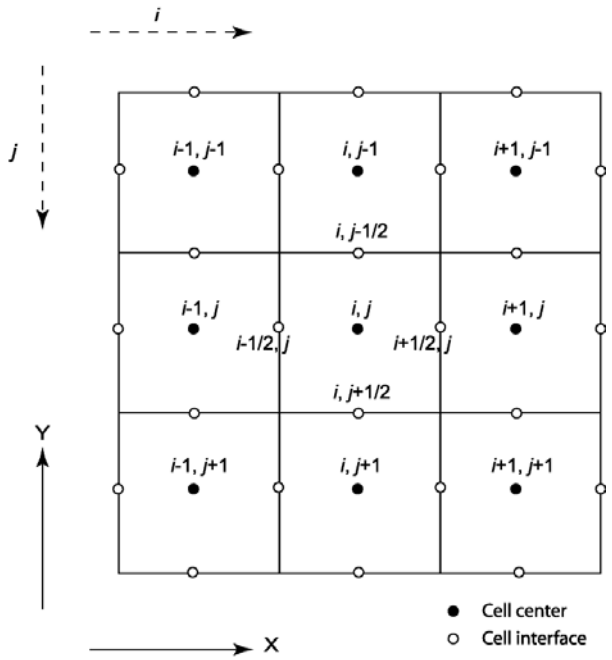


Figure PA-34. Finite-Difference Grid Showing Cell Index Numbering Convention Used by MODFLOW

medium when estimating radionuclide transport in groundwater. Groundwater flow and advective transport of dissolved or colloidal species and particles occur primarily in a small fraction of the rock's total porosity corresponding to the porosity of open and interconnected fractures and vugs. Diffusion and (much slower) advective flow occur in the remainder of the porosity, which is associated with the low-permeability dolomite matrix. Transported species, including actinides, if present, will diffuse into this porosity.

Diffusion from the advective porosity into the dolomite matrix will retard An transport by two mechanisms. Physical retardation occurs simply because actinides that diffuse into the matrix are no longer transported with the flowing groundwater, so transport is interrupted until they diffuse back into the advective porosity. In situ tracer tests have been conducted to demonstrate this phenomenon (Meigs, Beauheim, and Jones 2000). Chemical retardation also occurs within the matrix as actinides are sorbed onto dolomite grains. The relationship between sorbed and liquid concentrations is assumed to be linear and reversible. The distribution coefficients (K_ds) that characterize the extent to which actinides will sorb on dolomite are based on experimental data. After their review of the CCA, the EPA required the DOE to use the same ranges, but to change the distribution from uniform to loguniform. The DOE continues to use the EPA's distributions in the CRA-2009 PA.

Modeling, supported by field tests and laboratory experiments, indicates that physical and chemical retardation will be extremely effective in reducing the transport of dissolved actinides in the Culebra. Experimental work has demonstrated that transport of colloidal actinides is not a significant mechanism in the Culebra. As a result, An transport through the Culebra to the subsurface boundary of the controlled area is not a significant pathway for releases from the WIPP. As discussed in Section PA-9.0, the location of the mean CCDF that demonstrates

compliance with the containment requirements of section 191.13 is determined almost entirely by direct releases at the ground surface during drilling (cuttings, cavings, and spallings).

Radionuclide transport in the Culebra is computed using the SECOTP2D computer code (WIPP Performance Assessment 1997b). The mathematical equations solved by SECOTP2D and the numerical methods used in the code are described in the following sections.

PA-4.9.1 Mathematical Description

Radionuclide transport in the Culebra is described by a parallel-plate, dual-porosity model (Meigs and McCord 1996). The parallel-plate, dual-porosity conceptualization assumes that the numerous fractures within the formation are aligned in a parallel fashion and treats the fractured porous media as two overlapping continua: one representing the fractures and the other representing the surrounding porous rock matrix (see Figure PA-35). In this model, one system of PDEs is used to represent advective transport in fractures within the Culebra and another PDE system is used to represent diffusive transport and sorption in the matrix that surrounds the fractures.

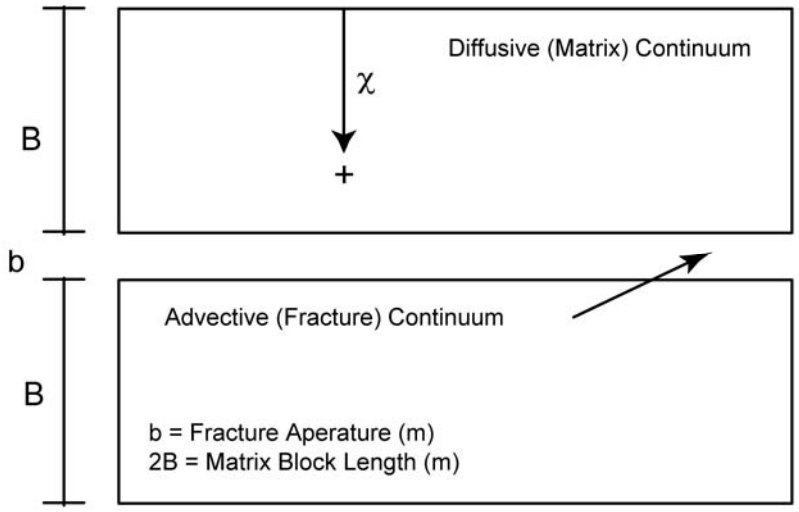


Figure PA-35. Parallel-Plate, Dual-Porosity Conceptualization

PA-4.9.1.1 Advective Transport in Fractures

The PDE system used to represent advective transport in fractures is given by (WIPP Performance Assessment 1997b)

$$\nabla\cdot\left[\phi\mathbf{D}_k\nabla C_k-\mathbf{v}C_k\right]=\phi R_k\left(\frac{\partial C_k}{\partial t}\right)+\phi R_k\lambda_k C_k-\phi R_{k-1}\lambda_{k-1}C_{k-1}-Q_k-\Gamma_k, \quad \text{(PA.263)}$$

for k = 1, 2, …, *nR*, where

nR = number of radionuclides under consideration

C_k = concentration of radionuclide *k* in brine (kg/m^3)

$\mathbf{D}_k$ = hydrodynamic dispersion tensor (m^2/s)

$\mathbf{v}$ = Darcy velocity (i.e., specific discharge) of brine ($m/s = (m^3/m^2)/s$)

ϕ = advective (i.e., fracture) porosity (dimensionless)

R_k = advective retardation coefficient (dimensionless)

λ_k = decay constant for radionuclide k (s^{-1})

Q_k = injection rate of radionuclide *k* per unit bulk volume of formation ($(kg/s)/m^3$) (Note: $Q_k > 0$ corresponds to injection into the fractures)

Γ_k = mass transfer rate of radionuclide *k* per unit bulk volume of formation due to diffusion between fractures and surrounding matrix ($(kg/s)/m^3$) (Note: $\Gamma_k > 0$ corresponds to diffusion into fractures)

The Darcy velocity v is obtained from the solution of Equation (PA.258); specifically, v is defined by the relationship in Equation (PA.261). The advective porosity ϕ, defined as the ratio of the interconnected fracture pore volume to the total volume, is determined by an uncertain parameter (see CFRCPOR in Table PA-19).

The hydrodynamic dispersion tensor is defined by (WIPP Performance Assessment 1997b; Bear 1972)

$$\mathbf{D}_k = \frac{1}{\|v\|\phi}\begin{bmatrix} u & -v \\ v & u \end{bmatrix}\begin{bmatrix} \alpha_L & 0 \\ 0 & \alpha_T \end{bmatrix}\begin{bmatrix} u & v \\ -v & u \end{bmatrix} + \tau D_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad \text{(PA.264)}$$

where α_L and α_T are the longitudinal and transverse dispersivities (m); u and v are the x and y components of $\mathbf{v}$ (i.e., $\mathbf{v} = [u, v]$); $\mathbf{D}_k^*$ is the free water molecular diffusion coefficient ($m^2\ s^{-1}$) for radionuclide *k*; and τ is the advective tortuosity, defined as the ratio of the true length of the flow path of a fluid particle to the straight-line distance between the starting and finishing points of the particle's motion. As in the CCA PA (Helton et al. 1998), the CRA-2009 PA uses $\alpha_L = \alpha_T = 0$ m and $\tau = 1$. Thus, the definition of $\mathbf{D}_k$ used in PA reduces to

$$\mathbf{D}_k = \mathbf{D}_k^* \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad \text{(PA.265)}$$

The diffusion coefficients, D*k, for the oxidation states of the radionuclides under consideration are shown in Table PA-18 (see Fox 2008, Table 35). The existence of Pu in the (III) or (IV) oxidation state (i.e., as Pu(III) or Pu(IV)) and the existence of U in the (IV) or (VI) oxidation state (i.e., as U(IV) or U(VI)) is determined by an uncertain parameter (see WOXSTAT in Table PA-19).

Table PA-18. Radionuclide Culebra Transport Diffusion Coefficients

Oxidation State	III	IV	VI
Diffusion Coefficient (m^2/s)	3.00×10^{-10}	1.53×10^{-10}	4.26×10^{-10}

Table PA-19. Variables Representing Epistemic Uncertainty in the CRA-2009 PA

Material	Property	Name	Description
AM+3	MKD_AM	CMKDAM3	Matrix distribution coefficient (m^3/kg) for Am in the III oxidation state. Defines K_{dk} in Equation (PA.271).
BH_SAND	PRMX_LOG	BHPERM	Logarithm of intrinsic permeability (m^2) of the silty-sand-filled borehole (Table PA-7). Used in regions Upper Borehole and Lower Borehole in Figure PA-15.
BOREHOLE	DOMEGA	DOMEGA	Drill string angular velocity (rad/s). Defines $\Delta\Omega$ in Equation (PA.133).
BOREHOLE	TAUFAIL	WTAUFAIL	Shear strength of waste (Pa). Defines $\tau(R, 1)$ in Equation (PA.131).
CASTILER	COMP_RCK	BPCOMP	Bulk compressibility (Pa^{-1}) of Castile brine reservoir. Defines c_{fB} in Equation (PA.35) for region CASTILER of Figure PA-15.
CASTILER	PRESSURE	BPINTPRS	Initial brine pore pressure in the Castile brine reservoir (region CASTILER in Figure PA-15).
CASTILER	PRMX_LOG	BPPRM	Logarithm of intrinsic permeability (m^2) of the Castile brine reservoir. Used in region CASTILER in Figure PA-15.
CELLULS	FBETA	FBETA	Factor beta for microbial reaction rates.
CONC_PCS	PORE_DIS	CONBCEXP	Brooks-Corey pore distribution parameter (dimensionless) for panel closure concrete (Section PA-4.2.8.1). Defines λ in Equation (PA.38), Equation (PA.39), and Equation (PA.40) for region CONC_PCS of Figure PA-15 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equation (PA.44), Equation (PA.45), and Equation (PA.46) for use with van Genuchten-Parker model in region CONC_PCS.
CONC_PCS	PRMX_LOG	CONPRM	Logarithm of intrinsic permeability (m^2) for the concrete portion of the panel closure (Section PA-4.2.8.1). Used in region CONC_PCS in Figure PA-15.
CONC_PCS	SAT_RBRN	CONBRSAT	Residual brine saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{br} in Equation (PA.43) for use in region CONC_PCS in Figure PA-15.
CONC_PCS	SAT_RGAS	CONGSSAT	Residual gas saturation (dimensionless) in panel closure concrete (Section PA-4.2.8.1). Defines S_{gr} in Equation (PA.43) for area CONC_PCS in Figure PA-15.
CONC_PLG	PRMX_LOG	PLGPRM	Logarithm of intrinsic permeability (m^2) of the concrete borehole plugs (Table PA-7). Used in region Borehole Plugs in Figure PA-15.
CULEBRA	APOROS	CFRACPOR	Culebra fracture (i.e., advective) porosity (dimensionless). Defines ϕ in Equation (PA.263).
CULEBRA	DPOROS	CMTRXPOR	Culebra matrix (i.e., diffusive) porosity (dimensionless). Defines ϕ' in Equation (PA.270).

Table PA-19. Variables Representing Epistemic Uncertainty in the CRA-2009 PA (Continued)

Material	Property	Name	Description
CULEBRA	HMBLKLT	CFRACSP	Culebra fracture spacing (m). Equal to half the distance between fractures (i.e., the Culebra half-matrix-block length). Defines *B* in Equation (PA.276) and Figure PA-34.
CULEBRA	MINP_FAC	CTRANSFM	Multiplier (dimensionless) applied to transmissivity of the Culebra within the LWB after mining of potash reserves. Defines *MF* in Equation (PA.256) (see Section PA-4.8.2).
DRZ_1	PRMX_LOG	DRZPRM	Logarithm of intrinsic permeability (m^2) of the DRZ. Used in regions Upper DRZ and Lower DRZ in Figure PA-15.
DRZ_PCS	PRMX_LOG	DRZPCPRM	Logarithm of intrinsic permeability (m^2) of the DRZ immediately above the panel closure concrete (Section PA-4.2.8.3). Used in region DRZ_PCS in Figure PA-15.
GLOBAL	CLIMTIDX	CCLIMSF	Climate scale factor (dimensionless) for Culebra flow field. Defines *SFC* in Equation (PA.261).
GLOBAL	OXSTAT	WOXSTAT	Indicator variable for elemental oxidation states (dimensionless). WOXSTAT <= 0.5 indicates radionuclides in lower oxidation states. WOXSTAT >0.5 indicates radionuclides in higher oxidation states.
GLOBAL	PBRINE	BPPROB	Probability that a drilling intrusion penetrates pressurized brine in the Castile. Defines pB_1; see Section PA-3.6.
GLOBAL	TRANSIDX	CTRAN	Indicator variable for selecting T field. See Section PA-4.8.2.
PHUMOX3	PHUMCIM	WPHUMOX3	Ratio (dimensionless) of concentration of actinides attached to humic colloids to dissolved concentration of actinides for oxidation state III in Castile brine. Defines SF_{Hum}(Castile, +3, Am) and SF_{Hum}(Castile, +3, Pu) for Equation (PA.103).
PU(III)	MKD_PU	CMKDPU3	Matrix distribution coefficient (m^3/kg) for Pu in III oxidation state. Defines K_{dk} in Equation (PA.271).
PU(IV)	MKD_PU	CMKDPU4	Matrix distribution coefficient (m^3/kg) for Pu in IV oxidation state. Defines K_{dk} in Equation (PA.271).
S_HALITE	COMP_RCK	HALCOMP	Bulk compressibility of halite (Pa^{-1}). Defines c_r in Equation (PA.37) for Salado region of Figure PA-15.
S_HALITE	POROSITY	HALPOR	Halite porosity (dimensionless). Defines ϕ_0 in Equation (PA.30) for Salado region in Figure PA-15.
S_HALITE	PRESSURE	SALPRES	Initial brine pore pressure (Pa) in the Salado halite, applied at an elevation consistent with the intersection of MB 139. Defines $p_{b,ref}$ for Equation (PA.55) for Salado region in Figure PA-15.
S_HALITE	PRMX_LOG	HALPRM	Logarithm of intrinsic halite permeability (m^2). Used in region Salado in Figure PA-15.

Table PA-19. Variables Representing Epistemic Uncertainty in the CRA-2009 PA (Continued)

Material	Property	Name	Description
S_MB139	PORE_DIS	ANHBCEXP	Brooks-Corey pore distribution parameter for anhydrite (dimensionless). Defines λ in Equation (PA.38), Equation (PA.39), and Equation (PA.40) for regions MB 138, Anhydrite AB, and MB 139 of Figure PA-15 for use with Brooks-Corey model; defines λ in $m = \lambda/(1 + \lambda)$ in Equation (PA.44), Equation (PA.45), and Equation (PA.46) for use with van Genuchten-Parker model in the same regions.
S_MB139	PRMX_LOG	ANHPRM	Logarithm of intrinsic anhydrite permeability (m^2). Used in regions MB 138, Anhydrite AB, and MB 139 in Figure PA-15.
S_MB139	RELP_MOD	ANHBCVGP	Indicator for relative permeability model (dimensionless) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-15. See Table PA-4.
S_MB139	SAT_RBRN	ANRBRSAT	Residual brine saturation in anhydrite (dimensionless). Defines S_{br} in Equation (PA.43) for regions MB 138, Anhydrite AB, and MB 139 in Figure PA-15.
SHFTL_T1	PRMX_LOG	SHLPRM2	Logarithm of intrinsic permeability (m^2) of lower shaft-seal materials for the first 200 years after closure. Used in Lower Shaft region in Figure PA-15.
SHFTL_T2	PRMX_LOG	SHLPRM3	Logarithm of intrinsic permeability (m^2) of lower shaft-seal materials from 200 years to 10,000 years after closure. Used in Lower Shaft region in Figure PA-15.
SHFTU	PRMX_LOG	SHUPRM	Logarithm of intrinsic permeability (m^2) of upper shaft-seal materials. Used in Upper Shaft region in Figure PA-15.
SHFTU	SAT_RBRN	SHURBRN	Residual brine saturation in upper shaft-seal materials (dimensionless). Defines S_{br} in Equation (PA.43) for Upper Shaft region in Figure PA-15.
SHFTU	SAT_RGAS	SHURGAS	Residual gas saturation in upper shaft-seal materials (dimensionless). Defines S_{gr} in Equation (PA.42) for Upper Shaft region in Figure PA-15.
SOLMOD3	SOLVAR	WSOLVAR3	Solubility multiplier (dimensionless) for III oxidation states. Used by ALGEBRA prior to PANEL (Section PA-4.4, Garner and Leigh 2005).
SOLMOD4	SOLVAR	WSOLVAR4	Solubility multiplier (dimensionless) for IV oxidation states. Used by ALGEBRA prior to PANEL (Section PA-4.4, Garner and Leigh 2005).
SPALLMOD	PARTDIAM	SPLPTDIA	Particle diameter of waste (m) after tensile failure, implemented by parameter SPALLMOD/PARTDIAM. Loguniform distribution from 0.001 to 0.1 (m). Defines d_p in Equation (PA.186).
SPALLMOD	REPIPERM	REPIPERM	Waste permeability of gas (m^2) local to intrusion borehole. Defines k in Equation (PA.168).
SPALLMOD	REPIPOR	SPLRPOR	Waste porosity (dimensionless) at time of drilling intrusion. Defines ϕ in Equation (PA.167).

Table PA-19. Variables Representing Epistemic Uncertainty in the CRA-2009 PA (Continued)

Material	Property	Name	Description
SPALLMOD	TENSLSTR	TENSLSTR	Tensile strength (Pa) of waste. Defines $\bar{\sigma}_r$ in Section PA-4.6.2.3.4.
STEEL	CORRMCO2	WGRCOR	Rate of anoxic steel corrosion (m/s) under brine-inundated conditions with no CO_2 present. Defines R_{ci} in Equation (PA.68) for areas Waste Panel, South RoR, and North RoR in Figure PA-15.
TH(IV)	MKD_TH	CMKDTH4	Matrix distribution coefficient (m^3/kg) for Th in IV oxidation state. Defines K_{dk} in Equation (PA.271).
U(IV)	MKD_U	CMKDU4	Matrix distribution coefficient (m^3/kg) for U in IV oxidation state. Defines K_{dk} in Equation (PA.271).
U(VI)	MKD_U	CMKDU6	Matrix distribution coefficient (m^3/kg) for U in VI oxidation state. Defines K_{dk} in Equation (PA.271).
WAS_AREA	BIOGENFC	WBIOGENF	Probability of obtaining sampled microbial gas generation rates.
WAS_AREA	GRATMICH	WGRMICH	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ /s) under anaerobic, humid conditions. Defines R_{mh} in Equation (PA.70) for areas Waste Panel, South RoR, and North RoR in Figure PA-15.
WAS_AREA	GRATMICI	WGRMICI	Rate of CPR biodegradation (mol $C_6H_{10}O_5$ / kg $C_6H_{10}O_5$ /s) under anaerobic, brine-inundated conditions. Defines R_{mi} in Equation (PA.70) for areas Waste Panel, South RoR, and North RoR in Figure PA-15.
WAS_AREA	PROBDEG	WMICDFLG	Index for model of CPR material microbial degradation (dimensionless). Used in Waste Panel, South RoR, and North RoR areas in Figure PA-15.
WAS_AREA	SAT_RBRN	WRBRNSAT	Residual brine saturation in waste (dimensionless). Defines S_{br} in Equation (PA.42) for Waste Panel, South RoR, and North RoR areas in Figure PA-15; also used in waste material in Figure PA-28 for DBR calculation; see Section PA-4.7.
WAS_AREA	SAT_RGAS	WRGSSAT	Residual gas saturation in waste (dimensionless). Defines S_{gr} in Equation (PA.43) for Waste Panel, South RoR, and North RoR areas in Figure PA-15; also used in waste material in Figure PA-28 for DBR calculation; see Section PA-4.7.
WAS_AREA	SAT_WICK	WASTWICK	Increase in brine saturation of waste due to capillary forces (dimensionless). Defines S_{wick} in Equation (PA.90) for Waste Panel, South RoR, and North RoR areas in Figure PA-15.

The advective retardation coefficient R_k is defined by

$$R_k = 1 + \left(1 - \phi\right) \rho_A K_{Ak} / \phi \qquad \text{(PA.266)}$$

where

ρ_A = surface area density of fractures in Culebra (m^2/m^3 = 1/m) (i.e., surface area of fractures (m^2) divided by volume of fractures (m^3))

K_{Ak} = surface area distribution coefficient ((kg/m^2)/(kg/m^3) = m) (i.e., concentration of radionuclide *k* sorbed on fracture surfaces (kg/m^2) divided by concentration of radionuclide *k* dissolved in brine within fractures (kg/m^3))

Following the logic used in the CCA (Helton et al. 1998), $K_{Ak} = 0$ and thus $R_k = 1$ are used in the PA.

In concept, the term Q_k in Equation (PA.263) provides the link between the releases to the Culebra calculated with NUTS and PANEL (Section PA-6.7) and transport within the Culebra. In the computational implementation of PA, radionuclide transport calculations in the Culebra were performed for unit radionuclide releases to the Culebra, and the outcomes of these calculations were used to construct the release to the accessible environment associated with time-dependent releases into the Culebra derived from NUTS and PANEL calculations (Section PA-6.8.3). The definition of Q_k is discussed in more detail in Section PA-4.9.1.4.

The initial condition for Equation (PA.263) is

$$C_k(x, y, 0) = 0 \text{ kg/m}^3 \tag{PA.267}$$

Furthermore, the boundary value conditions for Equation (PA.263) are defined at individual points on the boundary of the grid in Figure PA-32 on the basis of whether the flow vector $v = [u, v]$ defines a flow entering the grid or leaving the grid. The following Neumann boundary value condition is imposed at points (x, y) where flow leaves the grid:

$$\nabla C_k(x, y, t) \cdot n(x, y) = 0 \left(\text{kg}/\text{m}^3\right)/\text{m}^3 \tag{PA.268}$$

where $n(x, y)$ is an outward-pointing unit normal vector defined at (x, y). The following Dirichlet boundary value condition is imposed at points (x, y) where flow enters the grid:

$$C_k(x, y, t) = 0 \text{ kg/m}^3 \tag{PA.269}$$

PA-4.9.1.2 Diffusive Transport in the Matrix

The system of PDEs used to represent diffusive transport in the matrix surrounding the fractures is given by (WIPP Performance Assessment 1997b)

$$\frac{\partial}{\partial \chi}\left(\phi'_k D'_k \frac{\partial C'_k}{\partial \chi}\right) = \phi' R'_k \left(\frac{\partial C'_k}{\partial t}\right) + \phi' R'_k \lambda_k C'_k - \phi' R'_{k-1} \lambda_{k-1} C'_{k-1} \tag{PA.270}$$

where χ is the spatial coordinate in Figure PA-35, D'_k is the matrix diffusion coefficient (m^2/s) for radionuclide *k* defined by $D'_k = D^*_k \tau'$, and τ' is the matrix tortuosity. The remaining terms

have the same meaning as those in Equation (PA.263), except that the prime denotes properties of the matrix surrounding the fractures. A constant value ($\tau' = 0.11$) for the matrix (i.e., diffusive) tortuosity is used in PA (Meigs 1996). The matrix (i.e., diffusive) porosity ϕ' is an uncertain input to the analysis (see CMTRXPOR in Table PA-19). The matrix retardation R'_k is defined by

$$R'_k = 1 + \left(1 - \phi'\right) \rho_s K_{dk} / \phi' \qquad \text{(PA.271)}$$

where ρ_s is the particle density (kg/m^3) of the matrix and K_{dk} is the distribution coefficient ((Ci/kg)/(Ci/m^3) = m^3/kg) for radionuclide k in the matrix. The density ρ_s is assigned a value of 2.82×10^3 kg/m^3 (Martell 1996b). The distribution coefficients K_{dk} are uncertain inputs to the analysis and dependent on the uncertain oxidation state of the relevant element (see CMKDAM3, CMKDPU3, CMKDPU4, CMKDTH4, CMKDU4, CMKDU6, and WOXSTAT in Table PA-19).

The initial and boundary value conditions used in the formulation of Equation (PA.270) are

$$C'_k\left(x, y, \chi, 0\right) = 0 \ kg / m^3 \qquad \text{(PA.272)}$$

$$\partial C'_k\left(x, y, 0, t\right) / \partial z = 0 \ \ kg / m^2 \qquad \text{(PA.273)}$$

$$C'_k\left(x, y, B, t\right) = C_k(x, y, t) \qquad \text{(PA.274)}$$

where (x, y) corresponds to a point in the domain on which Equation (PA.263) is solved and B is the matrix half-block length (m) in Figure PA-35 (i.e., $2B$ is the thickness of the matrix between two fractures). The initial condition in Equation (PA.272) means that no radionuclide is present in the matrix at the beginning of the calculation. The boundary value condition in Equation (PA.273) implies that no radionuclide movement can take place across the centerline of a matrix block separating two fractures. The boundary value condition in Equation (PA.274) ensures that the dissolved radionuclide concentration in the matrix at the boundary with the fracture is the same as the dissolved radionuclide concentration within the fracture. The matrix half-block length B is an uncertain input to the analysis (see CFRACSP in Table PA-19).

PA-4.9.1.3 Coupling Between Fracture and Matrix Equations

The linkage between Equation (PA.263) and Equation (PA.270) is accomplished through the term Γ_k, defining the rate at which radionuclide k diffuses across the boundary between a fracture and the adjacent matrix (see Figure PA-35). Specifically,

$$\Gamma_k = -\frac{2\phi}{b}\left(\phi' D'_k \left. \frac{\partial C'_k}{\partial \chi} \right|_{z=\chi} \right) \qquad \text{(PA.275)}$$

where b is the fracture aperture (m) defined by

$$b = \phi B\left(1-\phi\right) \tag{PA.276}$$

PA-4.9.1.4 Source Term

As already indicated, Equation (PA.263) and Equation (PA.270) are solved for unit radionuclide releases to the Culebra. Specifically, a release of 1 kg of each of the four lumped radionuclides (^{241}Am, ^{234}U, ^{230}Th, and ^{239}Pu) under consideration was assumed to take place over a time interval from 0 to 50 years, with this release taking place into the computational cell WPAC, located at the center of the Waste Panel Area in Figure PA-32, that has dimensions of 50 m × 50 m. The volume of this cell is given by

$$V = \left(50m\right)\left(50m\right)\left(4m\right) = 1\times10^{4}\ m^{3} \tag{PA.277}$$

where 4 m is the assumed thickness of the Culebra Dolomite (Meigs and McCord 1996). As a result, $Q_k(x, y, t)$ has the form

$$Q_k\left(x,y,t\right) = \frac{1\ kg}{\left(1\times10^{4}\ m^{3}\right)\left(50\ yr\right)\left(3.16\times10^{7}\ s/yr\right)} = 6.33\times10^{-14}\ kg/m^{3}/s \tag{PA.278}$$

for $0 \le t \le 50$ yr and (x, y) in cell WPAC, and $Q_k(x, y, t) = 0$ (kg/m^3/s) otherwise.

PA-4.9.1.5 Cumulative Releases

If B denotes an arbitrary boundary (e.g., the LWB) in the domain of Equation (PA.263) (i.e., Figure PA-32), then the cumulative transport of $C_k(t, B)$ of radionuclide k from time 0 to time t across B is given by

$$C_k\left(t,B\right) = \int_0^t\left[\int_B\left\{v\left(x,y\right)C_k\left(x,y,\tau\right) - \phi D_k\left(x,y,t\right)\nabla C_k\left(x,y,\tau\right)\right\}b\cdot n\left(x,y\right)ds\right]d\tau \tag{PA.279}$$

where h is the thickness of the Culebra (4 m), ϕ is the advective porosity in Equation (PA.263), $n(x, y)$ is an outward pointing unit normal vector, and $\int_B ds$ denotes a line integral over B.

PA-4.9.2 Numerical Solution

The numerical solution to the coupled PDE system represented by Equation (PA.263) and Equation (PA.270) is computed using SECOTP2D, an implicit finite-volume code for the simulation of multispecies reactive transport. A high-level description of the numerical procedures implemented in SECOTP2D follows, with more detail available in WIPP Performance Assessment (1997b).

PA-4.9.2.1 Discretization of Fracture Domain

The fracture domain is discretized in space using the block-centered finite-difference method indicated in Figure PA-36. In this formulation, cell concentrations are defined at grid block centers while the velocity components [u, v] are defined on grid cell faces. A uniform mesh with 50 m × 50 m cells is used for the spatial discretization. Ghost cells are placed outside the problem domain for the purpose of implementing boundary conditions. The temporal discretization is accomplished using variable time step sizes.

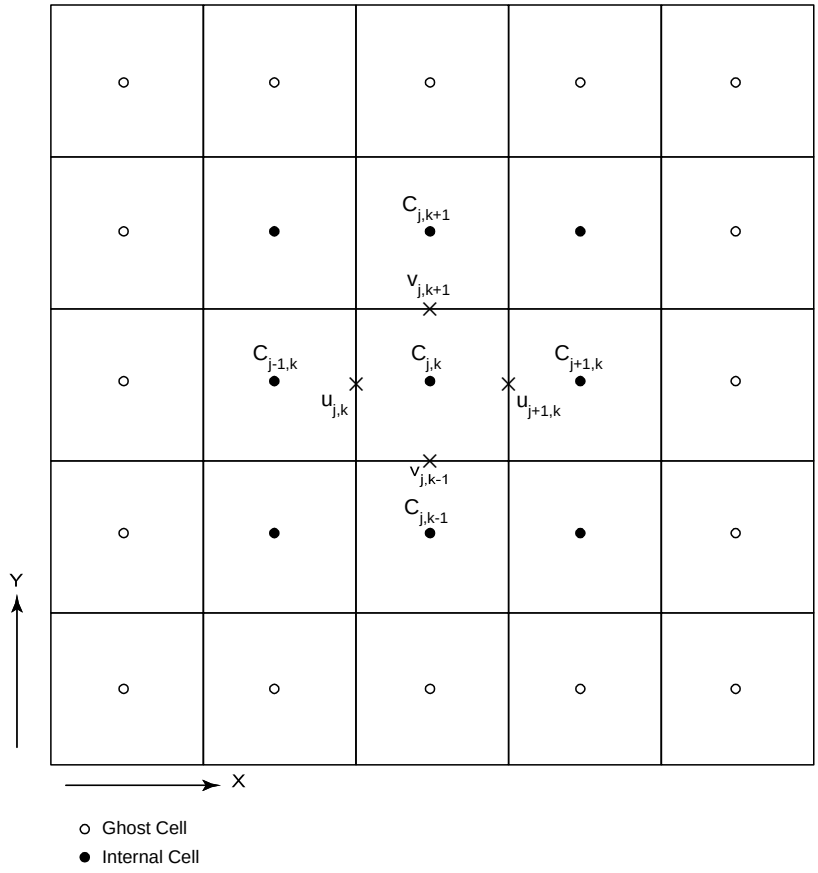


Figure PA-36. Schematic of Finite-Volume Staggered Mesh Showing Internal and Ghost Cells

The dispersive term, $\nabla\cdot(\phi D_k \nabla C_k)$, in Equation (PA.263) is approximated using a second-order central difference formula (Fletcher 1988).

The advective term, $\nabla\cdot\mathbf{v}C_k$, is approximated using the Total Variation Diminishing (TVD) method (Sweby 1984). The TVD method provides a way of accurately resolving advection-dominated transport problems without the occurrence of nonphysical oscillations commonly present in second-order solutions. This method invokes a weighted upstream differencing scheme that locally adjusts the weighting to prevent oscillatory behavior and maximize solution accuracy. The weighting parameters are known as the TVD flux limiters $\Phi(x, y, r)$, where r is a

function of the concentration gradient and direction of flow. PA uses the van Leer TVD limiter (Sweby 1984, p. 1005), which is defined as

$$\Phi(x,y,r) = \max\left\{0, \min\left\{2r, \frac{r+|r|}{1+|r|}\right\}\right\} \quad \text{(PA.280)}$$

At locations where u (i.e., the Darcy velocity in the x direction) is positive, r is defined at the $j-1/2$, k interface by

$$r_{j-1/2,k} = \frac{\partial C/\partial x|_{j-3/2,k}}{\partial C/\partial x|_{j-1/2,k}} \quad \text{(PA.281)}$$

and at locations where u is negative, r is defined by

$$r_{j-1/2,k} = \frac{\partial C/\partial x|_{j+1/2,k}}{\partial C/\partial x|_{j-1/2,k}} \quad \text{(PA.282)}$$

Similar definitions are made for r at the j, $k-1/2$ interface in the y-direction with v (i.e., the Darcy velocity in the y direction) used instead of u.

Because Φ_k is a function of C_k, the discretized set of equations is nonlinear. This nonlinearity is addressed by treating the flux limiters explicitly (i.e., time lagged). Explicit treatment of the limiter functions, however, can lead to oscillatory and sometimes unstable solutions when the Courant number exceeds unity ($Cr > 1$), where Cr is defined by

$$Cr = \max\left\{Cr_x, Cr_y\right\}, \quad \textit{where } Cr_x = |u|\Delta t/\phi\Delta x \quad \textit{and} \quad Cr_y = |v|\Delta t/\phi\Delta y \quad \text{(PA.283)}$$

To avoid this behavior, the application of the TVD method is restricted to regions in which the Courant numbers are less than one. In regions where $Cr > 1$, a first-order full upwinding scheme is invoked, which is unconditionally stable and nonoscillatory.

The discretized form of Equation (PA.263) can be expressed in a delta formulation as

$$\left(\mathbf{I} + \mathbf{L}_{xx} + \mathbf{L}_{yy} + \mathbf{S}\right)\Delta\mathbf{C}^{n+1} = \mathbf{RHS}^{n} \quad \text{(PA.284)}$$

where $\mathbf{I}$ is the identity matrix, $\mathbf{L}_{xx}$ and $\mathbf{L}_{yy}$ are finite-difference operators in the x and y directions, $\mathbf{S}$ is an implicit source term that accounts for decay and mass transfer between the matrix and the fracture, **RHS** consists of the right-hand-side known values at time level n, and $\Delta\mathbf{C}_{n+1} = \mathbf{C}_{n+1} - \mathbf{C}_n$. Direct inversion of Equation (PA.284) for a typical Culebra transport problem is very computationally intensive, requiring large amounts of memory and time. To reduce these requirements, the operator in Equation (PA.284) is factored as follows:

$$\left(\mathbf{I}+\mathbf{L}_{xx}+\alpha_x\mathbf{S}\right)\left(\mathbf{I}+\mathbf{L}_{yy}+\alpha_y\mathbf{S}\right)\Delta\mathbf{C}^{n+1}=\mathbf{RHS}^n \quad \text{(PA.285)}$$

where α_x and α_y are constants that must sum to one (i.e., $\alpha_x + \alpha_y = 1$). The left-hand sides in Equation (PA.284) and Equation (PA.285) are not equivalent, with the result that the factorization of Equation (PA.284) and Equation (PA.285) is referred to as an approximate factorization (Fletcher 1988). The advantage of approximately factoring Equation (PA.284) is that the resulting equation consists of the product of two finite-difference operators that are easily inverted independently using a tridiagonal solver. Hence, the solution to the original problem is obtained by solving a sequence of problems in the following order:

$$\left(\mathbf{I}+\mathbf{L}_{xx}+\alpha_x\mathbf{S}\right)\Delta\overline{\mathbf{C}}=\mathbf{RHS}^n \quad \text{(PA.286)}$$

$$\left(\mathbf{I}+\mathbf{L}_{yy}+\alpha_y\mathbf{S}\right)\Delta\mathbf{C}^{n+1}=\Delta\overline{\mathbf{C}} \quad \text{(PA.287)}$$

$$\mathbf{C}^{n+1}=\mathbf{C}^n+\Delta\mathbf{C}^{n+1} \quad \text{(PA.288)}$$

PA-4.9.2.2 Discretization of Matrix Equation

The nonuniform mesh used to discretize the matrix equation is shown in Figure PA-37. Straightforward application of standard finite-difference or finite-volume discretizations on nonuniform meshes results in truncation error terms that are proportional to the mesh spacing variation (Hirsch 1988). For nonuniform meshes, the discretization can be performed after a transformation from the Cartesian physical space (χ) to a stretched Cartesian computational space (ξ). The transformation is chosen so that the nonuniform grid spacing in physical space is transformed to a uniform spacing of unit length in computational space (the computational space is thus a one-dimensional domain with a uniform mesh). The transformed equations contain metric coefficients that must be discretized, introducing the mesh size influence into the difference formulas. Standard unweighted differencing schemes can then be applied to the governing equations in the computational space.

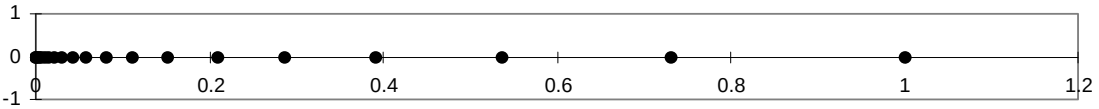


Figure PA-37. Illustration of Stretched Grid Used for Matrix Domain Discretization

The SECOTP2D code applies such a coordinate transformation to the nonuniform diffusion domain mesh, solving the transformed system of equations in the uniform computational space. The transformed matrix equation is written as

$$\phi' R'_k \frac{\partial \hat{C}'_k}{\partial t} - \frac{\partial \hat{F}'_v}{\partial \xi'} = -\phi' R'_k \lambda_k \hat{C}'_k + \phi' R'_{k-1} \lambda_{k-1} \hat{C}'_{k-1} \quad \text{(PA.289)}$$

where

$$\hat{C}'_k = \frac{C'_k}{J} \tag{PA.290}$$

$$\hat{F}'_v = D'\xi'_x \frac{\partial C'_k}{\partial \xi'} \tag{PA.291}$$

In the uniform computational space, a first-order backwards difference formula is used to approximate the temporal derivative, while a second-order accurate central difference is used to approximate spatial derivatives.

PA-4.9.2.3 Fracture-Matrix Coupling

The equations for the fracture and the matrix are coupled through the mass transfer term, Γ_k. In the numerical solution, these equations are coupled in a fully implicit manner and solved simultaneously. A procedure outlined in Huyakorn, Lester, and Mercer (1983) was adapted and redeveloped for an approximate factorization algorithm with the delta formulation and a finite-volume grid. The coupling procedure consists of three steps:

Step 1. Write the mass transfer term Γ_k in a delta (Δ) form.

Step 2. Evaluate Δ terms that are added to the implicit part of the fracture equation. This is accomplished using the inversion process (LU factorization) in the solution of the matrix equation. After the construction of the lower tridiagonal matrix L and the intermediate solution, there is enough information to evaluate the Δ terms. This new information is fed into the fracture equation that is subsequently solved for concentrations in the fracture at the new time level (n+1).

Step 3. Construct the boundary condition for the matrix equation at the fracture-matrix interface using fracture concentrations at the (n+1) time level. Matrix concentrations are then obtained using the upper tridiagonal matrix U by back substitution. A detailed description of this technique and its implementation is given in the SECOTP2D user's manual (WIPP Performance Assessment 1997b).

PA-4.9.2.4 Cumulative Releases

The cumulative transport $C_k(t, B)$ of individual radionuclides across specified boundaries indicated in Equation (PA.279) is also accumulated during the numerical solution of Equation (PA.263) and Equation (PA.270).

PA-4.9.3 Additional Information

Because neither the Culebra flow fields nor the random seed used in LHS sampling have been changed from the CRA-2004 PABC, the radionuclide transport calculations from the CRA-2004 PABC were used in the CRA-2009 PA. Additional information on SECOTP2D and its use to determine radionuclide transport in the Culebra can be found in the SECOTP2D user's manual

(WIPP Performance Assessment 1997b) and in the CRA-2004 PABC analysis package for radionuclide transport in the Culebra Dolomite (Lowry and Kanney 2005).

PA-5.0 Probabilistic Characterization of Subjective Uncertainty

This section summarizes the treatment of uncertainty in the CRA-2009 PA parameters. This uncertainty gives rise to the epistemic uncertainty in the CCDFs defined in Section PA-2.2.4.

PA-5.1 Probability Space

As discussed in Section PA-2.2.4, the statement of confidence in the CCDFs of releases from the CRA-2009 PA is based on a probabilistic characterization of the uncertainty in important input parameters to the analysis. The probability distribution for each parameter is based on all available knowledge about the parameter, including measurements, and describes a degree of belief as to the appropriate range of the parameter value. This degree of belief depends on the numerical, spatial, and temporal resolution of the models selected for use in PA (Section PA-4.0). Correlations and other dependencies between imprecisely known variables are also possible. These relationships represent observed or logical dependencies between the possible parameter values.

The probability space that characterizes epistemic uncertainty can be represented as ($\mathcal{S}_{su}$, $\mathbb{S}_{su}$, p_{su}). The subscript *su* indicates that epistemic (i.e., subjective) uncertainty is being considered; the letters *su* are retained for historical context. The individual elements of $\mathcal{S}_{su}$ are vectors $\boldsymbol{v}_{su}$ of the form

$$\boldsymbol{v}_{su} = \left[v_1, v_2, \ldots, v_{nv}\right] \tag{PA.292}$$

where each v_j is an imprecisely known input to the analysis, and *nv* is the number of such inputs.

The uncertainty in the v_j, and hence in $\boldsymbol{v}_{su}$, is characterized by developing a distribution

$$D_j, \quad j = 1, 2, \ldots, nV \tag{PA.293}$$

for each v_j. Each distribution is based on available knowledge about the corresponding variable and describes a degree of belief as to the appropriate range of this variable. This degree of belief depends on the numerical, spatial, and temporal resolution of the models selected for use in PA (Section PA-4.0). When appropriate, correlations between imprecisely known variables are also possible, indicating a dependency in the knowledge about the correlated variables. It is the distributions in Equation (PA.292) and any associated correlations between the v_j that define ($\mathcal{S}_{su}$, $\mathbb{S}_{su}$, p_{su}).

The uncertain parameters incorporated into the CRA-2009 PA are discussed in Section PA-5.2, and the distributions and correlations assigned to these variables are described in Section PA-5.3 and Section PA-5.4. Finally, a discussion of the concept of a scenario is given in Section PA-5.5.

PA-5.2 Variables Included for Subjective Uncertainty

The CRA-2009 PA identified 56 imprecisely known variables for inclusion in the analysis (Table PA-19). Most of the variables listed in Table PA-19 were also treated as uncertain in the CRA 2004. Table PA-20 and Table PA-21 list the additions and removals between the sets of uncertain parameters in the CRA-2004 PA and the CRA-2009 PA, that resulted from changes made for the CRA-2004 PABC. All subjectively uncertain variables incorporated into the CRA-2009 PA are used as input to the models discussed in Section PA-2.2.3 and Section PA-4.0.

Table PA-20. Sampled Parameters Added Since the CRA-2004 PA

Material	Property
SOLMOD3	SOLVAR
SOLMOD4	SOLVAR
WAS_AREA	BIOGENFC

Table PA-21. Sampled Parameters Removed Since the CRA-2004 PA

Material	Property
SOLU4	SOLCIM
SOLTH4	SOLCIM
S_MB139	COMP_RCK
S_MB139	SAT_RGAS
SOLAM3	SOLSIM
SOLAM3	SOLCIM
SOLPU3	SOLSIM
SOLPU3	SOLCIM
SOLPU4	SOLSIM
SOLPU4	SOLCIM
SOLU4	SOLSIM
SOLU6	SOLSIM
SOLU6	SOLCIM
SOLTH4	SOLSIM
SPALLMOD	RNDSPALL

PA-5.3 Variable Distributions

Each uncertain variable is assigned a distribution that characterizes the subjective uncertainty in that variable. Distributions for each parameter are described in Fox (2008), which also contains documentation for each of the 56 parameters sampled by the LHS code during the PA.

PA-5.4 Correlations and Dependencies

Most of the variables in Table PA-19 are assumed to be uncorrelated. However, the pairs (S_HALITE:PRMX_LOG, S_HALITE:COMP_RCK), and (CASTILER:PRMX_LOG, CASTILER:COMP_RCK) are assumed to have rank correlations of –0.99 and –0.75, respectively (Figure PA-38 and Figure PA-39). These correlations result from a belief that the underlying physics imply that a large value for one variable in a pair should be associated with a small value for the other variable in the pair. The scatterplots in Figure PA-38 and Figure PA-39 result from the Replicate 1 samples generated by the LHS code and described in Section PA-6.4, with the rank correlations within the pairs induced with the Iman and Conover (1982) restricted pairing technique.

A conditional relationship had previously been enforced between WAS_AREA:GRATMICH and WAS_AREA:GRATMICI using ALGEBRA prior to running the BRAGFLO code (Nemer and Stein 2005). This relationship was implemented by setting WAS_AREA:GRATMICH to the value of WAS_AREA:GRATMICI if WAS_AREA:GRATMICH exceeded WAS_AREA: GRATMICI in any particular sample of parameter values (vector). Changing these values in this way introduced a small error into the sensitivity analysis for WAS_AREA:GRATMICH because the regression analysis was based on the sampled values rather than the conditional values used in the code. For the CRA-2009 PA, it was assumed that WAS_AREA:GRATMICH was uniformly distributed between 0 and the minimum of either 1.02717E-9 (the upper bound of the uniform distribution specified in the parameter database for the variable) or the value selected for WAS_AREA:GRATMICI. The sampled value of WAS_AREA:GRATMICH was rescaled from the range 0 to 1.02717E-9 to the new range using the equation

$$v_i' = \frac{v_i - U_{V,lower}}{U_{V,upper} - U_{V,lower}} \times \left(\min(x_i, U_{V,upper}) - U_{V,lower} \right) + U_{V,lower} \qquad \text{(PA.294)}$$

where v_i' is the conditioned value of WAS_AREA:GRATMICH, v_i is the sampled value of WAS_AREA:GRATMICH, x_i is the sampled value of WAS_AREA:GRATMICI, and $U_{V,lower}$ and $U_{V,upper}$ are the bounds of the uniform distribution assigned to WAS_AREA:GRATMICH (Figure PA-40). This method preserves the quantile associated with the value of WAS_AREA:GRATMICH. The nature of the correlation is fundamentally different than that which LHS could induce between the variables: if, instead of limiting the value of WAS_AREA:GRATMICH, a correlation had been specified between the variables in the input file to LHS, then LHS would have generated values for WAS_AREA:GRATMICH that exceeded the corresponding value for WAS_AREA:GRATMICI.

The distributions and associated dependencies indicated in Table PA-19 and Figure PA-38, Figure PA-39, and Figure PA-40 define the epistemic uncertainty described in Section PA-2.2.4. The set of sampled parameters constitutes a vector, $\boldsymbol{v}_{su}$, of the form

$$\boldsymbol{v}_{su} = \left[\text{ANHBCEXP, ANHBCVGP, ..., WTAUFAIL} \right] \qquad \text{(PA.295)}$$

where the individual elements of $\boldsymbol{v}_{su}$ are the subjectively uncertain variables described in Table PA-19.

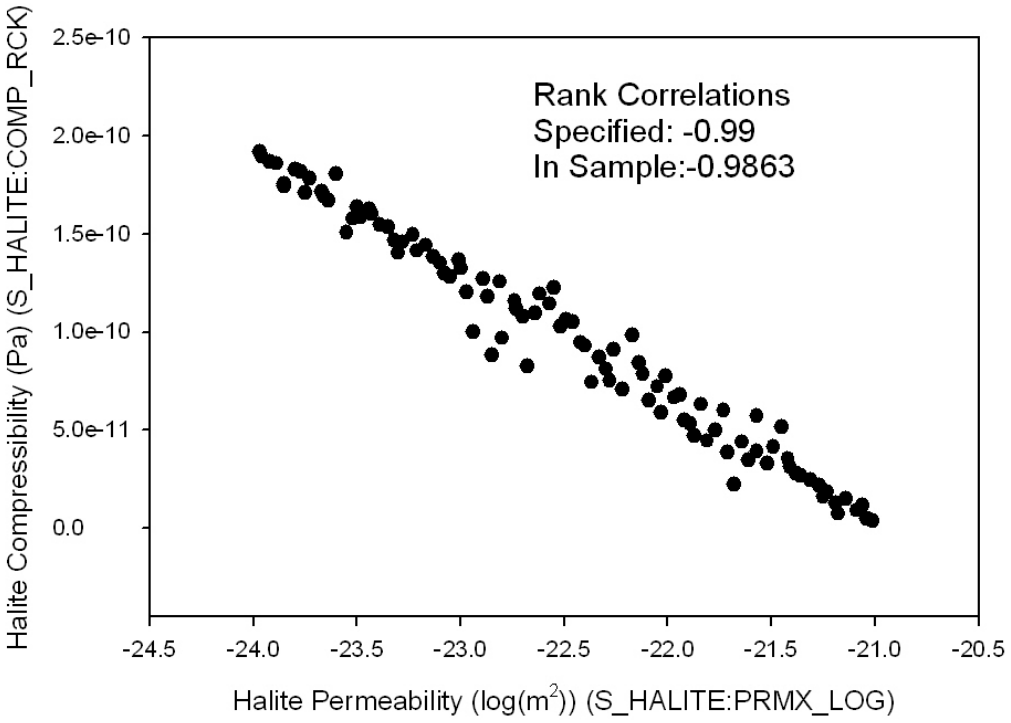


Figure PA-38. Correlation Between S_HALITE:PRMX_LOG and S_HALITE:COMP_RCK

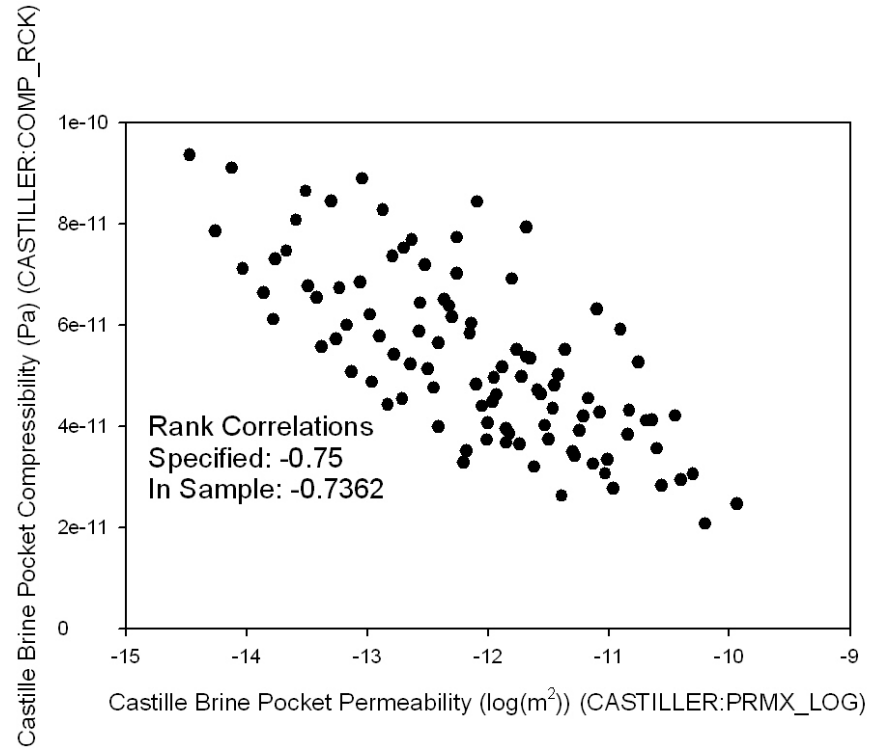


Figure PA-39. Correlation between CASTILLER:PRMX_LOG and CASTILLER:COMP_RCK

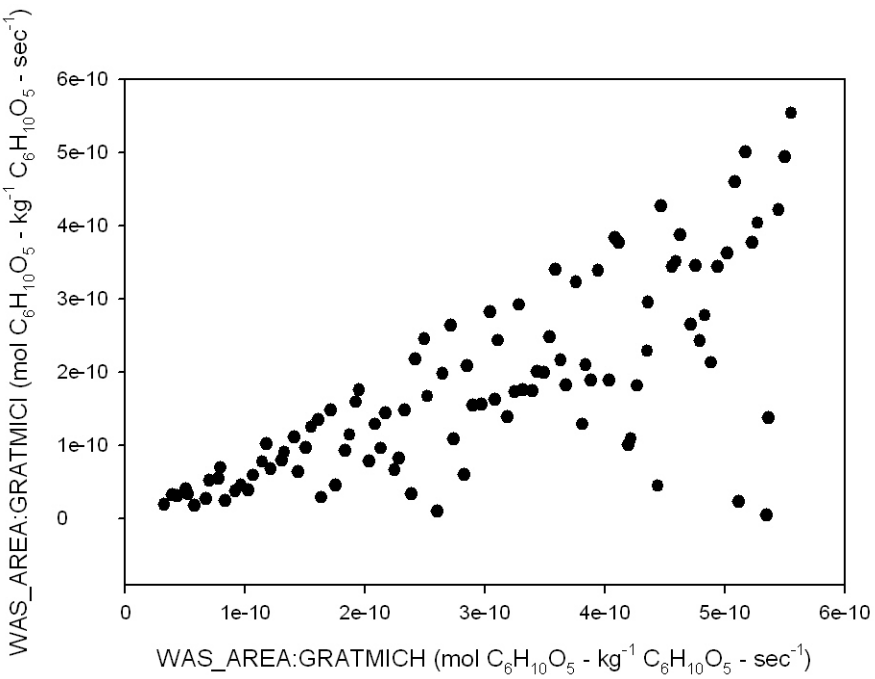


Figure PA-40. Dependency between WAS_AREA:GRATMICI and WAS_AREA:GRATMICH

PA-5.5 Separation of Aleatory and Epistemic Uncertainty

PA uses the term *scenario* to refer to specific types of events within the sample space for aleatory uncertainty (E0, E1, E2, or E1E2; see Section PA-3.10). This definition is consistent with the concept that a scenario is something that could happen in the future. To maintain the important distinction between the two sample spaces, subsets of the sample space for subjective uncertainty are not referred to as scenarios. A future contains events of the form defined in Equation (PA.2) and is associated with a probability, one that characterizes the likelihood that a possible future will match the occurrences that will take place at the WIPP over the next 10,000 years. In contrast, the probability associated with a specific vector $\boldsymbol{v}_{su}$, i.e., a specific set of parameter values, characterizes a degree of belief that the vector contains the appropriate values for the 56 uncertain variables in Table PA-19. This probability represents the impact that epistemic uncertainty in the parameters has on the distribution of possible futures and is used to establish confidence in the results.

PA-6.0 Computational Procedures

This section outlines the computational procedures used to execute the CRA-2009 PA. First, the sampling procedures applied to evaluate performance accounting for epistemic and aleatory uncertainty are outlined. The mechanistic calculations used to evaluate the function $f(\mathbf{x}_{st})$ in Equation (PA.23) are tabulated, followed by a description of the algorithms used to compute releases. This section concludes with a discussion of sensitivity analysis techniques used to identify which uncertain parameters are primary contributors to the uncertainty in the PA results.

PA-6.1 Sampling Procedures

Extensive use is made of sampling procedures in PA. In particular, simple random sampling is used to generate individual CCDFs (Section PA-2.2.3) and LHS is used to assess the effects of imprecisely known model parameters (Section PA-2.2.4).

Using simple random sampling, a possible future, $\mathbf{x}_{st,i,k}$, is thus characterized by the collection of intrusion events occurring in that future (Equation (PA.2)). The subscript *st* denotes that intrusion is modeled as a stochastic process, the subscript *i* indicates that the future is one of many possible futures, and the subscript *k* indicates that the variable set is one of many possible variable sets. The *nR* sets of values (possible futures) are selected according to the joint probability distribution for the elements of $\mathcal{S}_{st}$ as defined by $(\mathcal{S}_{st}, \mathbb{S}_{st}, p_{st})$. In practice, the joint probability distribution is defined by specifying a distribution D_j for each element x_j of $\mathcal{S}_{st}$. Points from different regions of the sample space occur in direct relationship to the probability of occurrence of these regions. Furthermore, each sample element is selected independently of all other sample elements. The values selected using simple random sampling provide unbiased estimates for means, variances, and distributions of the variables. The collection of *nR* samples can be denoted as a vector $\mathbf{x}_{st,k}$:

$$\mathbf{x}_{st,k} = \left[\mathbf{x}_{st,1,k}, \mathbf{x}_{st,2,k}, \ldots, \mathbf{x}_{st,nR,k} \right] \tag{PA.296}$$

The WIPP PA code CCDFGF is used to simulate possible futures based on the values of the variables sampled. These variables control the stochastic processes defined within CCDFGF, such as the time when a drilling intrusion can take place, where that drilling intrusion is located, and whether the drilling intrusion encounters an excavated area. The code CCDFGF is capable of generating and evaluating thousands of possible futures; PA uses a sample size (*nR*) of 10,000 to generate a distribution of possible repository releases. This sample size is sufficient to estimate the 0.999 quantile for the distribution of releases to the accessible environment.

LHS is used to sample the parameters for which distributions of epistemic uncertainty were defined to integrate over the probability space for subjective uncertainty $(\mathcal{S}_{su}, \mathbb{S}_{su}, p_{su})$. This technique was first introduced by McKay, Beckman, and Conover (1979). In LHS, the range of each uncertain parameter v_j is divided into *nLHS* intervals of equal probability and one value is selected at random from each interval. The *nLHS* values thus obtained for v_1 are paired at random without replacement with the *nLHS* values obtained for v_2. These *nLHS* pairs are combined in a random manner without replacement with the *nLHS* values of v_3 to form *nLHS*

triples. This process is continued until a set of *nLHS* *nV*-tuples is formed. These *nV*-tuples are of the form

$$\mathbf{v}_{su,k} = \left[v_{k,1}, v_{k,2}, \ldots, v_{k,nV} \right], k = 1, ..., nLHS \quad \text{(PA.297)}$$

and constitute the Latin hypercube sample. The individual v_js must be independent of each other for the preceding construction procedure to work; a method for generating Latin hypercube and random samples from correlated variables was developed by Iman and Conover (1982) and is used in WIPP PA. For more information about LHS and a comparison with other sampling techniques, see Helton and Davis (2003).

LHS stratifies the sampling to ensure that the sampled values cover the full range of each v_j in the *nLHS* samples. LHS provides unbiased estimates for means and distribution functions of each sampled variable (McKay, Beckman, and Conover 1979). In particular, uncertainty and sensitivity analysis results obtained with LHS are robust even when relatively small samples (i.e., *nLHS* = 50 to 200) are used (Iman and Helton 1988 and 1991; Helton et al. 1995).

When sampling for both aleatory uncertainty and epistemic uncertainty are considered, the joint sample space, $\mathbf{x}$, consists of a vector of *nLHS* vectors of possible futures:

$$\mathbf{x} = \left[\mathbf{x}_{st,1,}, \mathbf{x}_{st,2}, \ldots, \mathbf{x}_{st,nLHS} \right] \quad \text{(PA.298)}$$

The differences between the *nLHS* futures are due to the uncertainty in the v_j, i.e. the epistemic uncertainty in model parameters.

PA-6.2 Sample Size for Incorporation of Subjective Uncertainty

40 CFR § 194.34(d) states that

> The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability.

For an LHS of size *nLHS*, the preceding guidance is equivalent to the inequality

$$1 - 0.99^{nLHS} > 0.95 \quad \text{(PA.299)}$$

which results in a minimum value of 298 for *nLHS*. PA uses a total sample size of 300 to represent the epistemic uncertainty. As discussed in the next section, the 300 samples are divided among 3 replicates of size 100 each to demonstrate convergence of the mean for the population of CCDFs.

PA-6.3 Statistical Confidence on Mean CCDF

40 CFR § 194.34(f) states,

> Any compliance assessment shall provide information which demonstrates that there is at least a 95% level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

Given that LHS is used, the confidence intervals required by section 194.34(f) are obtained with a replicated sampling technique proposed by Iman (1982). In this technique, the sampling in Equation (PA.300) is repeated *nS* times with different random seeds. These samples lead to a sequence $\overline{P}_r(R)$, $r = 1, 2, \ldots, nS$ of estimated mean exceedance probabilities, where $\overline{P}_r(R)$ defines the mean CCDF obtained for sample *r* (i.e., $\overline{P}_r(R)$ is the mean probability that a normalized release of size *R* will be exceeded; see Section PA-2.2.4) and *nS* is the number of independent samples generated with different random seeds. The seed of the random number generator determines the sequence of the numbers it generates. Then,

$$\overline{P}(R) = \sum_{r=1}^{nS} \overline{P}_r(R) / nS \qquad \text{(PA.300)}$$

and

$$SE(R) = \left\{ \sum_{r=1}^{nS} \left[\overline{P}_r(R) - \overline{P}(R) \right]^2 / nS(nS-1) \right\}^{1/2} \qquad \text{(PA.301)}$$

provide an additional estimate of the mean CCDF and an estimate of the standard error ($SE(R)$) associated with the mean exceedance probabilities. The t-distribution with $nS-1$ degrees of freedom can be used to place confidence intervals around the mean exceedance probabilities for individual *R* values (i.e., around $\overline{P}(R)$). Specifically, the $1-\alpha$ confidence interval is given by $\overline{P}_r(R) \pm t_{1-\alpha/2} SE(R)$, where $t_{1-\alpha/2}$ is the $1-\alpha/2$ quantile of the t-distribution with $nS-1$ degrees of freedom (e.g., $t_{1-\alpha/2} = 4.303$ for $\alpha = 0.05$ and $nS = 3$). The same procedure can also be used to place pointwise confidence intervals around percentile curves. The mean and its standard error could equally well be computed from one replicate of size 300. However, the use of three replicates, each with its own random seed, minimizes the impact of any one seed used in random number generation. The three replicates have also been useful in evaluating the presence of spurious correlations among parameters and releases in the sensitivity analyses.

PA-6.4 Generation of Latin Hypercube Samples

The LHS program (WIPP Performance Assessment 1996) is used to produce three independently generated Latin hypercube samples of size $nLHS = 100$ each, for a total of 300 sample elements. Each individual replicate is a Latin hypercube sample of the form

$$\mathbf{v}_{su,k} = \left[v_{k,1}, v_{k,2}, \ldots, v_{k,nV} \right], \; k = 1, 2, \ldots, nLHS = 100 \qquad \text{(PA.302)}$$

In the context of the replicated sampling procedure described in Section PA-6.2, $nS = 3$ replicates of 100 are used. For notational convenience, the replicates are designated by R1, R2, and R3.

The restricted pairing technique described in Section PA-6.1 is used to induce requested correlations and also to assure that uncorrelated variables have correlations close to zero. The variable pairs (S_HALITE:PRMX_LOG, S_HALITE:COMP_RCK) and (CASTILER: PRMX_LOG, CASTILER:COMP_RCK) are assigned rank correlations of –0.99 and –0.75, respectively (Section PA-5.4). All other variable pairs are assigned rank correlations of zero. The restricted pairing technique successfully produces these correlations (Table PA-22 and Table PA-23). Specifically, the correlated variables have correlations that are close to their specified values and uncorrelated variables have correlations that are close to zero.

Table PA-22. Correlation Observed Between Variables S_HALITE:PRMX_LOG and S_HALITE:COMP_RCK in Replicate 1. A Value of -0.99 was Specified.

	CONC_PCS: SAT_RGAS	CONC_PCS: SAT_RBRN	CONC_PCS: PORE_DIS	S_HALITE: POROSITY	S_HALITE: PRMX_LOG
CONC_PCS: SAT_RGAS	1.0000	–	–	–	–
CONC_PCS: SAT_RBRN	-0.0156	1.0000	–	–	–
CONC_PCS: PORE_DIS	0.0547	-0.0943	1.0000	–	–
S_HALITE:POROSITY	-0.0177	-0.0160	-0.0743	1.0000	–
S_HALITE:PRMX_LOG	-0.0022	0.0287	-0.0094	-0.0409	1.0000
S_HALITE:COMP_RCK	0.0119	-0.0249	-0.0066	0.0248	**-0.9863**

Table PA-23. Correlation Observed Between Variables CASTILER:PRMX_LOG and CASTILER:COMP_RCK in Replicate 1. A Value of -0.75 was Specified.

	CASTILER: PRMX_LOG	CASTILER: COMP_RCK	BH_SAND: PRMX_LOG	DRZ_1: PRMX_LOG
CASTILER: PRMX_LOG	1.0000	–	–	–
CASTILER: COMP_RCK	**-0.7362**	1.0000	–	–
BH_SAND: PRMX_LOG	0.0365	-0.0414	1.0000	–
DRZ_1: PRMX_LOG	-0.0292	0.0630	0.0081	1.0000

The code LHS_EDIT (Kirchner 2008a) was used to enforce a conditional relationship between WAS_AREA:GRATMICH and WAS_AREA:GRATMICI in the LHS transfer file, thus making the conditioned values available for use in the sensitivity analysis (Section PA-5.4). This code rescaled the sampled value of WAS_AREA:GRATMICH from the range 0 to 1.02717E-9 to the new range using the equation

$$v_i' = \frac{v_i - U_{V,lower}}{U_{V,upper} - U_{V,lower}} \times \left(\min(x_i, U_{V,upper}) - U_{V,lower} \right) + U_{V,lower} \qquad \text{(PA.303)}$$

where v_i' is the conditioned value of WAS_AREA:GRATMICH, v_i is the sampled value of WAS_AREA:GRATMICH, x_i is the sampled value of WAS_AREA:GRATMICI, and $U_{V,lower}$

and $U_{V,upper}$ are the bounds of the uniform distribution assigned to WAS_AREA:GRATMICH. This method preserves the cumulative probability associated with the original sampled value of WAS_AREA:GRATMICH.

PA-6.5 Generation of Individual Futures

Simple random sampling (Section PA-6.1) is used to generate 10,000 possible futures that are then used to construct CCDFs of potential releases. Table PA-24 outlines the algorithm used to generate a single future in PA.

Table PA-24. Algorithm to Generate a Single Future

1.	Sample $t_{i,1}$ with a time dependent λ_d given by $\lambda_d(t) = \begin{cases} 0 & \text{if } 0 \le t \le t_A \\ \lambda_d & \text{if } t > t_A \end{cases}$ where t_A = 100 yr (i.e., time at which administrative control ends) and $\lambda_d = 3.68 \times 10^{-3}$ yr^{-1} (see Section PA-3.3). The index i is the number of the future and 1 represents the first intrusion event.
2.	Sample $e_{i,1}$ with a probability of $p[E_0] = 0.797$ that the intrusion will be in an unexcavated area and a probability of $p[E_1] = 0.203$ that the intrusion will be in an excavated area (see Section PA-3.4).
3.	Sample $l_{i,1}$ with a probability of $p[L_j] = 6.94 \times 10^{-3}$ for each of the j = 1, 2, …, 144 nodes in Figure PA-14 (see Section PA-3.5).
4.	Sample $b_{i,1}$ with a probability of $p[B_1]$ that the intrusion will penetrate pressurized brine (see Section PA-3.6). $p[B_1]$ is sampled from a uniform distribution ranging from 0.01 to 0.60.
5.	Sample $p_{i,1}$ with probabilities of $p[PL_1] = 0.015$, $p[PL_2] = 0.696$, and $p[PL_3] = 0.289$ that plugging pattern 1, 2, or 3, respectively, will be used (see Section PA-3.7).
6.	Sample $\mathbf{a}_{i,1}$ (see Section PA-3.8).
6.1	Penetration of nonexcavated area (i.e., $e_{i,1} = 0$): $\mathbf{a}_{i,1} = a_{i,1} = 0$.
6.2	Penetration of excavated area (i.e., $e_{i,1} = 1$): Sample to determine if intrusion penetrates RH-TRU or CH-TRU waste with probabilities of $p[RH] = 0.124$ and $p[CH] = 0.876$ of penetrating RH-TRU and CH-TRU waste, respectively.
6.3	Penetration of RH-TRU waste: $\mathbf{a}_{i,1} = a_{i,1} = 1$.
6.4	Penetration of CH-TRU waste: Use probabilities $p[CH_j]$ of intersecting waste stream j, j = 1, 2, …, 690, (see Fox 2005) to independently sample three intersected waste streams iCH_{11}, iCH_{12}, iCH_{13} (i.e., each of iCH_{11}, iCH_{12}, iCH_{13} is an integer between 1 and 690). Then, $\mathbf{a}_{i,1} = [2, iCH_{11}, iCH_{12}, iCH_{13}]$.
7.	Repeat Steps 1 – 6 to determine properties (i.e., $t_{i,j}$, $e_{i,j}$, $l_{i,j}$, $b_{i,j}$, $p_{i,j}$, $\mathbf{a}_{i,j}$) of the j^{th} drilling intrusion.
8.	Continue until $t_{n+1} > 10{,}000$ yr; the n intrusions thusly generated define the drilling intrusions associated with $\mathbf{x}_{st,i}$.
9.	Sample t_{min} with a time dependent λ_m given by $\lambda_m(t) = \begin{cases} 0 & \text{if } 0 \le t \le t_A \\ \lambda_m & \text{if } t > t_A \end{cases}$ where t_A = 100 yr and $\lambda_m = 1 \times 10^{-4}$ yr^{-1} (see Section PA-3.9).

For each vector of the LHS sample, a total of $nS = 10{,}000$ individual futures of the form

$$\mathbf{x}_{st,i} = \left[\left(t_{i,1}, e_{i,1}, l_{i,1}, b_{i,1}, p_{i,1}, \mathbf{a}_{i,1} \right), \left(t_{i,2}, e_{i,2}, l_{i,2}, b_{i,2}, p_{i,2}, \mathbf{a}_{i,2} \right), \ldots, \left(t_{i,n}, e_{i,n}, l_{i,n}, b_{i,n}, p_{i,n}, \mathbf{a}_{i,n} \right), t_{i,min} \right], i = 1, 2, \ldots, nR = 10{,}000 \quad \text{(PA.304)}$$

are generated in the construction of all CCDFs for that LHS vector. As 300 LHS vectors are used in the analysis and 10,000 futures are sampled for each LHS vector, the total number of futures used in the analysis for CCDF construction is 3×10^6.

The drilling rate λ_d is used to generate the times at which drilling intrusions occur. For a Poisson process with a constant λ_d (i.e., a stationary process), the cumulative distribution function (CDF) for the time Δt between the successive events is given by (Ross 1987, p. 113)

$$prob\left(t \le \Delta t\right) = 1 - \exp\left(-\lambda_d \Delta t\right) \quad \text{(PA.305)}$$

A uniformly distributed random number r_1 is selected from [0, 1]. Then, solution of

$$r_1 = 1 - \exp\left(-\lambda_d t_1\right) \quad \text{(PA.306)}$$

for t_1 gives the time of the first drilling intrusion. An initial period of 100 years of administrative control is assumed; thus 100 years is added to the t_1 obtained in Equation (PA.306) to obtain the time of the first drilling intrusion. Selecting a second random number r_2 and solving

$$r_2 = 1 - \exp\left(-\lambda_d \Delta t_1\right) \quad \text{(PA.307)}$$

for Δt_1 gives the time interval between the first and second drilling intrusions, with the outcome that $t_2 = t_1 + \Delta t_1$. This process continues until t_{n+1} exceeds 10,000 years. The times t_1, t_2, …, t_n then constitute the drilling times in that possible future..

The mining time t_{min} is sampled in a manner similar to the drilling times. Additional uniformly distributed random numbers from [0,1] are used to generate the elements e_j, l_j, b_j, p_j, $\mathbf{a}_j$ of $\mathbf{x}_{st,i}$ from their assigned distributions (see Section PA-2.2.2).

PA-6.6 Construction of CCDFs

In PA, the sampling of individual futures (Section PA-6.5) and associated CCDF construction is carried out by the CCDFGF program (WIPP Performance Assessment 2003b). The sampled futures $\mathbf{x}_{st,i}$ in Equation (PA.304) are used to construct CCDFs for many different quantities (e.g., cuttings and cavings releases, spallings releases, DBRs, etc.). The construction process is the same for each quantity. For notational convenience, assume that the particular quantity under consideration can be represented by a function $f(\mathbf{x}_{st,i})$, with the result that 10,000 values

$$f\left(\mathbf{x}_{st,i}\right),\ \mathrm{i} = 1, 2, \ldots, 10{,}000 \qquad \text{(PA.308)}$$

are available for use in CCDF construction. Formally, the resultant CCDF is defined by the expression in Equation (PA.3). In practice, the desired CCDF is obtained after ordering $f(\mathbf{x}_{st,i})$ from smallest to largest or largest to smallest, as described below.

PA uses a binning procedure in CCDF construction to simplify sorting the individual $f(\mathbf{x}_{st,i})$ and to reduce the number of plot points. Specifically, the range of $f(\mathbf{x}_{st,i})$ is divided into intervals (i.e., bins) by the specified points

$$f_{\min} = b_0 < b_1 < b_2 < \ldots < b_n = f_{\max} \qquad \text{(PA.309)}$$

where f_{min} is the minimum value of $f(\mathbf{x}_{st,i})$ to be plotted (typically 10^{-6} or 10^{-5} for an EPA-normalized release), f_{max} is the maximum value of f to be plotted (typically 100 for an EPA-normalized release), n is the number of bins in use, and the b_i are typically loguniformly distributed with 20 values per order of magnitude. A counter nB_j is used for each interval $[b_{j-1}, b_j]$. All counters are initially set to zero. Then, as individual values $f(\mathbf{x}_{st,i})$ are generated, the counter nB_j is incremented by 1 when the inequality

$$b_{j-1} < f\left(\mathbf{x}_{st,i}\right) \le b_j \qquad \text{(PA.310)}$$

is satisfied. When necessary, f_{max} is increased in value so that the inequality $f(\mathbf{x}_{st,i}) < f_{\max}$ will always be satisfied. Once the 10,000 values for $f(\mathbf{x}_{st,i})$ have been generated, a value of nB_j exists for each interval $[b_{j-1}, b_j]$. The quotient

$$pB_j = nB_j / 10{,}000 \qquad \text{(PA.311)}$$

provides an approximation to the probability that $f(\mathbf{x}_{st,i})$ will have a value that falls in the interval $[b_{j-1}, b_j]$. The resultant CCDF is then defined by the points

$$\left(b_j,\ prob\left(value > b_j\right)\right) = \left(b_j,\ \sum_{k=j+1}^{n} pB_k\right) \qquad \text{(PA.312)}$$

for $j = 0, 1, 2, \ldots, n-1$, where $prob(value > b_j)$ is the probability that a value greater than b_j will occur.

The binning technique produces histograms that are difficult to read when multiple CCDFs appear in a single plot. As the number of futures is increased and the bins are refined, the histogram CCDF should converge to a continuous CCDF as additional points are used in its construction. The continuous CCDF is approximated by drawing diagonal lines from the left end of one bin to the left end of the next bin.

When multiple CCDFs appear in a single plot, the bottom of the plot becomes very congested as the individual CCDFs drop to zero on the abscissa. For this reason, each CCDF stops at the largest observed consequence value among the 10,000 values calculated for that CCDF.

Stopping at the largest consequence value, rather than the left bin boundary of the bin that contains this value, permits the CCDF to explicitly show the largest observed consequence. Because a sample size of 10,000 is used in the generation of CCDFs for comparison with the EPA release limits, the probability corresponding to the largest observed consequence is typically 10^{-4}; Figure PA-6 shows an example of CCDFs from the CRA-2009 PA.

PA-6.7 Mechanistic Calculations

In the CRA-2009 PA, calculations were performed with the models described in Section PA-4.0 for selected elements of S_{st} (see Section PA-3.10), and the results were used to determine the releases to the accessible environment for the large number (i.e., 10,000) of randomly sampled futures used to estimate individual CCDFs. The same set of mechanistic calculations was performed for each LHS element. This section summarizes the calculations performed with each of the models described in Section PA-4.0; Section PA-6.8 outlines the algorithms used to construct releases for the randomly sampled elements $\mathbf{x}_{st,i}$ of S_{st} from the results of the mechanistic calculations. Long (2008) documents execution of the calculations and archiving of calculation results.

PA-6.7.1 BRAGFLO Calculations

The BRAGFLO code (Section PA-4.2) computes two-phase (brine and gas) flow in and around the repository. BRAGFLO results are used as initial conditions in the models for Salado transport (implemented in NUTS and PANEL), spallings (implemented in CUTTINGS_S), and DBR (also calculated by BRAGFLO). Thus, the BRAGFLO scenarios are used to define scenarios for other codes.

The four fundamental scenarios for the CRA-2009 PA (Section PA-3.10) define four categories of calculations to be performed with BRAGFLO (i.e., E0, E1, E2, and E1E2). These four fundamental scenarios were expanded into six general scenarios by specifying the time of drilling intrusions. Table PA-25 summarizes the specific scenarios used in the CRA-2009 PA. A total of 6 scenarios $\times$ nR $\times$ $nLHS$ = 6 $\times$ 3 $\times$ 100 = 1,800 BRAGFLO calculations were conducted for the CRA-2009 PA.

Table PA-25. BRAGFLO Scenarios in the CRA-2009 PA

Fundamental Scenario (Section PA-3.10)	Specific Scenario	Time of Drilling Intrusion(s)
E0: no drilling intrusions.	S1	N/A
E1: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1), and Plugging Pattern 2 is used (p_1 = 2).	S2	350 years
	S3	1,000 years
E2: single intrusion into excavated area (e_1 = 1), pressurized brine is penetrated (b_1 = 1) and Plugging Pattern 3 is used (p_1 = 3), or pressurized brine is not penetrated (b_1 = 0).	S4	350 years
	S5	1,000 years
E1E2: two intrusions into the same waste panel (e_1 = e_2 = 1), the first being an E2 intrusion and the second being an E1 intrusion.	S6	1,000 years for E2 intrusion 2,000 years for E1 intrusion

Values for the activity level $\mathbf{a}_1$ and mining time t_{min} are not needed for the mechanistic calculations; these values are used in the construction of the releases from the results of the mechanistic calculations (Section PA-6.8). Although a value for drilling location l_1 is not specified, a drilling location is required for the BRAGFLO calculations. If equivalent grids were used in the definition of $\mathbf{x}_{st,i}$ (Figure PA-14) and in the numerical solution of the PDEs on which BRAGFLO is based (Figure PA-15), the location of the drilling intrusion used in the BRAGFLO calculations could be specified as a specific value for l_1, which in turn would correspond to one of the 144 locations in Figure PA-14 designated by l in the definition of $\mathbf{x}_{st,i}$. However, as these grids are not the same, a unique pairing between a value for l_1 and the location of the drilling intrusion used in the computational grid employed with BRAGFLO is not possible. The BRAGFLO computational grid divides the repository into a lower waste panel (Waste Panel area), a middle group of four waste panels (South RoR area), and an upper group of five waste panels (North RoR area), with the drilling intrusion taking place through the center of the lower panel (Figure PA-15). Thus, in the context of the locations in Figure PA-14 potentially indexed by l_1, the drilling intrusions in Scenarios S2-S5 occur at a location in Panel 5, which is the southernmost panel. In Scenario S6, both intrusions occur at a location in Panel 5, with the effects of flow between the two boreholes implemented through assumptions involving the time-dependent behavior of borehole permeability (Table PA-7).

PA-6.7.2 NUTS Calculations

For Scenarios S1–S5, radionuclide transport through the Salado is computed by the code NUTS (Section PA-4.3) using the flow fields computed by BRAGFLO. Two types of calculations are performed with NUTS. First, a set of screening calculations identifies elements of the sample from $\mathcal{S}_{su}$ for which radionuclide transport through the Salado to the LWB or Culebra is possible. The screening calculations identify a subset of the sample from $\mathcal{S}_{su}$ for which transport is possible and for which release calculations are performed. Screening calculations are performed for BRAGFLO Scenarios S1-S5, for a total of 1,500 screening calculations with NUTS (Table PA-25).

Table PA-26 summarizes the NUTS release calculations for the CRA-2009 PA. Based on the screening calculations, a total of 1,600 release calculations are performed for the CRA-2009 PA. For each vector that is retained (based on the screening calculations), release calculations are performed for a set of intrusion times.

Table PA-26 lists five scenarios for release calculations corresponding to the five BRAGFLO scenarios. Each NUTS scenario uses the flow field computed for the corresponding BRAGFLO scenario. The intrusion times for the NUTS scenarios are accommodated by shifting the BRAGFLO flow fields in time so that the NUTS and BRAGFLO intrusions coincide. For example, the NUTS S3 scenario with an intrusion at 3,000 years requires a flow field for the time interval between (3,000 years and 10,000 years); this scenario uses the BRAGFLO S3 scenario flow field for the time interval between (1,000 years and 8,000 years).

Table PA-26. NUTS Release Calculations in the CRA-2009 PA

NUTS Scenario	Number of Vectors with Releases				Flow field	Intrusion Time (t_1)
	R1	R2	R3	Total		
S1	1	0	0	1	BRAGFLO S1 scenario	N/A
S2	70	76	77	223	BRAGFLO S2 scenario	E1 intrusion at 100 and 350 years
S3	55	58	60	173	BRAGFLO S3 scenario	E1 intrusion at 1,000, 3,000, 5,000, 7,000, or 9,000 years
S4	15	14	15	44	BRAGFLO S4 scenario	E2 intrusion at 100 and 350 years
S5	14	13	13	40	BRAGFLO S5 scenario	E2 intrusion at 1,000, 3,000, 5,000, 7,000, or 9,000 years

Values for the variables indicating intrusion into an excavated area (e_1), penetration of pressurized brine (b_1), plugging pattern (p_1), and drilling location (l_1) are the same as in the corresponding BRAGFLO scenario. Values for the activity level $\mathbf{a}_1$ and mining time t_{min} are not specified for the NUTS scenarios.

PA-6.7.3 PANEL Calculations

As outlined in Section PA-4.4, the code PANEL is used to estimate releases to the Culebra associated with E1E2 scenarios and to estimate radionuclide concentrations in brine for use in estimating DBRs. An E1E2 scenario assumes two drilling intrusions into the same waste panel: the first an E2 intrusion (Table PA-25) occurring at time t_1 and the second an E1 intrusion (Table PA-25) occurring at time t_2. PANEL calculations are performed for t_2 = 100, 350, 1,000, 2,000, 4,000, 6,000, and 9,000 years using the flow field produced by the single BRAGFLO calculation for Scenario S6, for a total of $7 \times nR \times nLHS = 7 \times 3 \times 100 = 2{,}100$ PANEL calculations. The BRAGFLO flow field is shifted forward or backward in time as appropriate so that the time of the second intrusion (t_2) coincides with the flow field. The shifting of the BRAGFLO flow field results in values for the time (t_1) of the first intrusion (E2) for the PANEL calculations given by

$$t_1 = \max\left\{100\,yr,\ t_2 - 1200\,yr\right\} \tag{PA.313}$$

where the restriction that t_1 cannot be less than 100 years results from the definition of $\mathbf{x}_{st,i}$, which does not allow negative intrusion times, and from the assumption of 100 years of administrative control during which there is no drilling (i.e., $\lambda_d(t) = 0$ yr^{-1} for $0 \le t \le 100$ yr; see Equation (PA.6)). Under this convention, the definition of Scenario S6 for the BRAGFLO calculations differs from what is actually done computationally because t_1 does not always precede t_2 by 1,000 years in the PANEL calculation. Values for the other variables defining the element $\mathbf{x}_{st,i}$ of S_{st} for the PANEL E1E2 scenarios are the same as in the BRAGFLO S6 scenario.

Calculating radionuclide concentrations is not specific to any BRAGFLO scenario. The concentration calculations compute the mobilized activity in two different brines (Castile and

Salado) and are performed at 100; 125; 175; 350; 1,000; 3,000; 5,000; 7,500; and 10,000 years for a total of $2 \times 9 \times nR = 54$ calculations.

PA-6.7.4 DRSPALL Calculations

The code DRSPALL calculates the spallings volume produced by gas buildup within the repository. Because of the computational expense associated with running the code, rather than evaluating all possible pressures for each vector, a set of four pressures is evaluated for each vector in each replicate. These values are then passed to CUTTINGS_S to act as a lookup table used by the latter code to linearly interpolate the spallings volume as a function of the repository pressure. DRSPALL does not compute releases to the environment, which is computed by the CUTTINGS_S code. A total of 4 pressures $\times nR \times nLHS = 4 \times 3 \times 100 = 1{,}200$ DRSPALL calculations were performed. As none of the changes implemented for the CRA-2009 PA affected the DRSPALL calculations, the results from the CRA-2004 PABC DRSPALL calculations were used in the CRA-2009 PA.

PA-6.7.5 CUTTINGS_S Calculations

The code CUTTINGS_S computes the volumes of solids removed from the repository by cuttings and cavings (see Section PA-4.5) and spallings (see Section PA-4.6). Table PA-27 lists the CUTTINGS_S calculations performed for the CRA-2009 PA, totaling $78 \times nR \times nLHS = 78 \times 3 \times 100 = 23{,}400$ CUTTINGS_S calculations.

Table PA-27. CUTTINGS_S Release Calculations in the CRA-2009 PA

Scenario	Description
S1	Intrusion into lower, middle, or upper waste panel in undisturbed (i.e., E0 conditions) repository at 100; 350; 1,000; 3,000; 5,000; or 10,000 years: 18 combinations.
S2	Initial E1 intrusion at 350 years followed by a second intrusion into the same, adjacent, or nonadjacent waste panel at 550; 750; 2,000; 4,000; or 10,000 years: 15 combinations.
S3	Initial E1 intrusion at 1,000 years followed by a second intrusion into the same, adjacent, or nonadjacent waste panel at 1,200; 1,400; 3,000; 5,000; or 10,000 years: 15 combinations.
S4	Initial E2 intrusion at 350 years followed by a second intrusion into the same, adjacent, or nonadjacent waste panel at 550; 750; 2,000; 4,000; or 10,000 years: 15 combinations.
S5	Initial E2 intrusion at 1,000 years followed by a second intrusion into the same, adjacent, or nonadjacent waste panel at 1,200; 1,400; 3,000; 5,000; or 10,000 years: 15 combinations.

The CUTTINGS_S S1 scenario computes volumes of solid material released from the initial intrusion in the repository. Initial conditions for the CUTTINGS_S S1 scenario are taken from the results of the BRAGFLO S1 scenario during the intrusion of Waste Panel, South RoR, and North RoR areas in Figure PA-15, corresponding to the lower, middle, and upper waste panels. In this scenario, the excavated area is penetrated ($e_1 = 1$) and the drilling location (l_1) is defined as one of the nodes (Figure PA-14) in the appropriate panel of Figure PA-28. The actual locations where the intrusions are assumed to occur correspond to the points in Figure PA-28 designated “Down-dip well,” “Middle well,” and “Up-dip well” for the lower, middle, and upper

waste panel, respectively. Values for the variables indicating penetration of pressurized brine (b_1), plugging pattern (p_1), activity level ($\mathbf{a}_1$), and mining time (t_{min}) are not specified for the CUTTINGS_S S1 scenario.

The other CUTTINGS_S scenarios (Scenarios S2-S5) compute volumes of solids released by a second or subsequent intrusion. Initial conditions are taken from the results of the corresponding BRAGFLO scenario at the time of the second intrusion. As in the BRAGFLO scenarios, the first intrusion occurs in the lower waste panel (Waste Panel area in Figure PA-15), so the drilling location (l_1) is defined as one of the nodes in Panel 5 (Figure PA-14). The second intrusion occurs in the same waste panel as the first intrusion (area Waste Panel in Figure PA-15), an adjacent waste panel (South RoR area in Figure PA-15), or a nonadjacent waste panel (North RoR area in Figure PA-15); hence the drilling location (l_2) is defined as one of the nodes (Figure PA-14) in the appropriate panel of Figure PA-28.

The activity level for the first intrusion a_1 takes a value that indicates CH-TRU waste penetration (i.e., $\mathbf{a}_1 = [2, CH_{11}, CH_{12}, CH_{13}]$), but the specific waste streams penetrated (i.e. CH_{11}, CH_{12}, CH_{13}) are not specified. For the second intrusion, the excavated area is penetrated ($e_2 = 1$) and the drilling location (l_2) is defined as one of the nodes in the appropriate panel (Figure PA-14), as described above. As for the first intrusion, the activity level $\mathbf{a}_2$ only indicates CH-TRU waste penetration. Values for the other variables defining the first intrusion (e_1, b_1, and p_1) are the same as in the corresponding BRAGFLO scenario. Values for the other variables defining the second intrusion (b_2 and p_2) and the mining time $t_{\min}$ are not specified for the CUTTINGS_S scenarios.

PA-6.7.6 BRAGFLO Calculations for DBR Volumes

Volumes of brine released to the surface during an intrusion are calculated using BRAGFLO, as described in Section PA-4.7. Calculations of DBR volumes were conducted for the same scenarios as CUTTINGS_S (Table PA-27). Thus, the elements of $\mathcal{S}_{st}$ described in Section PA-6.7.5 also characterize the elements for which DBR volumes are computed. A total of 23,400 BRAGFLO calculations were performed.

PA-6.7.7 MODFLOW Calculations

As described in Section PA-4.8, the MODFLOW calculations produce flow fields in the Culebra for two categories of conditions: partially mined conditions in the vicinity of the repository and fully mined conditions in the vicinity of the repository (Figure PA-31). As specified in 40 CFR § 194.32(b), partially mined conditions are assumed to exist by the end of the administrative control period (i.e., at 100 years after closure). After the time that mining occurs within the LWB (t_{min}; see Section PA-3.9), fully mined conditions are assumed for the remainder of the 10,000-year regulatory period. The flow fields for partially mined conditions are calculated by MODFLOW using the T fields for partially mined conditions (see Section PA-4.8.2). Additional MODFLOW calculations determine the flow fields for fully mined conditions and are performed using the T fields for fully mined conditions. Thus, a total of $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$ MODFLOW calculations were performed (Table PA-28). As none of the changes implemented

for the CRA-2009 PA affected the Culebra flow and transport calculations, the results from the CRA-2004 PABC Culebra flow and transport calculations were used in the CRA-2009 PA.

PA-6.7.8 SECOTP2D Calculations

The SECOTP2D calculations are performed for the same elements $\mathbf{x}_{st,0}$ and $\mathbf{x}_{st,m}$ of $\mathcal{S}_{st}$ defined in Section PA-6.7.7 for the MODFLOW calculations, giving a total of $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$ SECOTP2D calculations (Table PA-29). As none of the changes implemented for the CRA-2009 PA affected the Culebra flow and transport calculations, the results from the CRA-2004 PABC Culebra flow and transport calculations were used in the CRA-2009 PA.

Table PA-28. MODFLOW Scenarios in the CRA-2009 PA

MODFLOW: 600 Flow-Field Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$
Note: Only 100 unique T fields were constructed with PEST and MODFLOW for use in the analysis. The T fields are an input to the calculation of flow fields. In each replicate, the T field used for a particular flow field was assigned using an index value (CTRAN; see Table PA-19) included in the LHS.

Table PA-29. SECOTP2D Scenarios in the CRA-2004 PA

SECOTP2D: 600 Calculations
PM: Partially mined conditions in vicinity of repository
FM: Fully mined conditions in vicinity of repository
Total calculations = $2 \times nR \times nLHS = 2 \times 3 \times 100 = 600$
Note: Each calculation includes a unit release for each of four radionuclides: ^{241}Am, ^{239}Pu, ^{230}Th, and ^{234}U.

PA-6.8 Computation of Releases

The mechanistic computations outlined in Section PA-6.7 are used to compute releases for each sampled element $\mathbf{x}_{st,i}$ of $\mathcal{S}_{st}$. Releases from the repository can be partitioned into three categories: undisturbed releases, which may occur in futures without drilling intrusions; direct releases, which occur at the time of a drilling event; and long-term releases, which occur as a consequence of a history of drilling intrusions. For a given future ($\mathbf{x}_{st,i}$ of $\mathcal{S}_{st}$ in Equation (PA.304)) other than undisturbed conditions ($\mathbf{x}_{st,0}$), the direct and long-term releases are computed by the code CCDFGF (WIPP Performance Assessment 2003a) from the results of the mechanistic calculations summarized in Section PA-6.7, performed with the models presented in Section PA-4.0. Releases from an undisturbed repository are computed from the results of the NUTS S1 scenario (Section PA-6.7.2).

PA-6.8.1 Undisturbed Releases

Repository releases for the futures ($\mathbf{x}_{st,0}$) in which no drilling intrusions occur are computed by the NUTS release calculations for E0 conditions (Table PA-26). The NUTS model computes the activity of each radionuclide that reaches the accessible environment during the regulatory period via transport through the MBs, the Dewey Lake Red Beds and land surface due to brine flow up a plugged borehole. These releases are represented as $f_{MB}[\mathbf{x}_{st,0}, f_B(\mathbf{x}_{st,0})]$, $f_{DL}[\mathbf{x}_{st,0}, f_B(\mathbf{x}_{st,0})]$ and $f_S[\mathbf{x}_{st,0}, f_B(\mathbf{x}_{st,0})]$ in Equation (PA.23). The undisturbed releases for the CRA-2009 PA are summarized in Section PA-7.2.

PA-6.8.2 Direct Releases

Direct releases include cuttings, cavings, spallings, and DBRs. The model for each direct release component computes a volume (solids or liquid) released directly to the surface for each drilling intrusion. These volumes are combined with an appropriate concentration of activity in the released waste. Summary information for the CRA-2009 PA direct releases are given in Section PA-8.5.

PA-6.8.2.1 Construction of Cuttings and Cavings Releases

Each drilling intrusion encountering waste is assumed to release a volume of solid material as cuttings, as described in Section PA-4.5.1. The uncompacted volume of waste removed by cuttings (V_{cut}) is computed by Equation (PA.124). In addition, drilling intrusions that encounter CH-TRU waste may release additional solid material as cavings, as described in Section PA-4.5.2. The uncompacted volume of material removed by cuttings and cavings combined ($V = V_{cut} + V_{cav}$) is computed by Equation (PA.125). For a drilling intrusion that encounters RH-TRU waste, the final eroded diameter D_f in Equation (PA.125) is equal to the bit diameter in Equation (PA.124). In PA, all drilling intrusions assume a drill bit diameter of 0.31115 m (Fox 2008, Table 13).

The uncompacted volume of material removed is not composed entirely of waste material; rather, the uncompacted volume includes MgO and any void space initially present around the waste containers. The volume of waste removed (V_w) is determined by multiplying the uncompacted volume by the fraction of excavated repository volume (FVW) occupied by waste, thus

$$V_w = V \times FVW \qquad \text{(PA.314)}$$

where $FVW = 0.385$ for CH-TRU waste and $FVW = 1.0$ for RH-TRU waste (Fox 2008, Table 45). The activity in the material released by cuttings and cavings is determined by stochastically selecting a subset of all waste streams. The vector ($\mathbf{a}_j$) described in Section PA-3.8 determines which type of waste (CH-TRU or RH-TRU) and which waste streams are selected. The activity per cubic meter of waste stream volume is computed for each waste stream at a discrete set of times accounting for radioactive decay and ingrowth by the code EPAUNI (Fox 2005); the results of the EPAUNI calculations are presented in Fox (2005). Activities at other times are determined by linear interpolation. The cuttings and cavings release $f_C(\mathbf{x}_{st,i})$ is the product of the

average activity per cubic meter (C_r, computed as the average activity over the waste streams comprising the selected subset with the assumption that each waste stream contributes an equal volume to the release) and the volume of waste released (Equation (PA.315)):

$$f_C\left(\mathbf{x}_{st,i}\right) = V_w \times C_r \qquad \text{(PA.315)}$$

PA-6.8.2.2 Construction of Spallings Releases

Spallings releases are calculated for all intrusions that encounter CH-TRU waste. The construction of the spallings release $f_{SP}(\mathbf{x}_{st,i})$ is nearly identical to that described in Section PA-6.8.2.3 for the calculation of DBRs, except that volumes of solid material released will be used rather than volumes of brine. These solid releases are calculated with the spallings submodel of the CUTTINGS_S program for the combinations of repository condition, distance from previous intrusions, and time between intrusions listed in Table PA-27. Linear interpolation determines the releases for other combinations of repository condition, distance, and time between intrusions (WIPP Performance Assessment 2003a).

The concentration of radionuclides in the spallings release volume is computed as the average activity per cubic meter in the CH-TRU waste at the time of intrusion. Activities in each waste stream are computed at a discrete set of times by the code EPAUNI (Fox 2005); activities at other times are determined by linear interpolation.

PA-6.8.2.3 Construction of DBRs

DBRs (also termed blowout releases) are calculated for all intrusions that encounter CH-TRU waste. DBRs $f_{DBR}(\mathbf{x}_{st,i})$ are constructed from the volume of brine released (V_{DBR}) to the surface (Equation (PA.202)) and radionuclide concentrations in brine (C_{bl}, see Equation (PA.96)). Brine volume released to the surface is computed by BRAGFLO (Section PA-4.7.3) for the times listed in Table PA-27; brine volumes released for intrusions at other times are computed by linear interpolation (WIPP Performance Assessment 2003b).

Calculating DBR volumes distinguishes between the first intrusion and subsequent intrusions. The release volumes for the initial intrusion (E0 repository conditions) are further distinguished by the panel group (upper, middle, and lower). As shown in Table PA-27, BRAGFLO computes release volumes for the initial intrusion at a series of intrusion times; the release volume for the initial intrusion at other times is computed by linear interpolation (WIPP Performance Assessment 2003a). Release volumes for subsequent intrusions are distinguished by the current state of the repository (E1 or E2) and the relative distance between the panel intruded by the current borehole and the panel of the initial intrusion (same, adjacent, nonadjacent). The algorithms for determining repository conditions and distance between intrusions are described in Section PA-6.7.5.

As indicated in Table PA-27, DBR volumes for a second intrusion are computed by BRAGFLO for combinations of repository condition, distance between intrusions, and time between intrusions. Brine release volumes for other combinations of condition, distance, and time are computed by linear interpolation (WIPP Performance Assessment 2003a). Brine releases from

the third and subsequent intrusions are computed as if the current intrusion was the second intrusion into the repository.

Radionuclide concentrations in brine (C_{bl}) are calculated by PANEL (Section PA-6.7.3) for the times listed in Table PA-26; concentrations at other times are computed by linear interpolation (WIPP Performance Assessment 2003a). The type of intrusion (E1 or E2) determines the brine (Salado or Castile brine) selected for the concentration calculation; Castile brine is used for E1 intrusions, and Salado brine is used for E2 intrusions.

The DBR is computed as the product of the release concentration and the volume, V_{DBR}:

$$f_{DBR}\left(\mathbf{x}_{st,i}\right) = V_{DBR} \times C_{bl} \tag{PA.316}$$

PA-6.8.3 Radionuclide Transport Through the Culebra

One potential path for radionuclides to leave the repository is through the boreholes to the Culebra, then through the Culebra to the LWB (Ismail and Garner 2008). As indicated in Table PA-26, the NUTS and PANEL models are used to estimate radionuclide transport through boreholes to the Culebra $f_{NP}(\mathbf{x}_{st,i})$ for a fixed set of intrusion times; releases to the Culebra for intrusions at other times are determined by linear interpolation (WIPP Performance Assessment 2003a). NUTS computes the release to the Culebra over time for E1 and E2 boreholes; PANEL computes the release to the Culebra for an E1E2 borehole.

Each borehole may create a pathway for releases to the Culebra. The first E1 or E2 borehole in each panel creates a release path, with the radionuclide release taken from the appropriate NUTS data. Subsequent E2 boreholes into a panel with only E2 boreholes do not cause additional releases; WIPP PA assumes that a subsequent E2 borehole into a panel having only earlier E2 intrusions does not provide a significant source of additional brine, and thus does not release additional radionuclides to the Culebra.

An E1E2 borehole results from the combination of two or more intrusions into the same panel, at least one of which is an E1 intrusion. A subsequent E1 borehole changes the panel's condition to E1E2, as does an E2 borehole into a panel that has an earlier E1 intrusion. Once E1E2 conditions exist in a panel, they persist throughout the regulatory period. However, releases from a panel with E1E2 conditions are restarted for each subsequent E1 intrusion into that panel, since additional E1 intrusions may introduce new volumes of brine to the panel.

Releases to the Culebra are summed across all release pathways to the Culebra to obtain total releases to the Culebra $r_k(t)$ for the k^{th} radionuclide at each time t. Releases to the Culebra include both dissolved radionuclides and radionuclides sorbed to colloids. The WIPP PA assumes that radionuclides sorbed to humic colloids disassociate and transport, as do dissolved radionuclides; other colloid species do not transport in the Culebra (see Appendix SOTERM-2009, Section SOTERM-4.7). The release to the Culebra is partitioned into dissolved and colloid species by multiplying $r_k(t)$ by radionuclide-specific factors for the fraction dissolved and the fraction on colloids. Dissolved radionuclides are always transported through the Culebra.

Radionuclide transport through the Culebra is computed by the code SECOTP2D (Section PA-4.9) for partially mined and fully mined conditions, as indicated in Table PA-29. These computations assume a 1 kg source of each radionuclide placed in the Culebra between 0 and 50 years and result in the fraction of each source $f_{m,k}(t)$, where m is the mining condition and k is the index for the radionuclide, reaching the LWB at each subsequent time t. For convenience, the time-ordering of the data from SECOTP2D is reversed so that the fraction $f_{m,k}(t)$ associated with year $t = 200$, for example, represents the release at the boundary at year 10,000 for a release occurring between 150 and 200 years.

The total release through the Culebra $R_{Cul,k}$ is calculated for the k^{th} radionuclide by

$$R_{Cul,k} = \sum_{t_i \le t_{\mathrm{m}}} r_k(t_i) f_{PM,k}(t_i) + \sum_{t_i > t_{\min}} r_k(t_i) f_{FM,k}(t_i) \qquad \text{(PA.317)}$$

where $r_k(t_i)$ is the release of the k^{th} radionuclide to the Culebra in kg at time t_i, and $f_{PM,k}(t_i)$ and $f_{FM,k}(t_i)$ are the fractions of a unit source placed in the Culebra in the interval (t_{i-1}, t_i) that reaches the LWB by the end of the 10,000-year regulatory period for partially mined and fully mined conditions within the LWB, respectively. The function $f_{m,k}(t)$ ($m = PM, FM$) changes when mining is assumed to occur within the LWB; hence the sum in the equation above is evaluated in two parts, where t_{min} is the time that mining occurs. The total releases through the Culebra $f_{ST}(\mathbf{x}_{st,i})$ is computed by converting the release of each radionuclide $R_{Cul,k}$ from kg to EPA units, then summing over all radionuclides.

PA-6.8.4 Determining Initial Conditions for Direct and Transport Releases

A sequence of intrusions into the repository can change the conditions in and around the repository and, hence, affect releases from subsequent intrusions. This section describes how panel and repository conditions are determined for a given intrusion.

PA-6.8.4.1 Determining Repository and Panel Conditions

Direct releases by DBR and spallings, and subsequent releases by radionuclide transport, require determining the conditions in the intruded panel and the repository at the time of the intrusion. One of three conditions is assigned to the repository:

- E0 the repository is undisturbed by drilling,
- E1 the repository has at least one E1 intrusion, or
- E2 the repository has one or more E2 intrusions, but no E1 intrusions.

In addition, each panel is assigned one of four conditions:

- E0 the excavated regions of the panel have not been intruded by drilling,
- E1 the panel has one previous E1 intrusions (intersecting a brine reservoir in the Castile),

- E2 the panel has one or more previous E2 intrusions (none intersect brine reservoirs), or

- E1E2 the panel has at least two previous intrusions, at least one of which is an E1 intrusion.

Repository conditions are used to determine direct releases for each intrusion by DBRs and spallings. Panel conditions are used to determine releases by transport through the Culebra.

When an intrusion into CH-TRU waste occurs, the stochastic variables in Table PA-24 are used in the algorithm shown in Figure PA-41 to determine the type of the intrusion (E1 or E2). The type of the intrusion is used to update the conditions for the intruded panel and the repository before stepping forward in time to the next intrusion.

PA-6.8.4.2 Determining Distance from Previous Intrusions

Direct releases by DBR and spallings require determining the distance between the panel hit by the current intrusion and the panels hit by previous intrusions. In PA, the 10 panels are divided into three groups: lower, consisting of only Panel 5; middle, including Panels 3, 4, 6, and 9; and upper, including Panels 1, 2, 7, 8, and 10, as shown in Figure PA-29. These divisions are consistent with the repository representation in the BRAGFLO model for Salado flow (Section PA-4.2) and for DBRs (Section PA-4.7).

The initial intrusion can occur in any of the 10 actual waste panels, so the direct releases for the initial intrusion are modeled as if the initial intrusion occurred in a lower, middle, or upper waste panel based on the division discussed above. Initial conditions for direct releases from subsequent intrusions are modeled by one of three cases: lower, middle, and upper, corresponding to the three panel groups shown in Figure PA-29 and listed in Table PA-27. The lower case represents a second intrusion into a previously intruded panel. The middle case represents an intrusion into an undisturbed panel that is adjacent to a previously disturbed panel. The upper case represents an intrusion into an undisturbed panel that is not adjacent to a previously disturbed panel. Adjacent panels share one side in common, and nonadjacent panels share no sides in common.

The time and location of the previous intrusion is used to determine distance from the current intrusion and depends on the repository condition, which is determined by the intrusion of greatest consequence across all panels prior to the current intrusion. E1 intrusions are assumed to be of greater consequence than E2 intrusions. The previous intrusion is selected by finding the closest panel (same, adjacent, nonadjacent) whose intrusion condition, excluding the current intrusion, is equal to the repository condition. The time of the previous intrusion is the time of the most recent intrusion with the greatest consequence and closest distance. Likewise, the condition of each panel is equal to the intrusion of greatest consequence into the panel prior to the current intrusion.

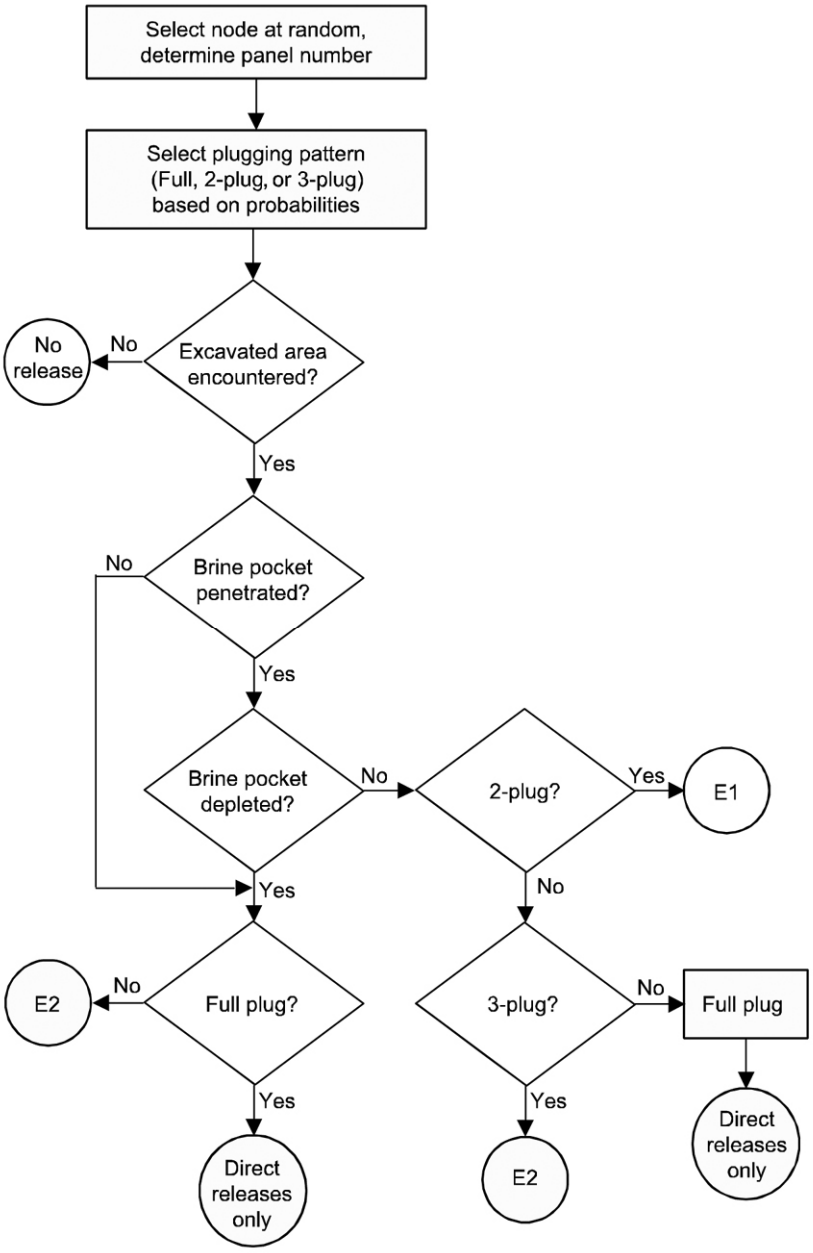


Figure PA-41. Logic Diagram for Determining the Intrusion Type

PA-6.8.5 CCDF Construction

For each vector $\mathbf{v}_{su,k}$ in the space of subjective uncertainty, the code CCDFGF samples a sequence $\mathbf{x}_{st,i}$, $i = 1, 2, \ldots, nR$ of futures. In PA, $nR = 10{,}000$; this number of futures is sufficient to adequately estimate the mean CCDF of total releases for comparison with the boundary line specified in section 191.13, as demonstrated in Section PA-9.0. A release $f(\mathbf{x}_{st,i})$ for each future is then constructed as described in Section PA-6.8.1, Section PA-6.8.2, and Section PA-6.8.3. Once the $f(\mathbf{x}_{st,i})$ are evaluated, the CCDF can be approximated as indicated in Equation (PA.318).

$$prob\left(Rel > R\right) = \int_{S_{st}} \delta_R \left[f\left(\mathbf{x}_{st,i}\right)\right] d_{st}\left(\mathbf{x}_{st,i}\right) \mathrm{d}V_{st} \cong \sum_{i=1}^{nR} \delta_R \left[f\left(\mathbf{x}_{st,i}\right)\right] \Big/ nR \qquad \text{(PA.318)}$$

A binning technique is used to construct the desired CCDF: the consequence axis is divided into a sequence of bins, and the number of values for $f(\mathbf{x}_{st,i})$ falling in each bin is accumulated. In addition, all values for $f(\mathbf{x}_{st,i})$ are saved and subsequently ordered to provide an alternative method for constructing the CCDFs. In addition to the total CCDF for all releases, it will be possible to obtain CCDFs for individual release modes (e.g., cuttings, spallings, DBRs, to Culebra, through MBs, through Culebra). The logic diagram for CCDF production is shown in Figure PA-42.

The CCDF construction indicated in this section is for a single sample element $\mathbf{v}_{su,k}$ of the form indicated in conjunction with Equation (PA.302). Repeated generation of CCDFs for individual sample elements $\mathbf{v}_{su,k}$, i.e. for the vectors representing epistemic uncertainty in the model results, will lead to the distribution of complete CCDFs.

PA-6.9 Sensitivity Analysis

Evaluating one or more of the models discussed in Section PA-4.0 with the LHS in Equation (PA.302) creates a mapping

$$\left\{\mathbf{v}_{su,k}, \mathbf{y}_{su,k}\right\}, \mathrm{k} = 1, 2, \ldots, \mathrm{nLHS} \qquad \text{(PA.319)}$$

from analysis inputs (i.e., $\mathbf{v}_{su,k}$) to analysis results (i.e., $y(\mathbf{v}_{su,k})$), where $\mathbf{y}_{su,k}$ denotes the results obtained with the model or models under consideration. In other words, for each vector of parameters samples, there is a corresponding CCDF of releases, $y(\mathbf{v}_{su,k})$. A vector notation is used for y because, in general, a large number of predicted results are produced by each of the models used in PA. Sensitivity analysis explores the mapping in Equation (PA.319) to determine how the uncertainty in individual elements of $\mathbf{v}_{su,k}$ affects the uncertainty in individual elements of $y(\mathbf{v}_{su,k})$. Understanding how uncertainty in analysis inputs affects analysis results aids in understanding PA and improving the models for future PAs.

The presentation of results from each major model in the WIPP PA is accompanied by sensitivity analyses of the most important output of the model. In some cases, sensitivity analysis results are based on pooling the results obtained for the three replicated LHSs (i.e., R1, R2, R3) discussed in Section PA-6.4. In other cases, the sensitivity analysis is based on the results for each replicate, and statistics are compared across the three replicates. Note that pooling LHS replicates that include correlated variables can introduce a small bias into the statistics, although there are methods that allow for correlated variables when pooling replicates (Sallaberry, Helton, and Hora 2006).

Three principal techniques are used in the sensitivity analysis: scatterplots, regression analyses to determine standardized regression coefficients and partial correlation coefficients, and stepwise regression analyses. Each technique is briefly discussed.

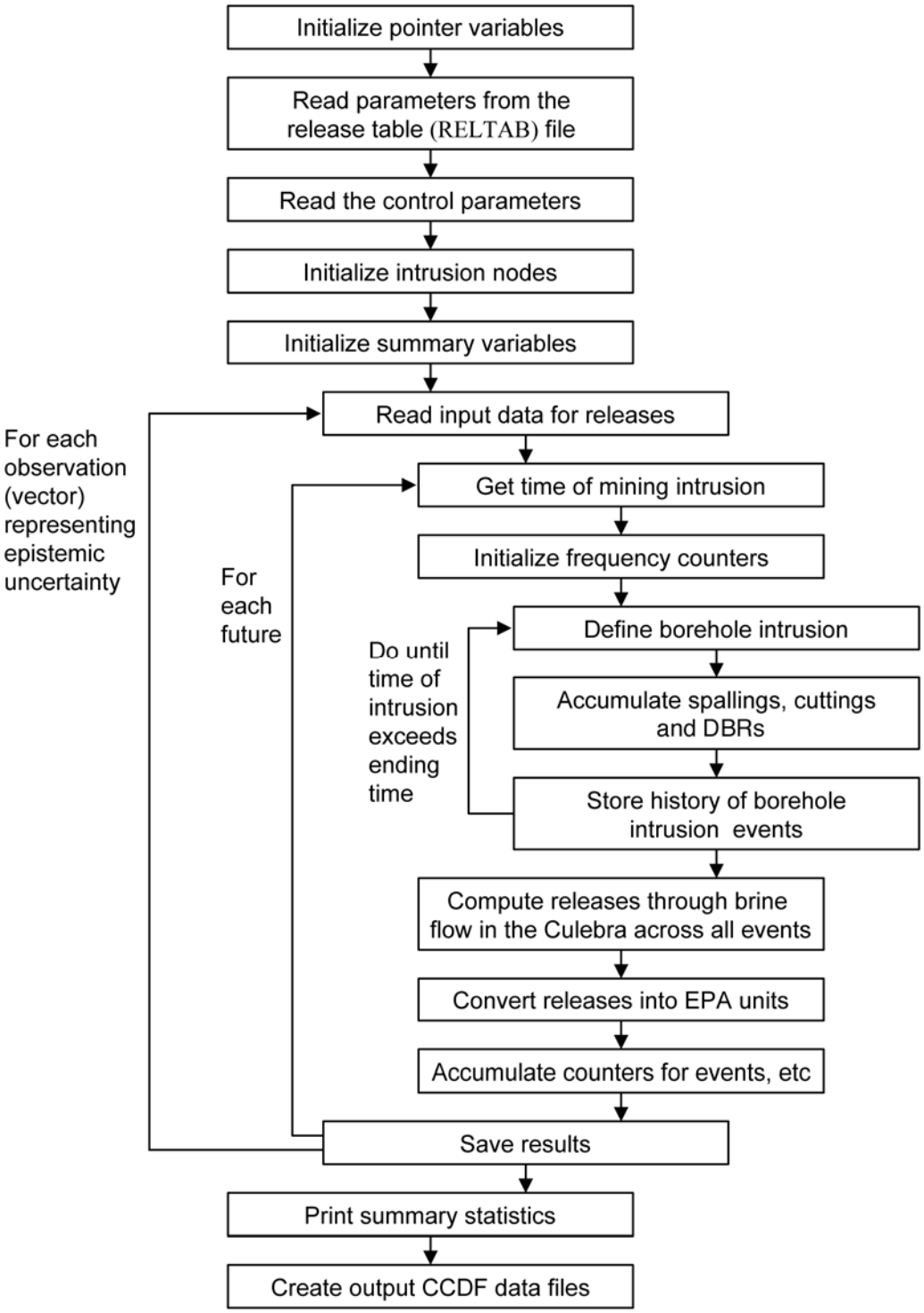


Figure PA-42. Processing of Input Data to Produce CCDFs

PA-6.9.1 Scatterplots

Scatterplots, the simplest sensitivity analysis technique, are performed by plotting the points

$$\left(v_{k,j}, y_k\right),\ k = 1, 2, \ldots, nLHS \tag{PA.320}$$

for each element v_j of $\mathcal{S}_{su}$. The resulting plots can reveal relationships between y and the elements of $\mathcal{S}_{su}$. Scatterplots can be effective at revealing nonlinear relationships or threshold values. Examining such plots when LHS is used can be particularly revealing because of the full stratification over the range of each input variable. Iman and Helton (1988) provide an example where the scatterplots revealed a rather complex pattern of variable interactions.

PA-6.9.2 Regression Analysis

A more formal investigation of the mapping in Equation (PA.319) can be based on regression analysis. In this approach, a model of the form

$$y = b_0 + \sum_{j=1}^{n} b_j x_j \tag{PA.321}$$

is developed from the mapping between analysis inputs and analysis results shown in Equation (PA.319), where the x_j are the input variables under consideration and the b_j are coefficients that must be determined. The coefficients b_j and other aspects of the regression model's construction in Equation (PA.321) can indicate the importance of the individual variables x_j with respect to the uncertainty in y. The PA employs the method of least squares to determine the coefficients b_j (Myers 1986).

Often the regression in Equation (PA.321) is performed after the input and output variables are normalized to mean zero and standard deviation one. The resulting coefficients b_j are called standardized regression coefficients (SRCs). When the x_j are independent, the absolute value of the SRCs can provide a measure of variable importance. Specifically, the coefficients provide a measure of importance based on the effect of moving each variable away from its expected value by a fixed fraction of its standard deviation while retaining all other variables at their expected values.

Partial correlation coefficients (PCCs) can also measure the linear relationships between the output variable y and the individual input variables. The PCC between y and an individual variable x_p is obtained through a sequence of regression models. First, the following two regression models are constructed:

$$\hat{y} = b_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} b_j x_j \ \ and \ \ \hat{x}_p = c_0 + \sum_{\substack{j=1 \\ j \neq p}}^{n} c_j x_j \tag{PA.322}$$

The results of the two preceding regressions are then used to define the new variables $y - \hat{y}$ and $x_p - \hat{x}_p$. By definition, the PCC between y and x_p is the correlation coefficient between $y - \hat{y}$ and $x_p - \hat{x}_p$. Thus, the PCC provides a measure of the linear relationship between y and x_p with the linear effects of the other variables removed.

Regression and correlation analyses often perform poorly when the relationships between the input and output variables are nonlinear. This is not surprising, as such analyses assume linear relationships between variables. The problems associated with poor linear fits to nonlinear data can be avoided by use of the rank transformation (Iman and Conover 1979). The rank transformation is a simple concept: data are replaced with their corresponding ranks, and then the usual regression and correlation procedures are performed on these ranks. Specifically, the smallest value of each variable is assigned Rank 1, the next largest value is assigned Rank 2, and so on up to the largest value, which is assigned the rank *m*, where *m* denotes the number of observations. The analysis is then performed with these ranks used as the values for the input and output variables. A formal development of PCCs and the relationships between PCCs and SRCs is provided by Iman, Shortencarier, and Johnson (1985).

PA-6.9.3 Stepwise Regression Analysis

Stepwise regression analysis provides an alternative to constructing a regression model containing all the input variables. With this approach, a sequence of regression models is constructed. The first regression model contains the single input variable with the largest impact on the uncertainty in the output variable (i.e., the input variable that has the largest correlation with the output variable *y*). The second regression model contains the two input variables with the largest impact on the output variable: the input variable from the first step, plus whichever of the remaining variables has the largest impact on uncertainty not accounted for by the first variable (i.e., the input variable that has the largest correlation with the uncertainty in *y* that cannot be accounted for by the first variable). Additional models in the sequence are defined in the same manner, until further models are unable to meaningfully increase the amount of uncertainty that can be accounted for in the output variable.

Stepwise regression analysis can provide insights into the importance of the individual variables. First, the order in which the variables are selected in the stepwise procedure indicates their importance, with the most important variable being selected first, the next most important variable being selected second, and so on. Second, the R^2 values at successive steps of the analysis also measure variable importance by indicating how much of the uncertainty in the dependent variable can be accounted for by all variables selected at each step. When the input variables are uncorrelated, the differences in the R^2 values for the regression models constructed at successive steps equals the fraction of the total uncertainty in the output variable accounted for by the individual input variable added at each step. Third, the absolute values of the SRCs in the individual regression models indicate variable importance. Further, the sign of an SRC indicates whether the input and output variable tend to increase and decrease together (a positive coefficient) or tend to move in opposite directions (a negative coefficient).

PA-7.0 Results for the Undisturbed Repository

The PA tabulates releases from the repository for undisturbed conditions. Releases from the undisturbed repository to the accessible environment fall under two sets of protection requirements. The first, as set forth in section 191.15, protects individuals from radiological exposure; the second, in Part 191 Subpart C, protects groundwater resources from contamination. This section shows how WIPP complies with these two requirements by presenting brine and gas flow (BRAGFLO) and radionuclide transport (NUTS) results from modeling the undisturbed repository. The results discussed in Section PA-7.2 show that there are no releases to the accessible environment from the undisturbed repository. Section PA-7.0 is taken from Clayton et al. (2008, Section 4.0).

PA-7.1 Salado Flow

This section summarizes the Salado flow calculation results for the undisturbed (S1) scenario. Pressure in the repository, brine saturation in the waste, and brine flow out of the repository are presented, along with sensitivity analyses that identify the uncertain parameters to which these results are most sensitive. The Salado flow model represents the repository as five regions in the numerical grid: three waste-filled regions (the Waste Panel, South RoR, and North RoR in Figure PA-15) and two excavated regions with no waste (the operations area and experimental area in Figure PA-15). The analysis package for Salado flow contains a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses (Nemer and Clayton 2008).

PA-7.1.1 Pressure in the Repository

In undisturbed conditions, pressure strongly influences the extent to which contaminated brine might migrate from the repository to the accessible environment. In addition, pressure developed under undisturbed conditions is an initial condition for the spallings and DBR models (Section PA-8.5.2 and Section PA-8.5.3, respectively).

Figure PA-43 shows the pressure in the Waste Panel region for 100 vectors in replicate R1 for the CRA-2009 PA. During the first 1,000 years, repository pressure may rapidly increase due to several factors: rapid initial creep closure of rooms, initial inflow of brine causing gas generation due to corrosion, and availability of CPR material to produce gas by microbial degradation. Pressure generally approaches a steady-state value after 2,000 years as room closure ceases, brine inflow slows (thereby reducing gas generation by corrosion), and CPR materials are consumed.

In general, pressure increased for the CRA-2009 PA compared to the CRA-2004 PABC (Nemer and Clayton 2008, Table 6-10). The increase was mainly caused by the correction of halite porosity. The upper bound of the halite porosity distribution was increased, while the lower bound and the mean remained the same. The halite porosity is positively correlated with pressure, so the increase in porosity resulted in an increase in pressure (Nemer and Clayton 2008).

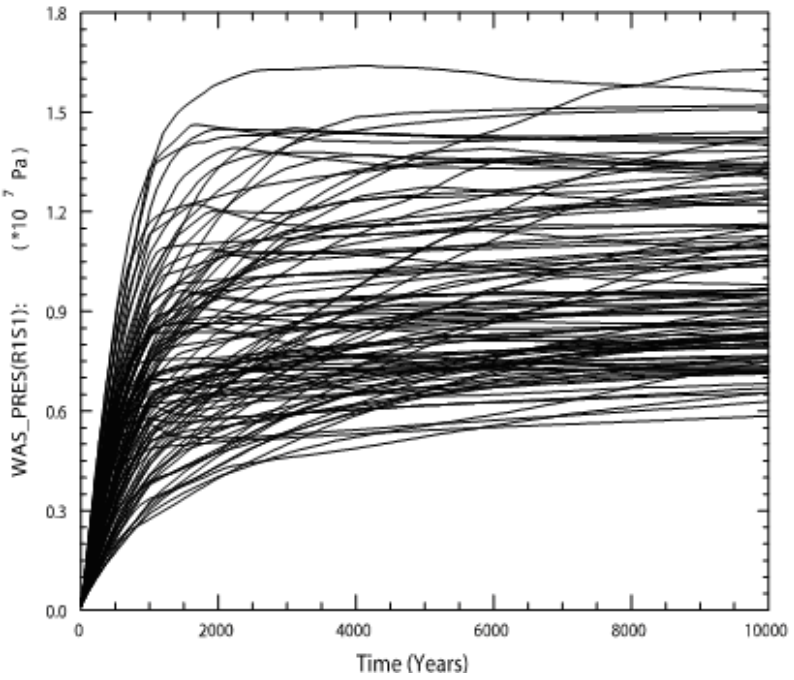


Figure PA-43. Pressure in the Waste Panel Region, Replicate R1, Scenario S1, CRA-2009 PA

Sensitivity analyses have determined the importance of parameter uncertainty to the uncertainty in model results. Figure PA-44 shows partial rank correlation coefficients (PRCCs) generated by the code PCCSRC (Gilkey 1995) from regression data between the pressure in the waste panel (WAS_PRES) and the uncertain variables in the LHS (Section PA-5.2) for the CRA-2009 PA. The figure shows that uncertain pressure in the waste panel is primarily determined by the sampled halite porosity (HALPOR) (Nemer and Clayton 2008).

The positive correlation indicates that higher pressures result from higher values of halite porosity (HALPOR). Increases in halite porosity linearly increases the DRZ porosity. This increases the volume of brine available in the material overlying the waste, which, as the brine flows, can then increase the amount of brine in the repository (Nemer and Clayton 2008). Microbial gas generation rates are a function of the brine in the repository and increase as more brine is available. Increased gas generation results in increased repository pressures. Increases in the DRZ permeability (DRZPRM) accelerate brine flow into the waste, which then also increases the gas generation rates, as seen by the positive correlation in Figure PA-44. The other PRCCs in Figure PA-44 indicate that the uncertainty factor for microbial gas generation (WBIOGENF), the corrosion rate for steel (WGRCOR), and the waste wicking parameter (WASTWICK) determine the remaining variability in waste panel pressure, as they affect the gas generation rate as well.

PA-7.1.2 Brine Saturation in the Waste

Brine saturation is an important result of the model for Salado flow because gas generation processes, which tend to increase pressure, require brine. Brine saturation is also an initial condition in the model for DBR (Section PA-8.5.3).

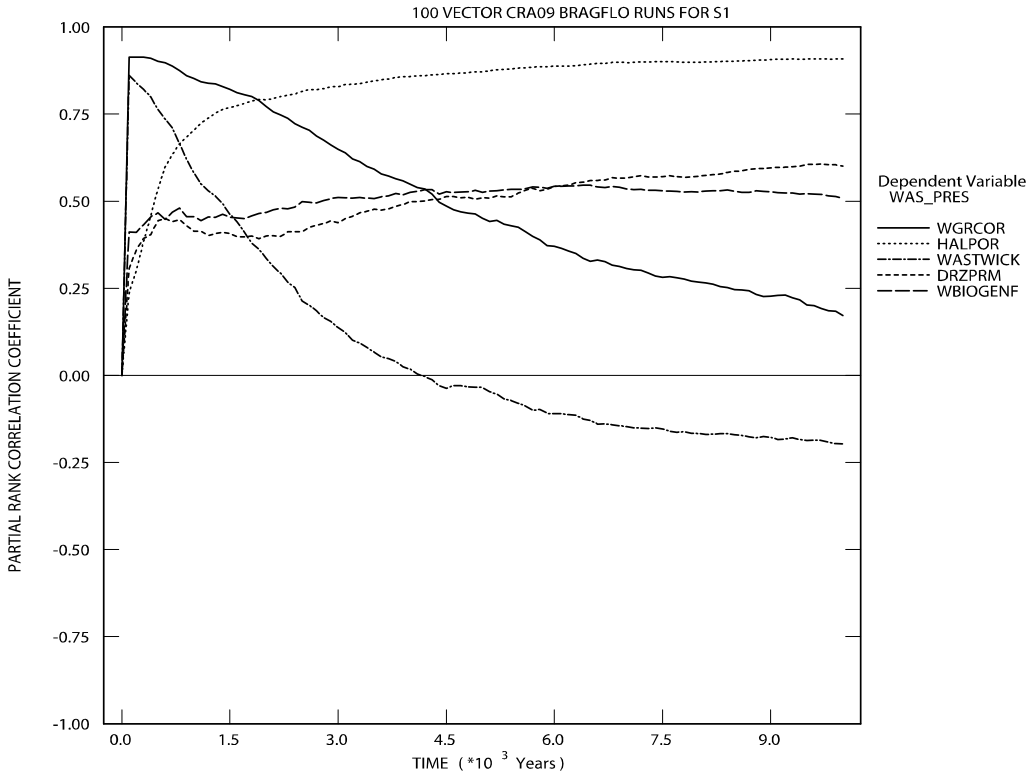


Figure PA-44. Primary Correlations of Pressure in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S1, CRA-2009 PA

Figure PA-45 shows brine saturation in the Waste Panel region of the repository for the 100 vectors of Replicate R1, Scenario S1 for the CRA-2009 PA. Brine saturation in the waste-filled areas is set initially to 0.015. Saturation increases very rapidly in the first 100 years in all excavated areas as brine flows toward the excavations, primarily from the DRZ above the excavation. Initially there is a large pressure differential between the DRZ and the excavated regions, and the relatively high permeability of the DRZ, compared to undisturbed halite, permits the rapid influx of brine. Brine inflow slows as the pressures equalize and as brine saturation in the DRZ decreases. Brine saturation in the waste areas decreases over time as brine is consumed by corrosion. Brine may also be driven out of the repository by high pressure.

The brine saturation patterns are similar, but are higher on average in the CRA-2009 PA than the CRA-2004 PABC (Nemer and Clayton 2008, Table 6-6 and Figure 6-8): there are more vectors with saturation greater than 60%. The increase in brine saturation is the result of the increased halite porosity (Nemer and Clayton 2008).

Computing PRCCs between the brine saturation in the waste panel (WAS_SATB) and the uncertain parameters in the LHS identifies a number of parameters that contribute to the uncertainty in brine saturation. The relative importance of these parameters varies over the 10,000-year modeling period, and none of the parameters are clearly dominant. Figure PA-46 shows positive correlations with anhydrite permeability (ANHPRM), DRZ permeability (DRZPRM), and halite porosity (HALPOR). Increases in halite porosity increase the volume of brine available in the material overlying the waste; increases in DRZ and anhydrite permeability accelerate brine flow into the waste. Negative correlations are found between brine saturation

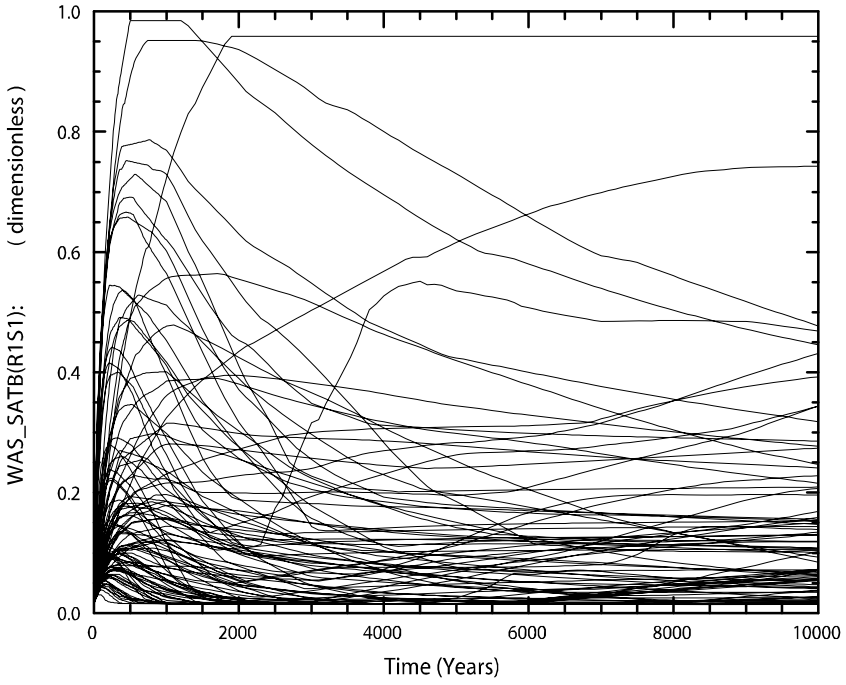


Figure PA-45. Brine Saturation in the Waste Panel Region, Replicate R1, Scenario S1, CRA-2009 PA

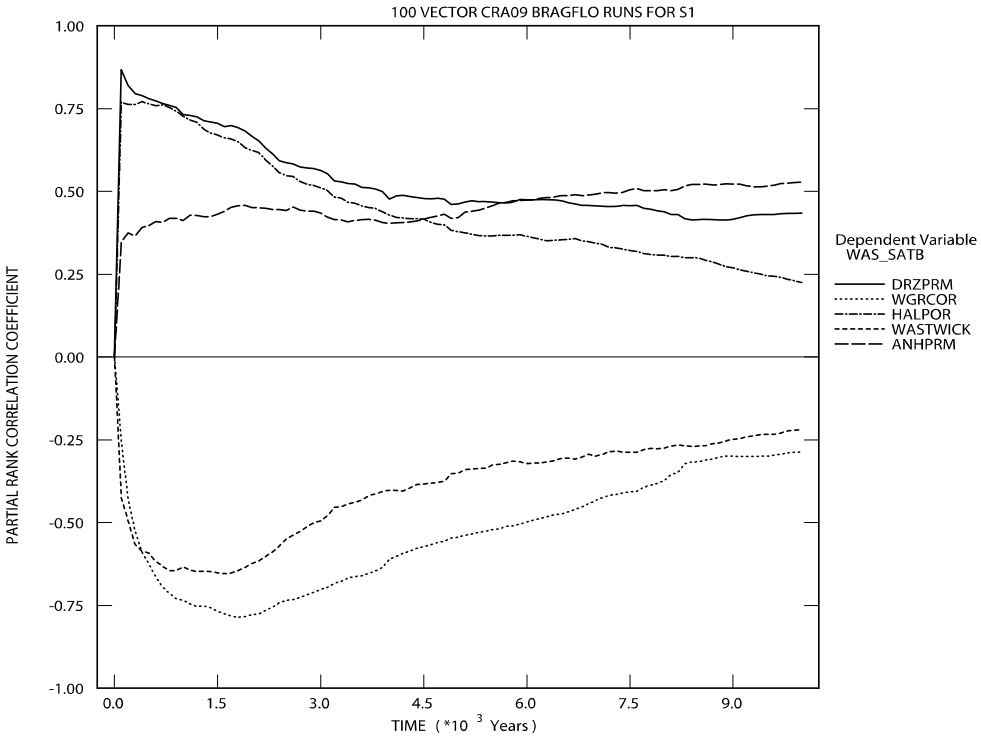


Figure PA-46. Primary Correlations of Brine Saturation in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S1, CRA-2009 PA

and the corrosion rate (WGRCOR) and the wicking factor (WASTWICK) because increases in these two variables increase the rate at which brine is consumed by corrosion, thus decreasing saturation.

PA-7.1.3 Brine Flow Out of the Repository

The anhydrite MBs and the shafts provide possible pathways for brine flow away from the repository in the undisturbed (S1) scenario. The Salado flow model only tabulates the volume of brine crossing boundaries within the model grid; it does not identify whether the brine contains radionuclides from the waste. Radionuclide transport is calculated separately from the flow and is discussed in Section PA-7.2.

Figure PA-47 shows cumulative brine outflow from the waste-filled regions of the repository (BRNREPOC), while Figure PA-48 shows the volumes of brine that cross the LWB through the MBs (BRAALLWC). The largest outflow across the LWB is ~1,600 m^3. Brine crossing the LWB or moving up the shaft does not necessarily indicate releases from the repository, since the brine may not have been in contact with the waste; the brine may have been present in the MBs at the start of the regulatory period. Section PA-7.2 presents the results of the radionuclide transport calculations that determine the amount of radionuclides that may be released through brine transport.

Compared with the CRA-2004 PABC, an increase in the average and maximum cumulative brine flow away from the repository was observed for the CRA-2009 PA (see Nemer and Clayton [2008], Table 6-11). The cumulative brine flow to the LWB through the MBs also increased for

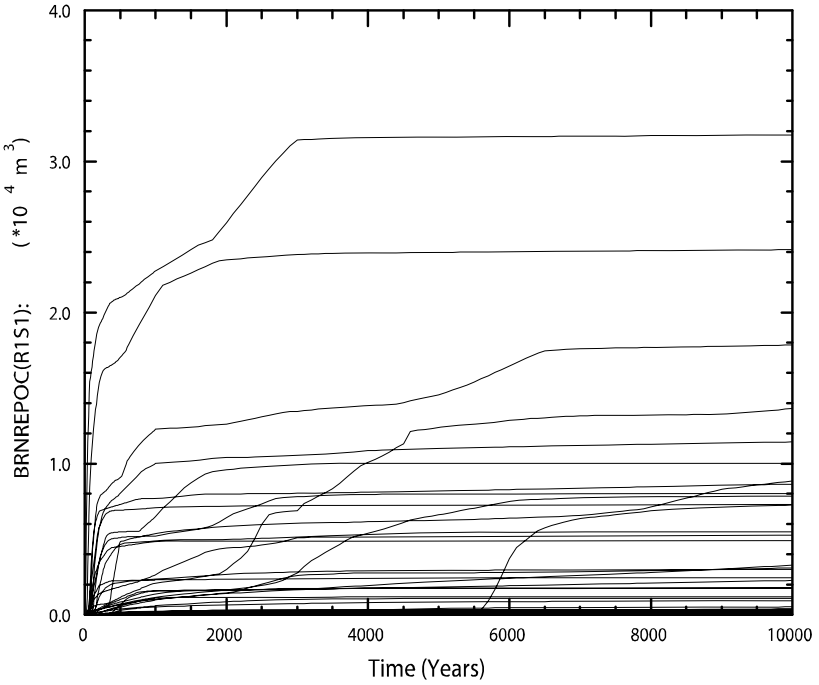


Figure PA-47. Brine Flow Away From the Repository, Replicate R1, Scenario S1, CRA-2009 PA

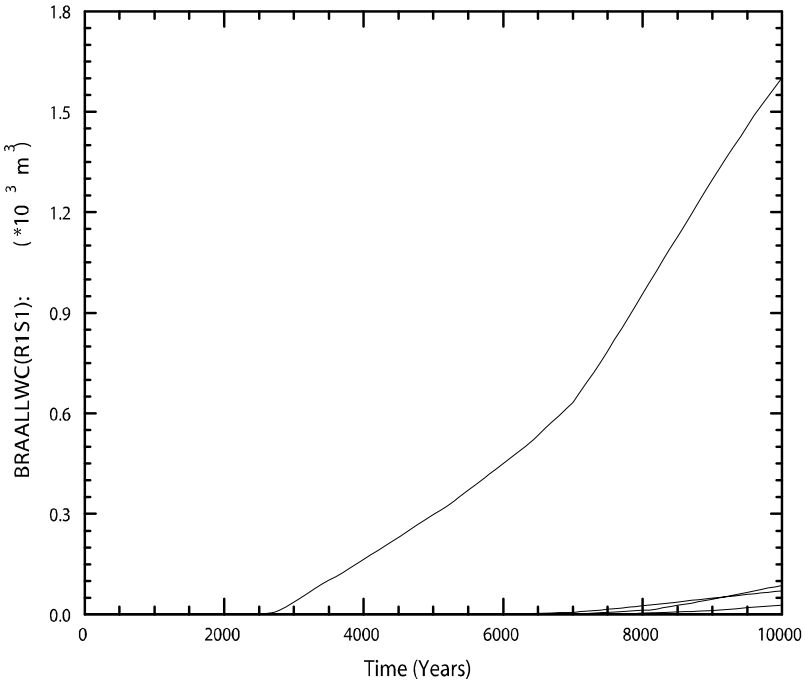


Figure PA-48. Brine Flow via All MBs Across the LWB, Replicate R1, Scenario S1, CRA-2009 PA

the CRA-2009 PA compared to the CRA-2004 PABC. These changes are the result of increased repository pressure (see Section PA-7.1.1).

Regression analyses between total cumulative brine flow out of the waste-filled regions (BRNREPOC) and the uncertain parameters are shown in Figure PA-49. The permeability of the DRZ (DRZPRM) has the largest positive correlation, followed by the permeability of the concrete panel seal (CONPRM) and the porosity of undisturbed halite (HALPOR). Increases in the permeability of the DRZ and the concrete panel seal allow more brine to flow out of the repository, as well as into the repository, which increases the gas generation and therefore the pressure. The increase in the halite porosity also increases the pressure, which in turn increases the amount of brine flow out of the repository. The largest negative correlation is with the waste residual brine saturation (WRBRNSAT), which determines the immobile portion of the brine in the waste-filled regions, and limits the amount of brine that can flow out.

PA-7.2 Radionuclide Transport

This section summarizes the radionuclide transport results for the undisturbed repository, both up the shaft to the Culebra and through the Salado to the LWB. Ismail and Garner (2008) present a detailed analysis of the NUTS results for the CRA-2009 PA.

Radionuclide transport in the undisturbed (S1) scenario is calculated by the code NUTS. Screening runs using a conservative tracer determine which vectors have the potential to transport radionuclides to the accessible environment. Full transport simulations are then performed for all screened-in vectors (with the potential to transport radionuclides to the accessible environment). Based upon results of the screening exercise, full radionuclide

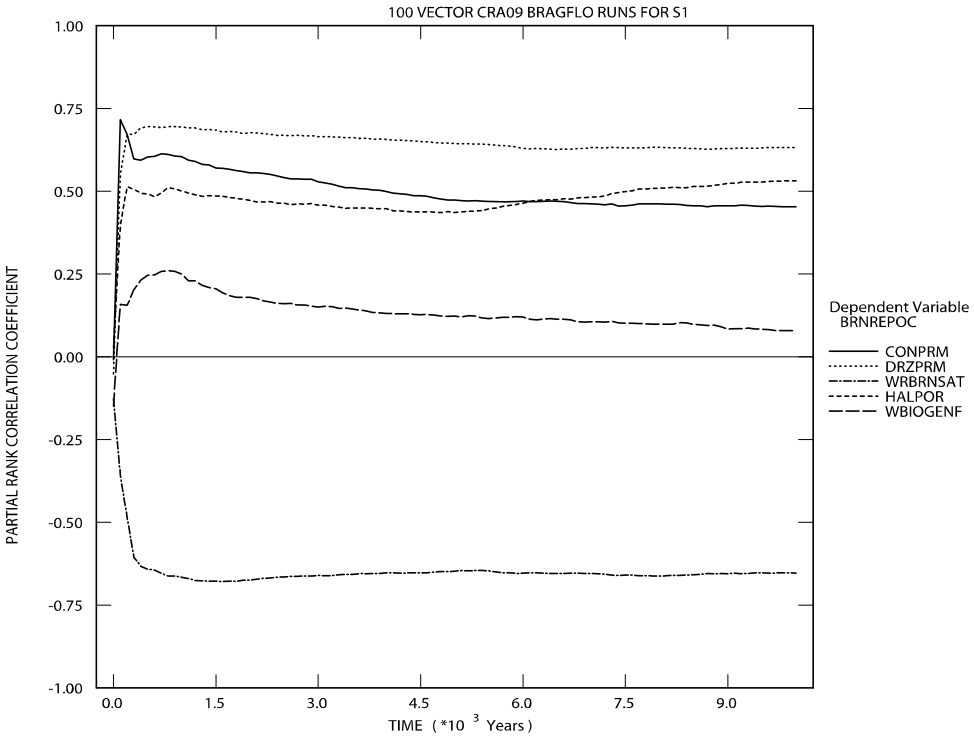


Figure PA-49. Primary Correlations of Total Cumulative Brine Flow Away from the Repository with Uncertain Parameters, Replicate R1, Scenario S1, CRA-2009 PA

transport simulations were performed for only one vector in the undisturbed case: Replicate R1, Vector 53. Radionuclide transport simulations were performed for other vectors in the undisturbed case to postprocess fluid-flow conditions for use in the disturbed scenario calculations.

PA-7.2.1 Radionuclide Transport to the Culebra

For the undisturbed repository, no vectors showed radionuclide transport through the shafts to the Culebra. Consequently, no radionuclides could be transported through the Culebra to the accessible environment under undisturbed conditions (Ismail and Garner 2008).

PA-7.2.2 Radionuclide Transport to the Land Withdrawal Boundary

Radionuclides can also be transported through the Salado MBs to the LWB. For the undisturbed case, only one vector was screened in. The maximum total integrated activity across the LWB at the Salado MBs for Replicate R1, Scenario S1, Vector 53 was 2.6×10^{-10} EPA units (Ismail and Garner 2008), which is the same vector with the largest outflow of brine across the LWB of ~1,600 m^3. This is comparable to the CRA-2004 PABC results for replicate R1, Scenario S1, Vector 53 (the only screened-in vector), which had 1.3×10^{-12} EPA units at the boundary (Lowry 2005). Note that these magnitudes are smaller than the effective numerical precision of the transport calculations. As explained in Lowry (2005), this value is most likely due to numerical dispersion as a result of NUTS's finite-difference solution method. The magnitude of

the nonzero release is indicative of numerical dispersion resulting from the coarse grid spacing between the repository and the LWB, rather than from actual transport of radionuclides.

Regardless of the significance attached to the numerical values reported above, the releases from the undisturbed scenario are insignificant compared to releases from drilling intrusions (see Section PA-8.4). Consequently, releases in the undisturbed (S1) scenario are omitted from the calculation of total releases from the repository.

PA-8.0 Results for a Disturbed Repository

The WIPP repository might be disturbed by exploratory drilling for natural resources during the 10,000-year regulatory period. Drilling could create additional pathways for radionuclide transport, especially in the Culebra, and could release material directly to the surface. In addition, mining for potash within the LWB might alter flow in the overlying geologic units and locally accelerate transport through the Culebra. The disturbed scenarios used in PA modeling capture the range of possible releases resulting from drilling and mining.

Total releases are computed by the code CCDFGF. Total releases comprise transport releases and direct releases. Transport releases generally involve movement of radionuclides up an abandoned borehole into the Culebra, then through the Culebra to the LWB. Transport of radionuclides to the Culebra is computed using the codes NUTS and PANEL (see Section PA-6.7.2 and Section PA-6.7.3) using the brine flows computed by BRAGFLO (see Section PA-6.7.1). Radionuclide transport through the Culebra is computed by the code SECOTP2D (see Section PA-6.7.8) using flow fields calculated by MODFLOW (see Section PA-6.7.7).

Direct releases occur at the time of a drilling intrusion and include releases of solids (cuttings, cavings, and spallings) computed using the code CUTTINGS_S (see Section PA-6.7.4) and DBRs computed using BRAGFLO (see Section PA-6.7.6). Pressure and brine saturation within the waste areas are used as initial conditions for the direct release models. Results from the undisturbed repository (see Section PA-7.0) are used as the initial conditions for the first intrusion. To calculate initial conditions for subsequent intrusions, and to compute the source of radionuclides for transport in the Culebra, BRAGFLO uses a set of drilling scenarios to calculate conditions within the repository after an intrusion (see Section PA-6.7.6).

This section first summarizes the scenarios used to represent drilling intrusions and the resulting repository conditions calculated by BRAGFLO. Transport releases are presented next, followed by cuttings, cavings, spallings, and DBRs. Section PA-8.0 is taken from Clayton et al. (2008, Section 5.0).

PA-8.1 Drilling Scenarios

As shown in Table PA-25, the PA considers two types of drilling intrusions: E1 and E2. The E1 intrusion scenario represents the possibility that a borehole creates a pathway between the repository and a pressurized brine reservoir located within the underlying Castile formation. The E2 intrusion scenario represents a borehole that intrudes into the repository, but does not connect the repository with an underlying brine reservoir. Repository conditions are calculated for the E1 intrusion scenario at 350 and 1,000 years, and are referred to as the BRAGFLO S2 and S3 scenarios, respectively. The BRAGFLO Scenarios S4 and S5 represent E2 intrusions that occur at 350 and 1,000 years, respectively. An additional BRAGFLO scenario, S6, simulates the effects of an E2 intrusion at 1,000 years followed by an E1 intrusion 1,000 years later into the same panel.

PA-8.2 Mining Scenarios

Long-term releases within the Culebra could be influenced by future mining activities that remove all the known potash reserves within the LWB and cause the transmissivity within the overlying Culebra to change (see Section PA-4.8). The full mining of known potash reserves within the LWB in the absence of AICs and PICs is modeled as a Poisson process, with a rate of 10^{-4} yr^{-1} (see Section PA-3.9). For any particular future, this rate is used to determine a time at which full mining has occurred. Flow fields are calculated for the Culebra for two conditions: partial mining, which assumes all potash has been mined from reserves outside the LWB; and full mining, which assumes all reserves have been mined both inside and outside the LWB. Radionuclide transport through the Culebra uses the partial-mining flow fields prior to the time at which full mining has occurred and the full-mining flow fields after that time.

PA-8.3 Salado Flow

This section summarizes the results of the Salado flow calculations for the disturbed scenarios. Nemer and Clayton (2008) provide a detailed presentation on the BRAGFLO model, calculation results, and further sensitivity analyses.

PA-8.3.1 Pressure in the Repository

Figure PA-50 and Figure PA-51 show pressure in the waste panel (WAS_PRES for Waste Panel area in Figure PA-15) for the 100 vectors of replicate R1 for BRAGFLO Scenarios S2 and S4, respectively. The pressure exhibits varying patterns depending on the type of intrusion.

Scenario S2 represents an E1 intrusion at 350 years. At the time of the intrusion, brine flow from the Castile brine reservoir leads to an increase in pressure (Figure PA-50). However, pressure drops sharply 200 years after the intrusion, when the borehole plugs above the repository are assumed to fail and the permeability of the borehole generally increases. In vectors with low borehole permeability, pressure does not change noticeably as a result of the borehole plug failure (Nemer and Clayton 2008).

Scenario S4 represents an E2 intrusion at 350 years. The borehole plugs effectively prevent any change in repository pressure from the time of the intrusion until the borehole plugs fail (Figure PA-51). As in the scenarios for E1 intrusions, pressure generally drops sharply when the plugs fail, except for vectors with low borehole permeability after plug failure. The pressure is generally lower in the E2 intrusion scenarios compared to the undisturbed and E1 intrusion scenarios (Nemer and Clayton 2008).

The pressure trends in the disturbed scenarios for the CRA-2009 PA are similar to the results obtained for the CRA-2004 PABC. The average and maximum pressures are comparable between the two analyses, as well (see Table 6-16 in Nemer and Clayton [2008]). As the intrusion creates a pathway for brine and gas to flow into and away from the repository, the effect of the increased halite porosity is minimized (Nemer and Clayton 2008).

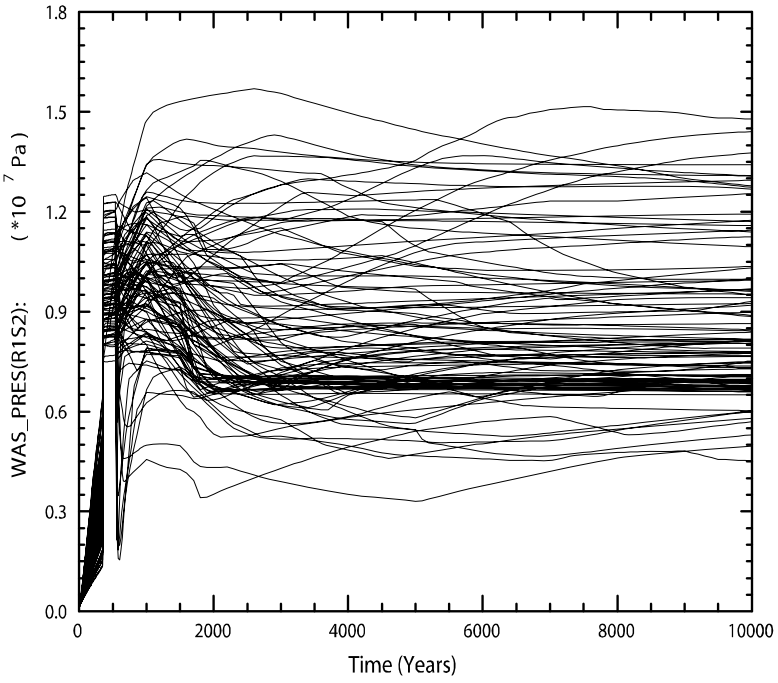


Figure PA-50. Pressure in the Waste Panel Region for Replicate R1, Scenario S2, CRA-2009 PA

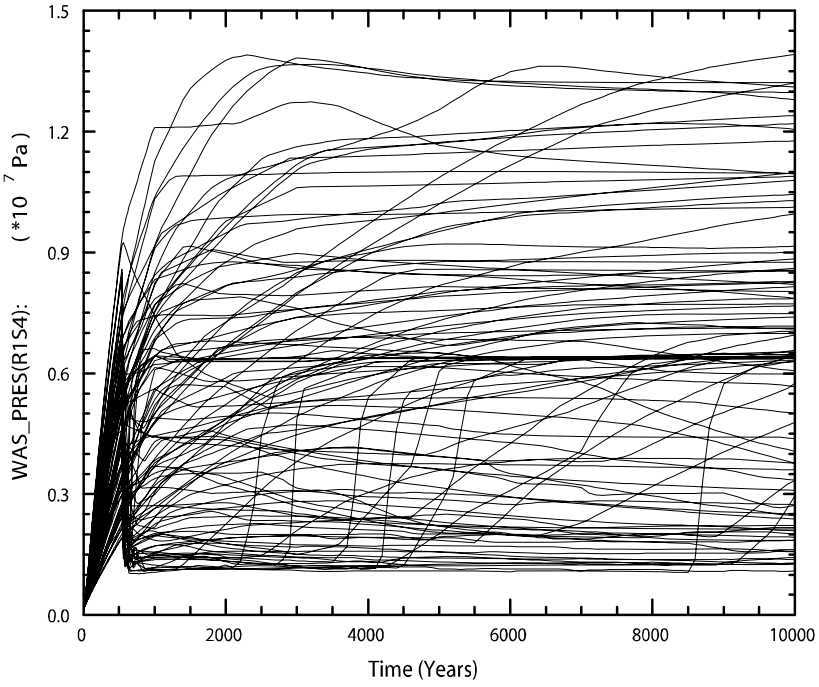


Figure PA-51. Pressure in the Waste Panel Region for Replicate R1, Scenario S4, CRA-2009 PA

Computing PRCCs between the pressure in the waste panel (WAS_PRES) and the uncertain parameters in the LHS identifies a number of parameters that contribute to the uncertainty in pressure for the disturbed scenarios. The relative importance of these parameters varies over the 10,000-year modeling period. Figure PA-52 and Figure PA-53 show the regression analysis results for pressure in the Waste Panel with uncertain parameters versus time for Scenarios S2 and S4, Replicate R1 from the CRA-2009 PA, respectively.

For both scenarios, the borehole permeability (BHPERM) has the largest negative correlation with pressure after the intrusion, as this is the primary means by which pressure may escape the repository in the disturbed scenarios. For Scenario S2 (Figure PA-52), the initial Castile brine pocket pressure (BPINTPRS) has the largest positive correlation after the intrusion, while for Scenario S4 (Figure PA-53), the largest positive correlation for the majority of the time after the intrusion, results from the halite porosity (HALPOR). The negative correlation of the borehole permeability is stronger than the positive correlation of the initial Castile brine pocket pressure and halite porosity for either scenario.

The higher initial Castile brine pocket pressure causes more brine at a higher pressure to flow into the repository, while increasing the halite porosity increases the volume of brine available in the material overlying the waste, which, as the brine flows into the waste panel, can then increase the amount of brine in the repository. Microbial gas generation rates are a function of the brine in the repository and increase as more brine is available. Increased gas generation results in increased repository pressures.

The pressure in the waste panel is also controlled by the corrosion rate for steel (WGRCOR), the waste wicking parameter (WASTWICK), and the index for the model of microbial degradation (WMICDFLG), which all affect the gas generation rates and therefore the pressure. For Scenario S2, increasing the brine pocket compressibility (BPCOMP) increases the brine inflow from the brine pocket to the repository, and thus the pressure in the repository.

PA-8.3.2 Brine Saturation

Brine saturation tends to increase after a drilling intrusion. Figure PA-54 and Figure PA-55 show brine saturation in the waste panel (WAS_SATB for area Waste Panel in Figure PA-15) for Replicate R1 for BRAGFLO Scenarios S2 and S4, respectively.

Scenario S2 represents an E1 intrusion at 350 years. At the time of the intrusion, brine flow from the Castile brine reservoir increases saturation (Figure PA-54). However, saturation can drop sharply 200 years after the intrusion when the borehole plugs above the repository are assumed to fail and the permeability of the borehole generally increases. In vectors with low borehole permeability, saturation does not change noticeably as a result of the borehole plug failure. Twelve hundred years after the drilling intrusion, the permeability of the borehole connecting the repository to the Castile is assumed to be reduced by an order of magnitude because of creep closure. This material change reduces saturation in some vectors, but does not appear to have a significant effect on the saturation in most vectors.

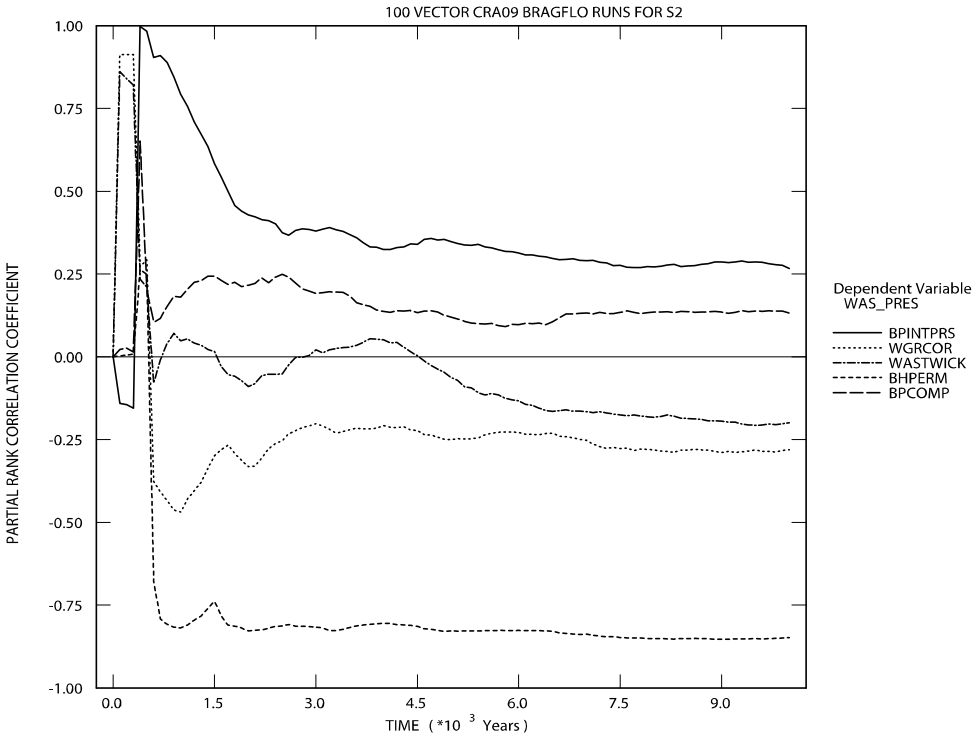


Figure PA-52. Primary Correlations of Pressure in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S2, CRA-2009 PA

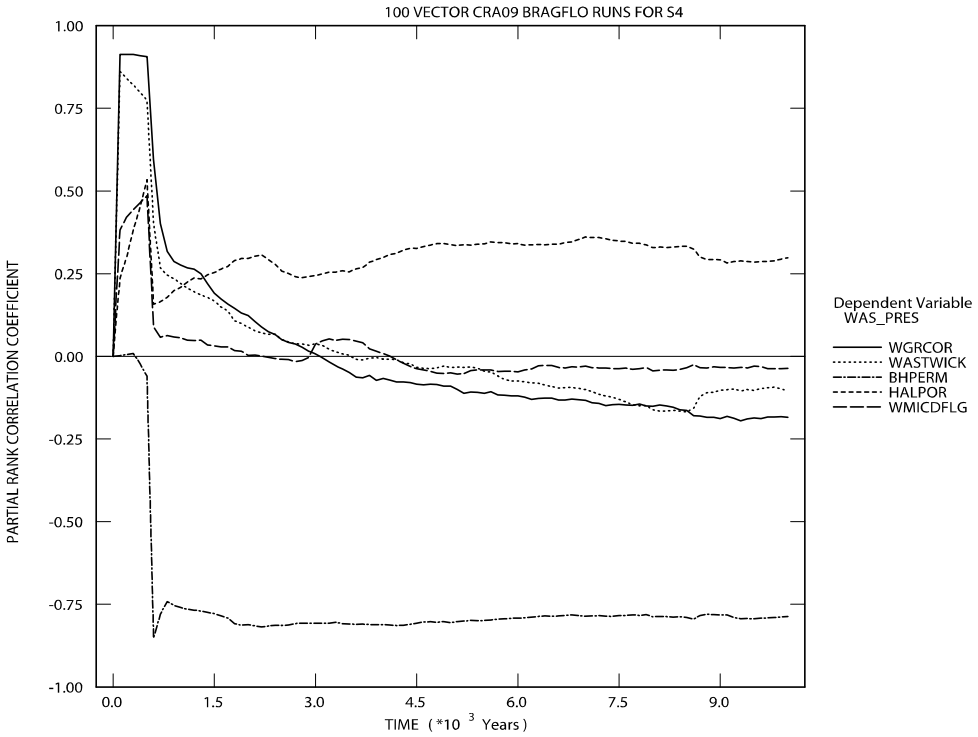


Figure PA-53. Primary Correlations of Pressure in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S4, CRA-2009 PA

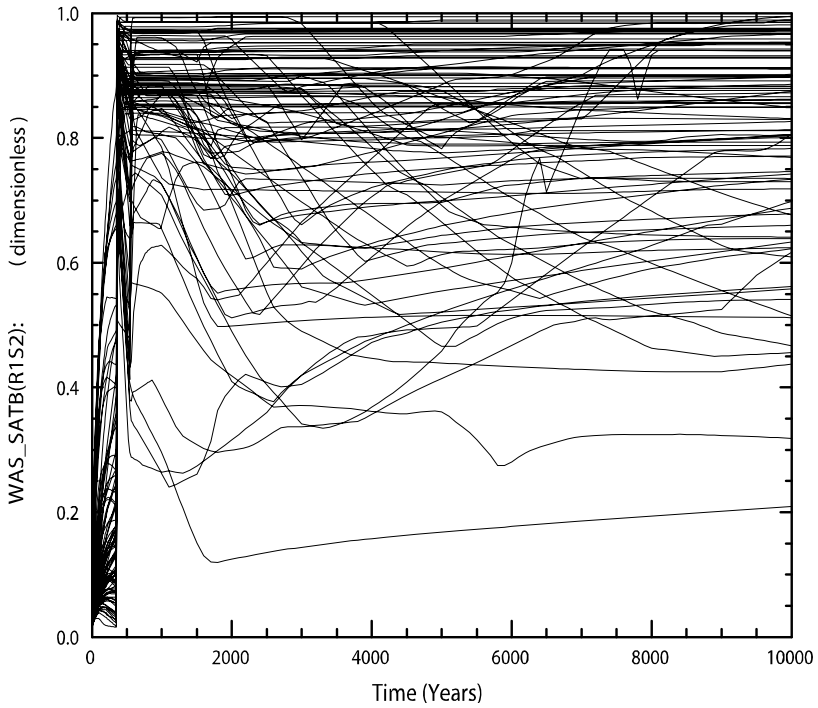


Figure PA-54. Brine Saturation in the Waste Panel Region for Replicate R1, Scenario S2, CRA-2009 PA

Scenario S4 represents an E2 intrusion at 350 years. The borehole plugs effectively prevent any change in repository saturation from the time of the intrusion until the borehole plugs fail (Figure PA-55). Unlike the E1 intrusions scenarios, saturation generally increases sharply when the plugs fail, except for vectors with low borehole permeability after plug failure. The saturation is generally lower in the E2 intrusion scenarios compared to the E1 intrusion scenarios.

The brine saturation trends in the disturbed scenarios for the CRA-2009 PA are similar to the results obtained for the CRA-2004 PABC. The average and maximum brine saturations are comparable between the two analyses, as well (see Nemer and Clayton [2008, Table 6-15]).

As the intrusion creates a pathway for brine and gas to flow into and away from the repository, the effect of the increased porosity is minimized (Nemer and Clayton 2008).

Computing PRCCs between the saturation in the waste panel (WAS_SATB) and the uncertain parameters in the LHS identifies a number of parameters that contribute to the uncertainty in pressure for the disturbed scenarios. The relative importance of these parameters varies over the 10,000-year modeling period. Figure PA-56 and Figure PA-57 show the regression analysis results for saturation in the Waste Panel with uncertain parameters versus time for Scenarios S2 and S4, and Replicate R1 from the CRA-2009 PA, respectively.

For Scenario S2 (Figure PA-56), the DRZ permeability (DRZPRM) and the borehole permeability (BHPERM) have positive correlations. Increases in DRZ and borehole permeability accelerate brine flow into the waste. The corrosion rate for steel (WGRCOR) and

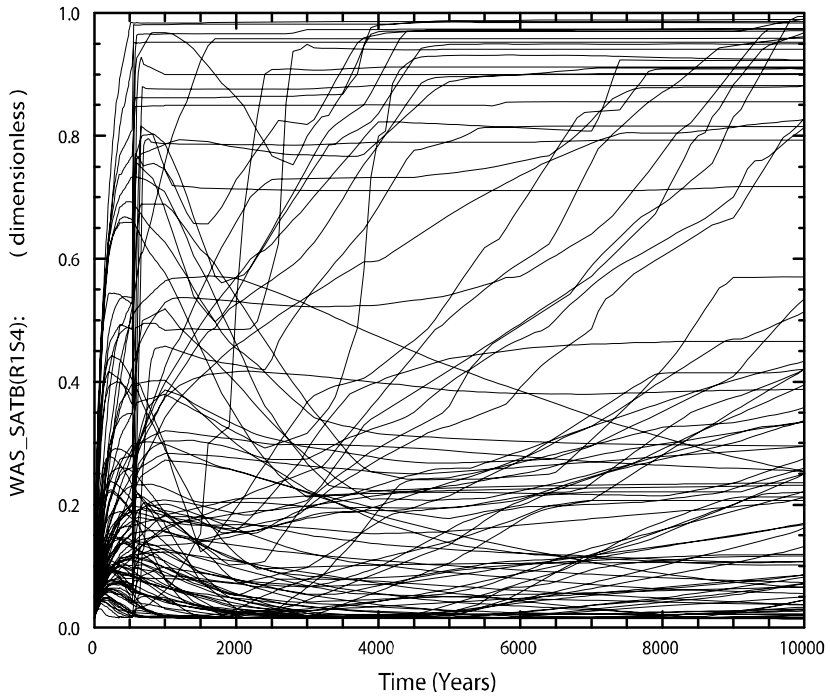


Figure PA-55. Brine Saturation in the Waste Panel Region for Replicate R1, Scenario S4, CRA-2009 PA

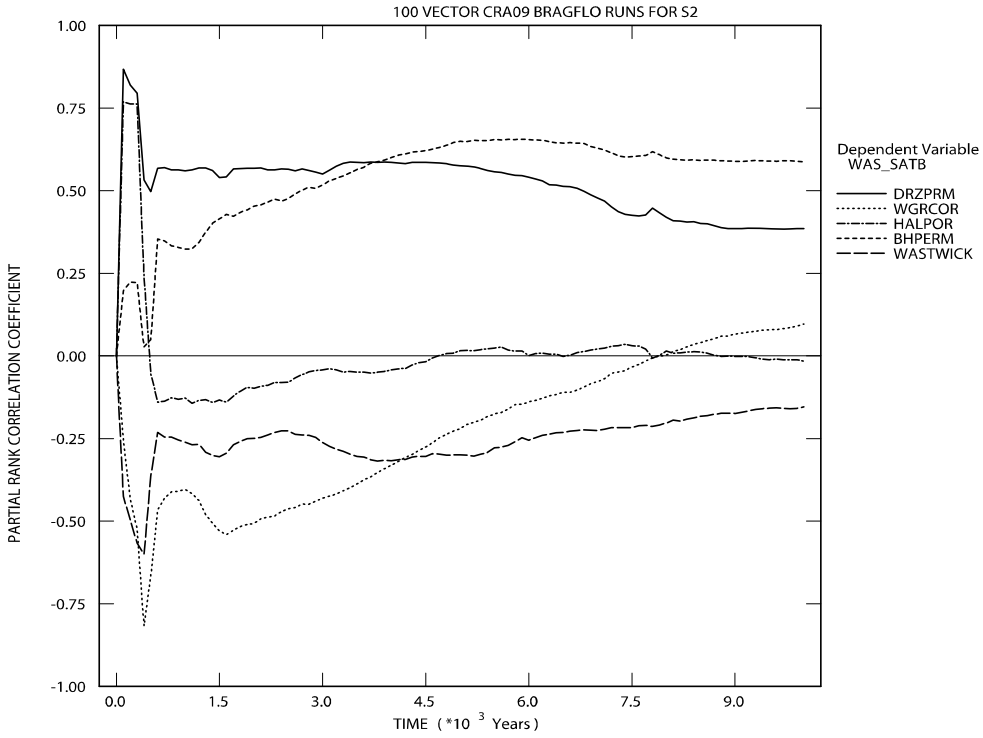


Figure PA-56. Primary Correlations of Brine Saturation in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S2, CRA-2009 PA

the waste wicking parameter (WASTWICK) are negatively correlated with the saturation, as these control the brine-consuming reactions. The halite porosity (HALPOR) has a high positive correlation before the intrusion, which then decreases.

For Scenario S4 (Figure PA-57), the largest positive correlation results from borehole permeability (BHPERM), with the DRZ permeability (DRZPRM), anhydrite permeability (ANHPRM), and the halite porosity (HALPOR) also showing high positive correlations. Increases in DRZ, borehole, and anhydrite permeability accelerate brine flow into the waste, while increases in halite porosity increase the volume of brine available in the material overlying the waste, all of which control the amount of brine flow into and out of the repository. The corrosion rate for steel (WGRCOR) is negatively correlated with the saturation, as this is a brine-consuming reaction.

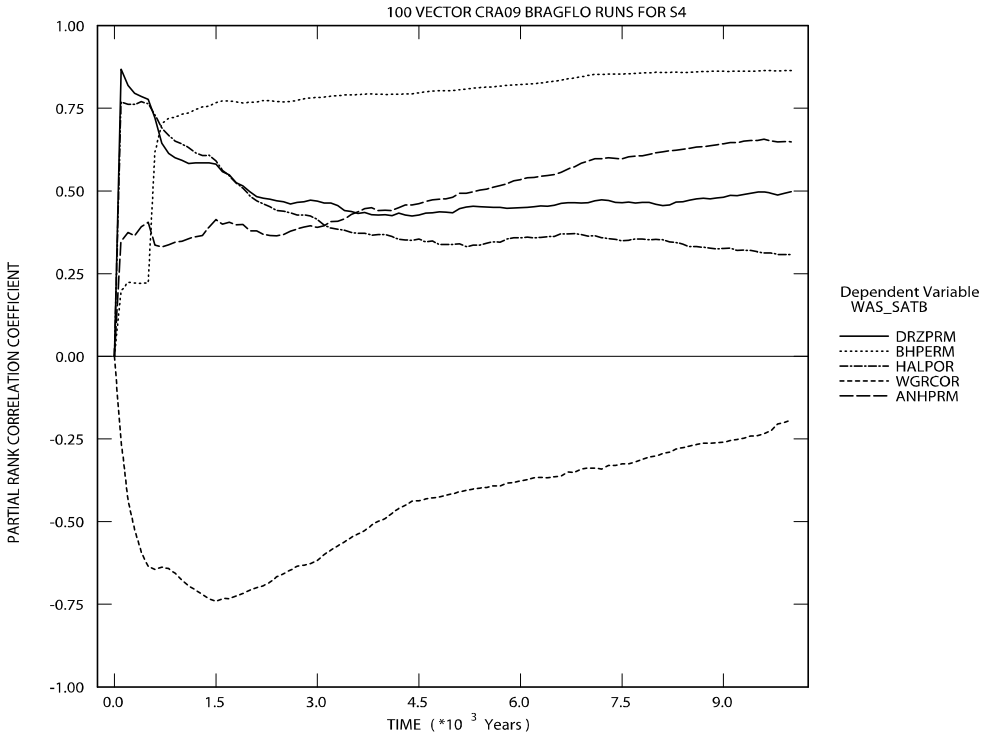


Figure PA-57. Primary Correlations of Brine Saturation in the Waste Panel Region with Uncertain Parameters, Replicate R1, Scenario S4, CRA-2009 PA

PA-8.3.3 Brine Flow out of the Repository

This section describes the flow of brine up a borehole to the Culebra. Brine flow to the Culebra is important in calculating long-term releases to the Culebra. Direct brine flow up the borehole to the surface at the time of drilling is modeled separately in the DBR calculations, presented in Section PA-8.5.3.

Figure PA-58 shows cumulative brine flow out of the repository (BRNREPOC) for Scenario S2. Scenario S2 represents an E1 intrusion at 350 years. At the time of the intrusion, brine flow from the Castile brine reservoir fills the repository. At 200 years after the intrusion, when the

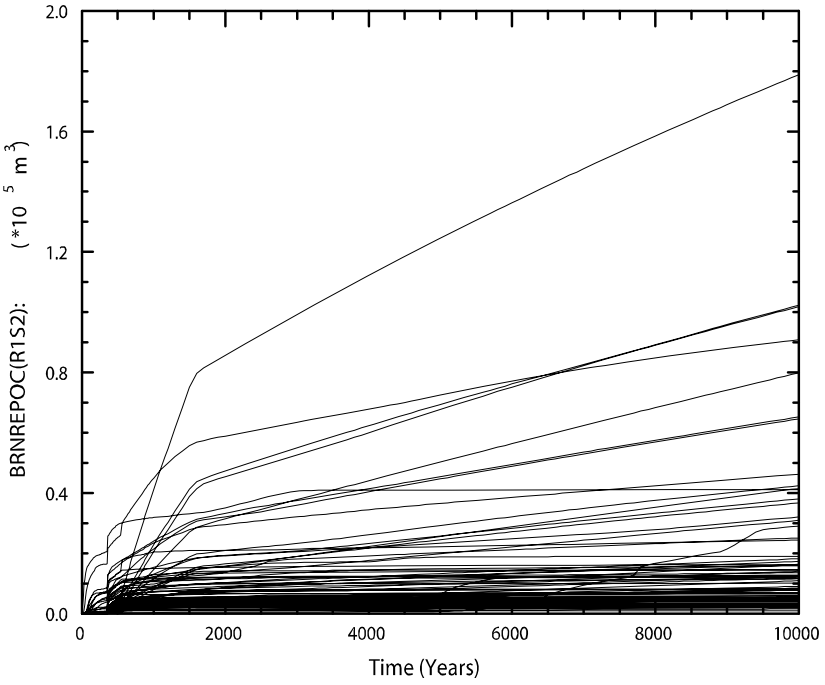


Figure PA-58. Total Cumulative Brine Outflow in Replicate R1, Scenario S2, CRA-2009 PA

borehole plugs above the repository are assumed to fail and the permeability of the borehole generally increases, most of the brine leaving the repository flows up the borehole to the Culebra. In vectors with low borehole permeability, the brine flow out of the repository does not noticeably change as a result of the borehole plug failure. Twelve hundred years after the drilling intrusion, the permeability of the borehole between the repository and the Castile is reduced by an order of magnitude because of creep closure, reducing brine flow into the repository and causing a corresponding decrease in brine flow out of the repository. This material change reduces brine flow out of the repository in some vectors, but does not appear to have a significant effect on the brine flow out of the repository in most vectors.

Figure PA-59 shows the volumes of brine that cross the LWB through the MBs for Scenario S2. The largest outflow across the LWB is ~127 m^3, which is significantly less than the undisturbed scenario results (see Section PA-7.1.3). As the intrusion creates a pathway to the Culebra, flow to the LWB is reduced. Brine crossing the LWB or moving up the shaft does not necessarily indicate releases from the repository because the brine may not have been in contact with the waste; the brine may have been present in the MBs at the start of the regulatory period. Section PA-8.4 presents the results of the radionuclide transport calculations that determine the amount of radionuclides that may be released by transport in brine for the disturbed scenarios.

The total cumulative brine flow away from the repository and the brine flow across the LWB in the disturbed scenarios for the CRA-2009 PA are similar to the results obtained for the CRA-2004 PABC. The average and maximum brine flows are comparable between the two analyses as well (see Nemer and Clayton [2008, Table 6-18]). As the intrusion creates a pathway for brine and gas to flow into and away from the repository, the effect of the increased porosity is minimized (Nemer and Clayton 2008).

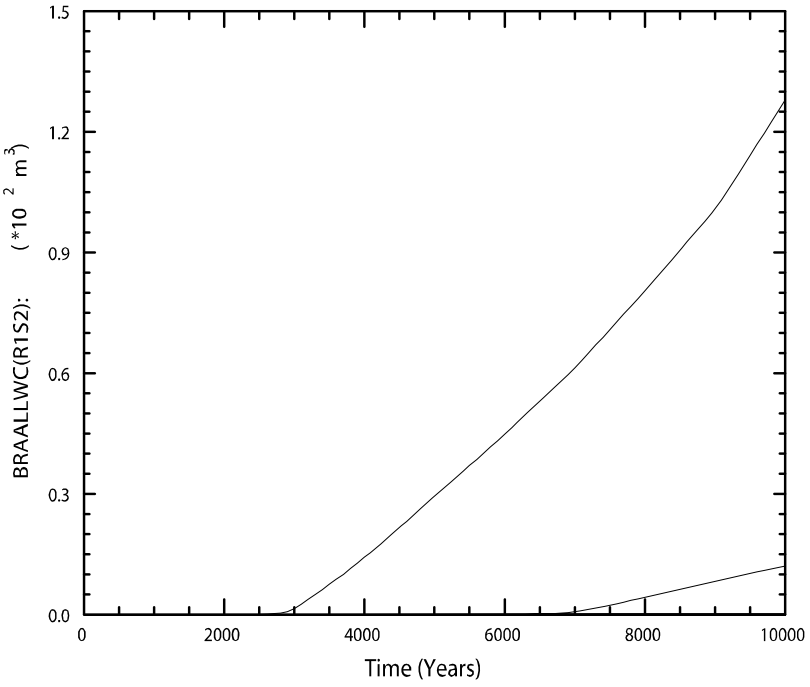


Figure PA-59. Brine Flow via All MBs Across the LWB in Replicate R1, Scenario S2, CRA-2009 PA

Figure PA-60 shows cumulative brine flow out of the repository (BRNREPOC) for the BRAGFLO Scenario S4, which represents an E2 intrusion at 350 years. The results for the S4 scenario are very similar to the results for the Undisturbed Scenario S1 (see Section PA-7.1.3).

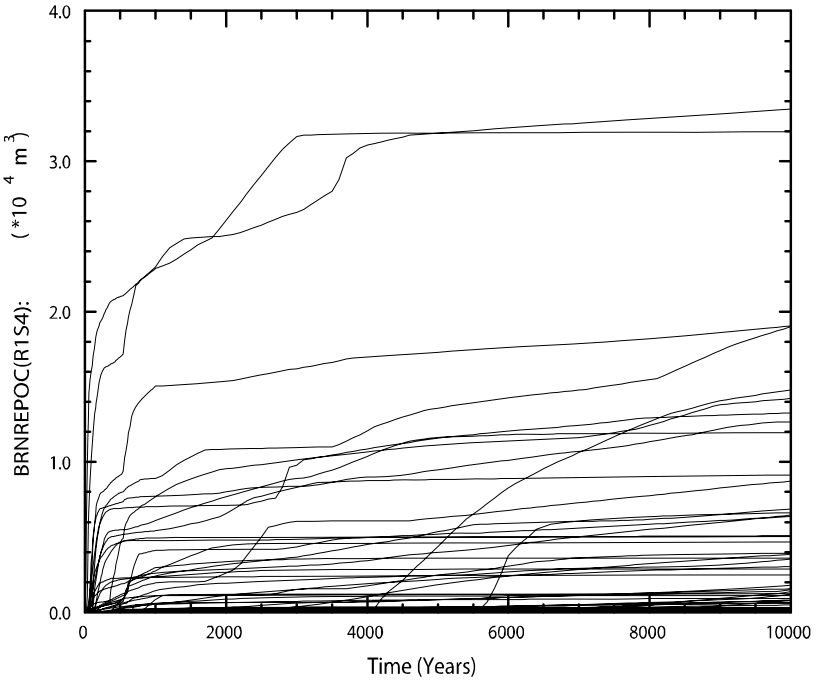


Figure PA-60. Total Cumulative Brine Outflow in Replicate R1, Scenario S4, CRA-2009 PA

Figure PA-61 shows the volumes of brine that cross the LWB through the MBs for the BRAGFLO Scenario S4. The largest outflow across the LWB is ~1,200 m^3, which is smaller than the undisturbed scenario results (see Section PA-7.1.3). As the intrusion creates a pathway to the Culebra, flow to the LWB is reduced. Brine crossing the LWB or moving up the shaft does not necessarily indicate releases from the repository, since the brine may not have been in contact with the waste; the brine may have been present in the MBs at the start of the regulatory period. Section PA-8.4 presents the results of the radionuclide transport calculations that determine the amount of radionuclides that may be released by transport in brine for the disturbed scenarios.

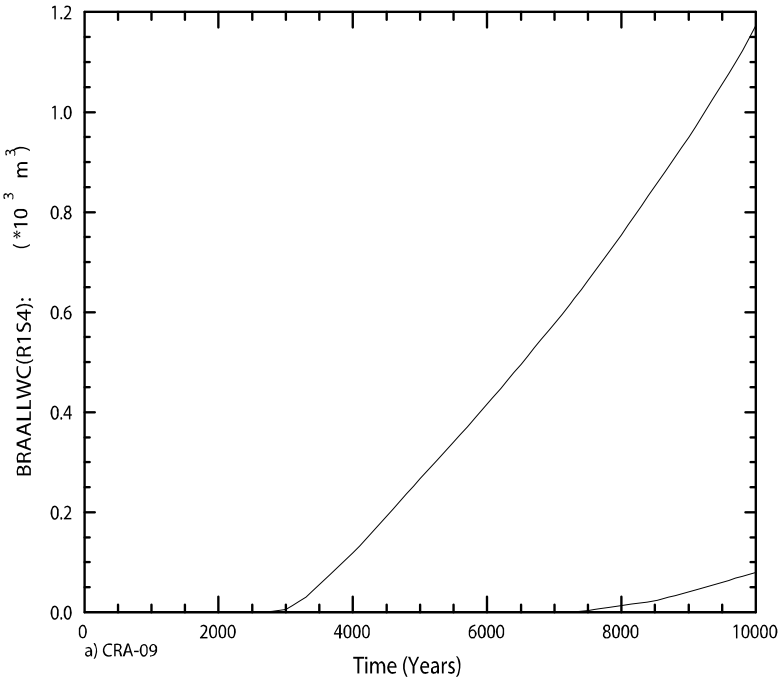


Figure PA-61. Brine Flow via All MBs Across the LWB in Replicate R1, Scenario S4, CRA-2009 PA

Regression between total cumulative brine flow out of the waste-filled regions (BRNREPOC) and the uncertain parameters are shown in Figure PA-62 and Figure PA-63 for the BRAGFLO Scenarios S2 and S4, respectively. For the S2 and S4 scenarios, the permeability of the DRZ (DRZPRM), the borehole permeability (BHPERM), and the porosity of undisturbed halite (HALPOR) have positive correlations. Increases in the DRZ and borehole permeability allow more brine to flow out of the repository. The increase in the halite porosity is correlated with the increase in pressure, and an increase in pressure increases the amount of brine flow out of the repository.

A negative correlation with the waste residual brine saturation (WRBRNSAT) is shown for both the S2 and S4 scenarios, which determines the immobile portion of the waste brine saturation, limiting the amount of brine that can flow out of the waste-filled regions. The permeability of the concrete panel seal (CONPRM) is negatively correlated for the S2 scenario and positively

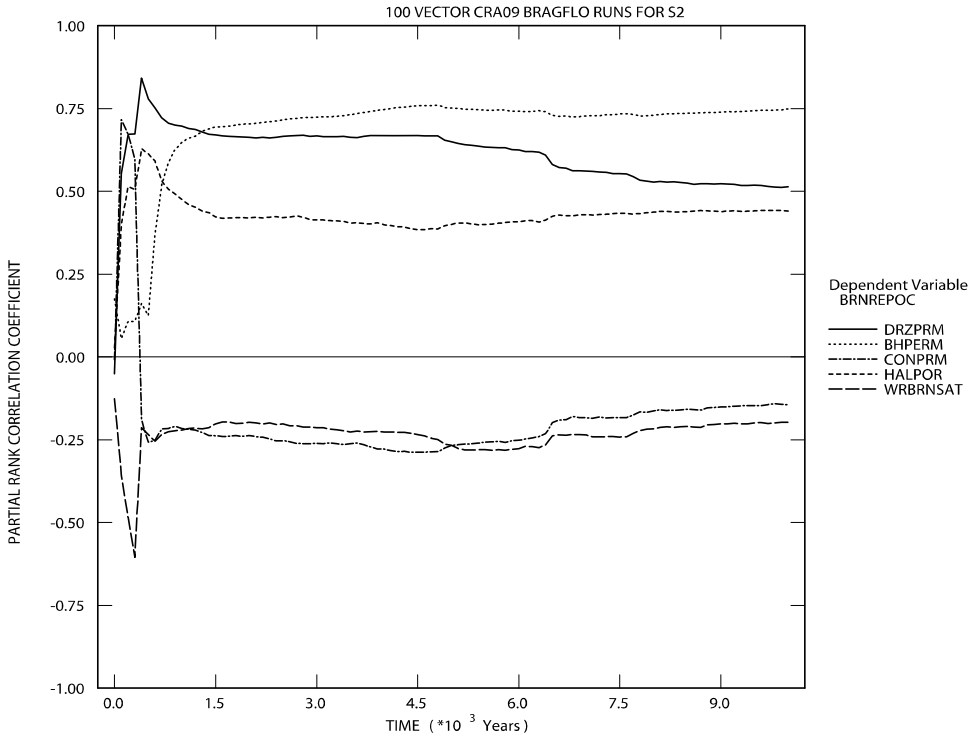


Figure PA-62. Primary Correlations of Cumulative Brine Flow Away from the Repository with Uncertain Parameters, Replicate R1, Scenario S2, CRA-2009 PA

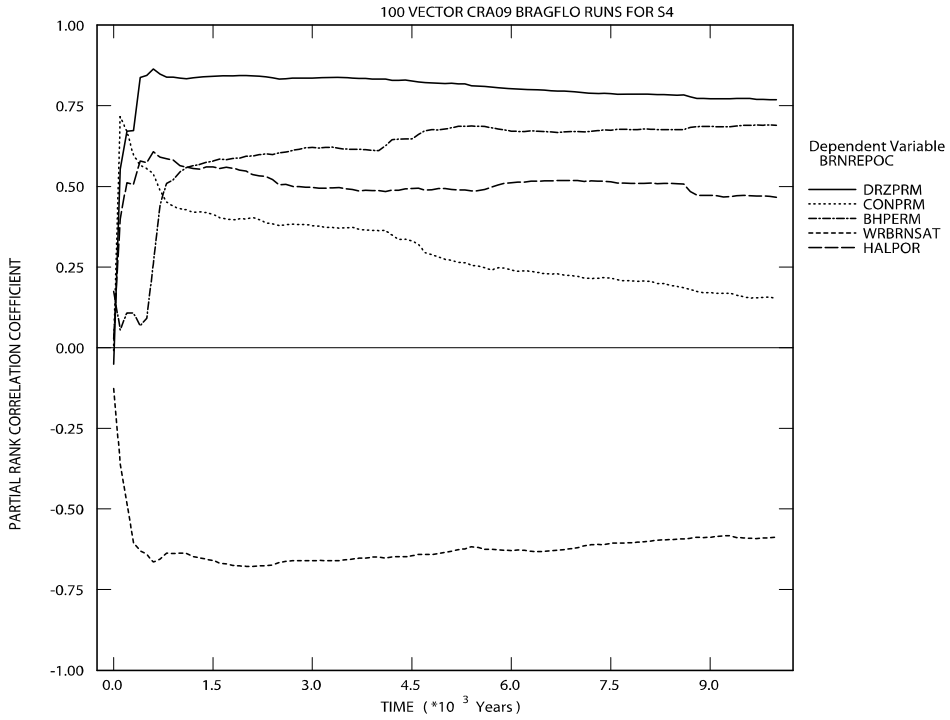


Figure PA-63. Primary Correlations of Cumulative Brine Flow Away from the Repository with Uncertain Parameters, Replicate R1, Scenario S4, CRA-2009 PA

correlated for the S4 scenario. The increased permeability of the concrete panel seal allows more brine to flow from the intruded panel to the remainder of the repository (flow into another panel is not considered out of the repository), reducing the higher-pressure conditions in the intruded panel in the S2 scenario, and therefore the flow out of the repository through the borehole. In contrast, in the S4 scenario, the increased permeability allows the brine from the remainder of the repository to flow into the depressurized intruded panel, increasing the pressure and flow out of the repository up the borehole.

PA-8.4 Radionuclide Transport

In the disturbed scenarios, radionuclide transport in the Salado is calculated by the code NUTS (see Section PA-6.7.2). Radionuclide transport from the Salado to the Culebra is calculated by NUTS and PANEL (see Section PA-6.7.2 and Section PA-6.7.3). Radionuclide transport within the Culebra is calculated by SECOTP2D (see Section PA-6.7.8). For all radionuclide transport calculations, mobilized concentrations of radionuclides in Salado and Castile brines are computed by the code PANEL (see Section PA-6.7.3).

This section summarizes the radionuclide transport results for the disturbed scenarios. Nemer and Clayton (2008) describe the brine and gas flow in the Salado. Detailed analysis of the radionuclide transport in the Salado is presented in Ismail and Garner (2008). Garner and Leigh (2005) provide an analysis of the mobilized concentrations of radionuclides in Salado and Castile brines. Lowry and Kanney (2005) present an analysis of the flow and radionuclide transport within the Culebra.

PA-8.4.1 Radionuclide Source Term

The code PANEL calculates the time-varying concentration of radionuclides mobilized in brine, either as dissolved isotopes or as isotopes sorbed to mobile colloids (see Equation (PA.118) and Equation (PA.119)). Two different brines are considered: Generic Weep Brine (GWB), a magnesium-rich interstitial brine present in the Salado Formation; and ERDA-6, a sodium-rich brine in the Castile. Radionuclide solubility in the two brines can be considerably different. Before an E1 intrusion, PA assumes that the brine in the repository is GWB; after an E1 intrusion, brine in the repository is assumed to be ERDA-6.

Figure PA-64 and Figure PA-65 show the concentration of radioactivity mobilized in Salado and Castile brines, respectively, as a function of time for all vectors in Replicate R1 for the CRA-2009 PA. Because the inventory is unchanged from the CRA-2004 PABC, the results are identical to the CRA-2004 PABC results. Concentrations are expressed as EPA units/m^3 to combine the radioactivity in different isotopes and reduce the computational time required for the transport calculations.

Short-lived radionuclides, such as ^{238}Pu, decay rapidly in the first few years. After this initial decay, the mobilized concentration is dominated by Am (Garner and Leigh 2005); the concentration of Am is limited by its solubility until all the inventory of Am is in solution. After all Am is in solution, the total radionuclide concentration generally decreases as the Am decays, until the mobilized concentration becomes dominated by Pu (Garner and Leigh 2005). The

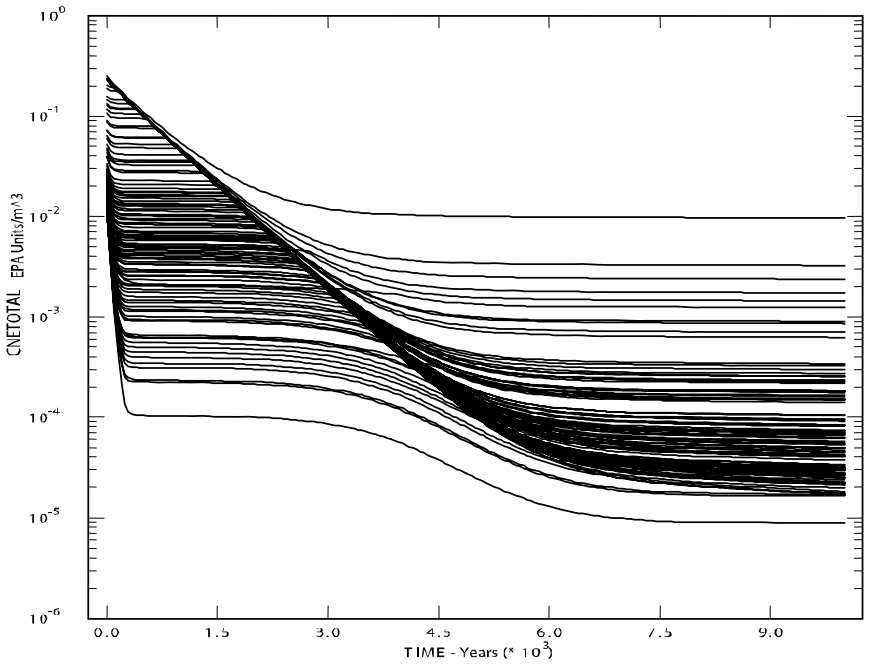


Figure PA-64. Total Mobilized Concentrations in Salado Brine, Replicate R1, CRA-2009 PA

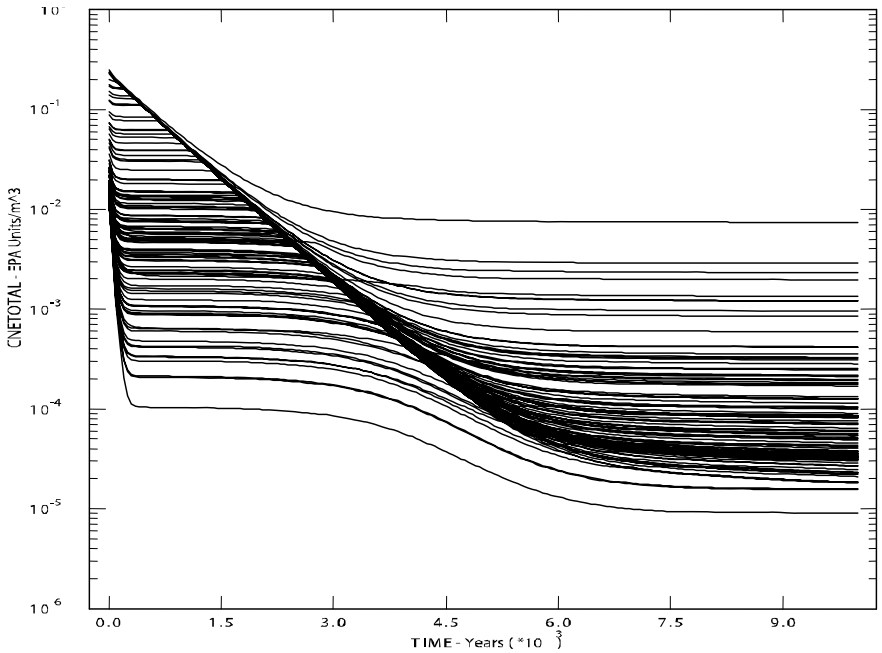


Figure PA-65. Total Mobilized Concentrations in Castile Brine, Replicate R1, CRA-2009 PA

horizontal lines in the figures indicate periods of time when the total radionuclide concentration is limited by the solubility of Am (before about 3,000 years) or Pu (after about 6,000 years). Thus, the uncertainty in total radionuclide concentration is determined by the uncertainty factors used to calculate solubilities for Am and Pu.

PA-8.4.2 Transport through MBs and Shaft

In the disturbed scenarios, of the 300 realizations, only Vectors 53 and 59 in Replicate R1 resulted in transport of radionuclides through the MBs and across the LWB, with a maximum total integrated activity of 3.6×10^{-10} EPA units (Ismail and Garner 2008). This is comparable to the CRA-2004 PABC results for maximum integrated activity, which had 2.4×10^{-12} EPA units at the boundary (Lowry 2005). The releases through the MBs and across the LWB are insignificant compared to releases from drilling intrusions. In addition, no realization showed transport of radionuclides through the shaft to the Culebra.

PA-8.4.3 Transport to the Culebra

Radionuclide transport to the Culebra via a single intrusion borehole (Disturbed Scenarios S2, S3, S4, and S5) is modeled with the code NUTS (Section PA-4.3). Transport to the Culebra in the multiple intrusion scenario (S6) is modeled with the code PANEL (Section PA-4.4). Detailed discussion of the radionuclide transport to the Culebra calculations can be found in Ismail and Garner (2008).

PA-8.4.3.1 Single Intrusion Scenarios

Figure PA-66 through Figure PA-69 show cumulative radioactivity transported up the borehole to the Culebra in the single intrusion scenarios. Transport to the Culebra is larger and occurs for more vectors in the S2 and S3 scenarios (E1 intrusions) than in the S4 or S5 scenarios (E2 intrusions). For most vectors that show significant transport, most of the transport occurs over a relatively short period of time immediately after the borehole plugs fail.

When compared to the results of the CRA-2004 PABC, the CRA-2009 PA showed minor differences (see Ismail and Garner [2008, Section 4.2.4]). The primary changes from the CRA-2004 PABC to the CRA-2009 PA that affected the calculations of transport to the Culebra are the correction of the input files (Ismail 2007b) and the correction of the halite porosity (Ismail 2007a). Neither change significantly affected the results (Ismail and Garner 2008).

PA-8.4.3.2 Multiple Intrusion Scenario

Figure PA-70 shows total EPA units transported to the Culebra via the borehole in the S6 scenario. Only two vectors show radionuclide transport after the E2 intrusion at 1,000 years; most radionuclide transport occurs immediately following the E1 intrusion at 2,000 years. The results from the CRA-2009 PA are almost identical to the results from the CRA-2004 PABC (see Ismail and Garner [2008, Section 4.3.2]). As the disturbed results from BRAGFLO are similar and the source term for the two calculations are the same, it follows that the radionuclide transport to the Culebra results would be the same (Ismail and Garner 2008).

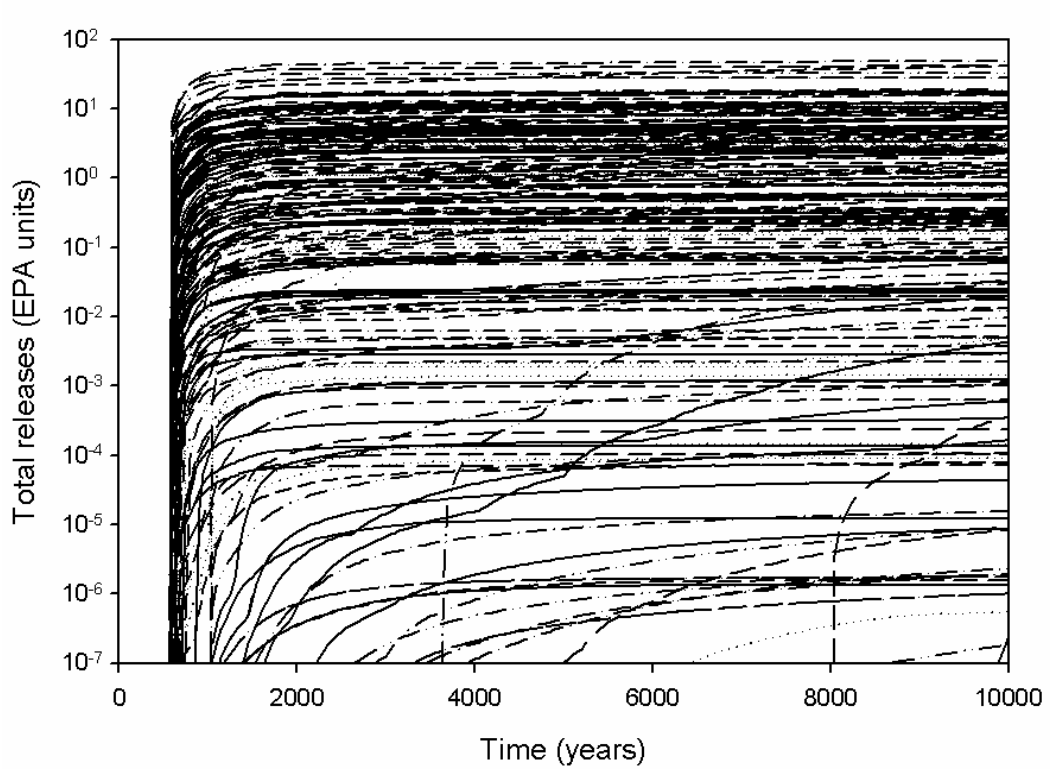


Figure PA-66. Cumulative Normalized Release to the Culebra, Scenario S2, CRA-2009 PA

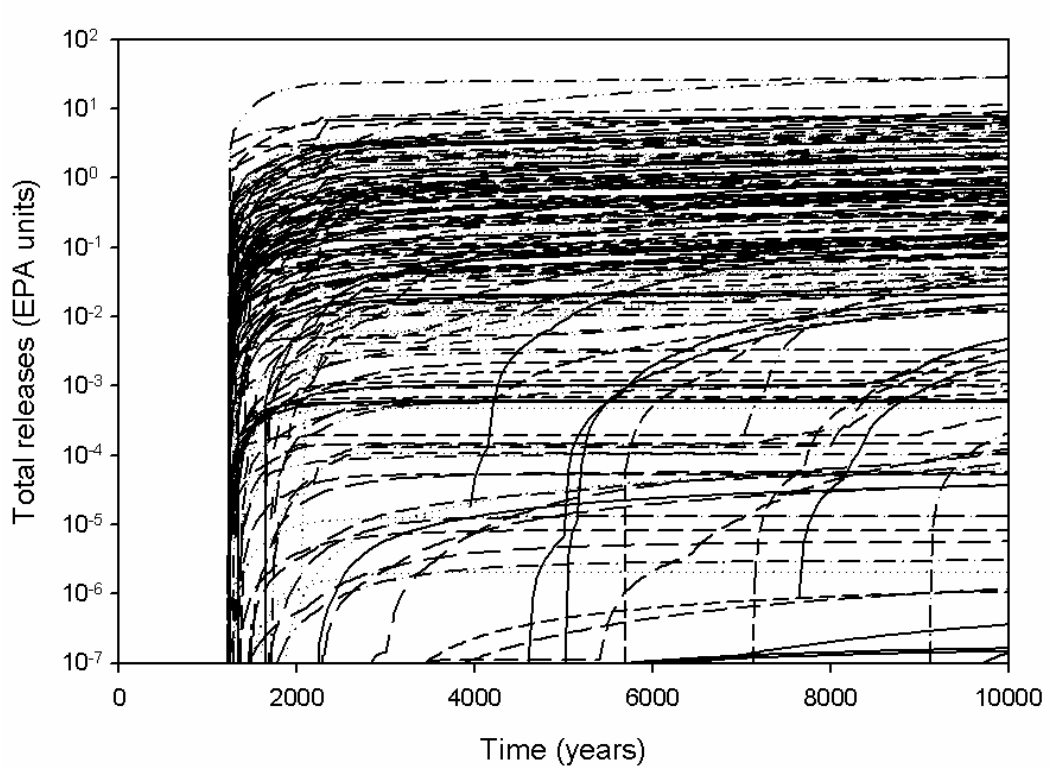


Figure PA-67. Cumulative Normalized Release to the Culebra, Scenario S3, CRA-2009 PA

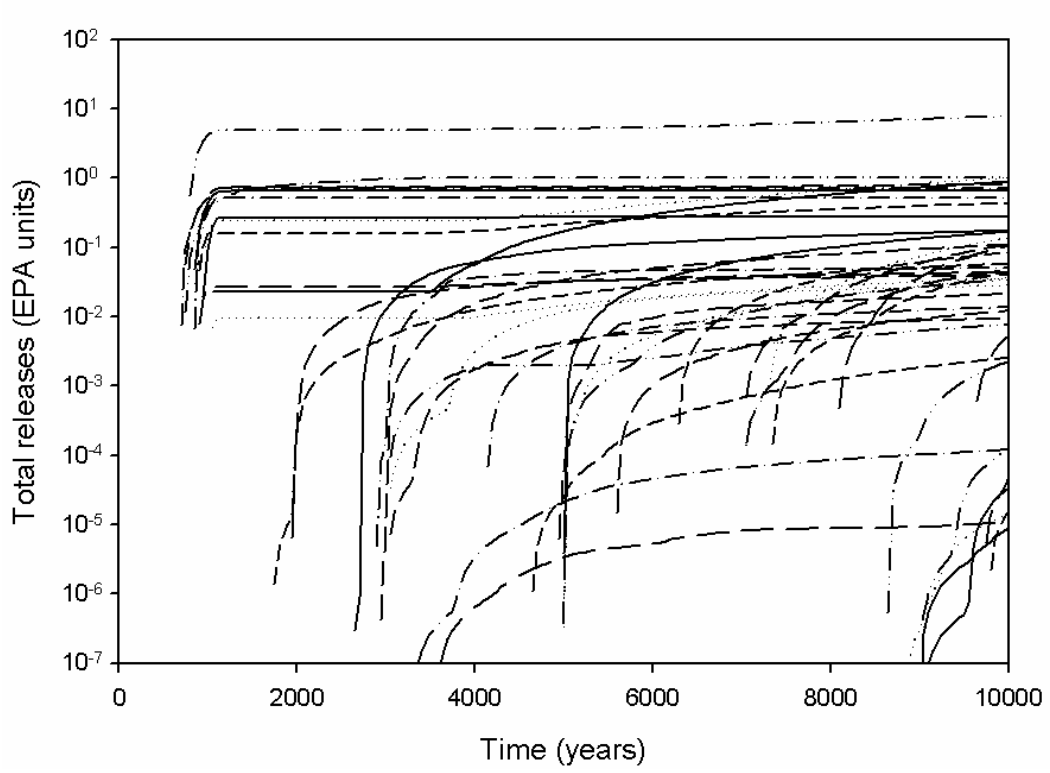


Figure PA-68. Cumulative Normalized Release to the Culebra, Scenario S4, CRA-2009 PA

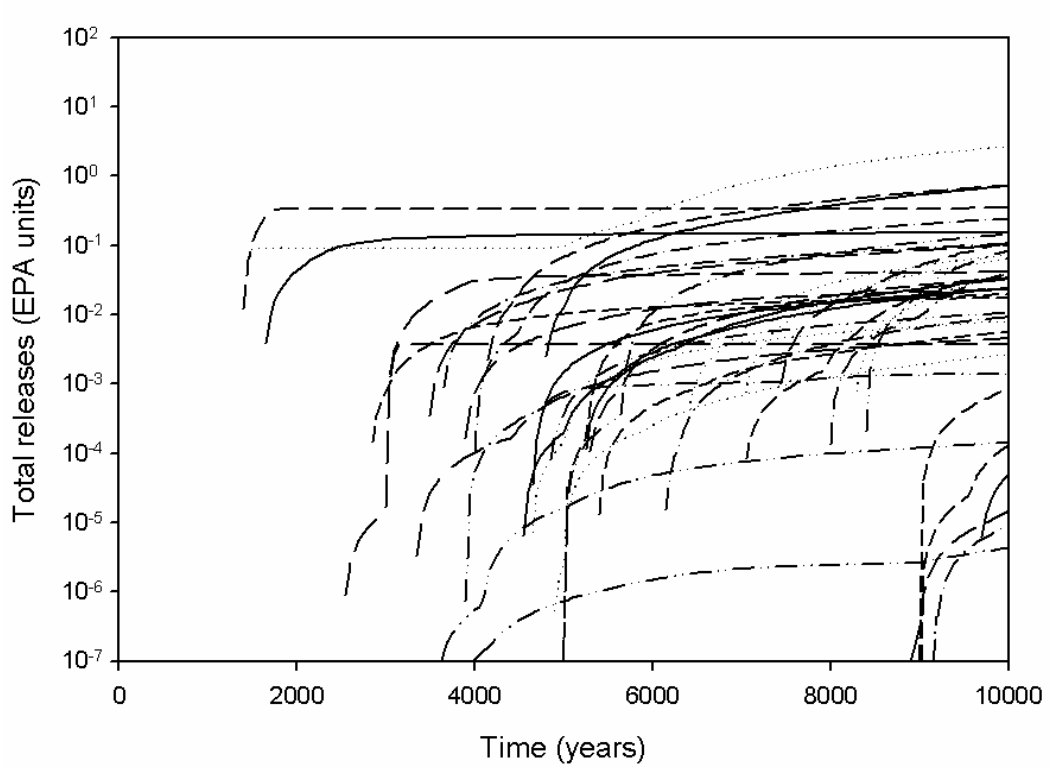


Figure PA-69. Cumulative Normalized Release to the Culebra, Scenario S5, CRA-2009 PA

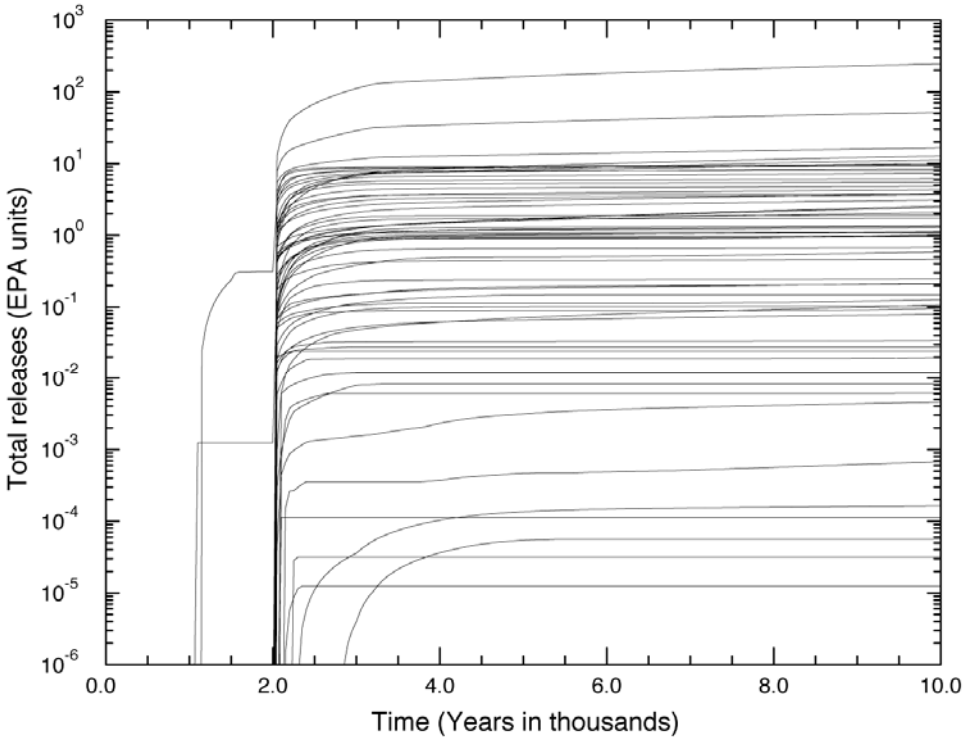


Figure PA-70. Cumulative Normalized Release to the Culebra, Replicate R1, Scenario S6, CRA-2009 PA

PA-8.4.4 Transport Through the Culebra

Radionuclide transport through the Culebra for a given set of uncertain parameters is calculated with the code SECOTP2D (see Section PA-6.7.8). Note that the total release of radionuclides across the LWB at the Culebra for given futures is calculated with the code CCDFGF by convolving the SECOTP2D results with the radionuclide transport to the Culebra calculated by NUTS and PANEL. This section discusses the SECOTP2D results; total releases through the Culebra are presented in Section PA-9.4. As none of the changes implemented for the CRA-2009 PA affected the Culebra flow and transport calculations, the results from the CRA-2004 PABC Culebra flow and transport calculations were used in the CRA-2009 PA.

Culebra radionuclide transport calculations were performed for three replicates of 100 vectors each for both partial-mining and full-mining scenarios (600 total simulations). Each of the 600 radionuclide transport simulations used a unique flow field computed separately with the code MODFLOW (see Section PA-6.7.7 and Lowry and Kanney [2005]). The partial-mining scenario assumes the extraction of all potash reserves outside the LWB, while the full-mining scenario assumes that all potash reserves both inside and outside the LWB are exploited.

In each radionuclide transport simulation, 1 kg of each of four radionuclides (^{241}Am, ^{234}U, ^{230}Th, and ^{239}Pu) are released in the Culebra above the center of the waste panel area. Radionuclide transport of the ^{230}Th daughter product of ^{234}U decay is calculated and tracked as a separate species. In the following discussion, ^{230}Th will refer to the ^{234}U daughter product and ^{230}ThA will refer to that released at the waste panel area.

All SECOTP2D results, regardless of magnitude, are included in the calculation of releases through the Culebra. In practice, most nonzero releases computed by SECOTP2D are vanishingly small and result from numerical dispersion (Lowry and Kanney 2005). Consequently, the analysis of SECOTP2D results focused on realizations in which at least one billionth (10^{-9}) of the 1-kg source was transported to the LWB.

More detailed information on the results of the Culebra radionuclide transport calculations can be found in the Analysis Package for the Culebra Flow and Transport Calculations: Compliance Recertification Application Performance Assessment Baseline Calculations (Lowry and Kanney 2005).

PA-8.4.4.1 Partial Mining Results

Under partial-mining conditions, only the ^{234}U species and its ^{230}Th decay product were transported to the LWB in any significant amount during the course of the 10,000-year simulation (Lowry and Kanney 2005). Table PA-30 shows that no releases greater than one billionth of the 1-kg source were calculated for Replicates R1 and R3. For Replicate R2, 3 vectors produced ^{234}U releases greater than 10^{-9} kg. One of the 3 vectors also resulted in a ^{230}Th release greater than 10^{-9} kg. These results are identical to the CRA-2004 PABC results.

Table PA-30. Number of Realizations with Radionuclide Transport to the LWB Under Partial-Mining Conditions[a,b]

Replicate	^{241}Am	^{239}Pu	^{234}U	^{230}Th	^{230}ThA
R1	0	0	0	0	0
R2	0	0	3	1	0
R3	0	0	0	0	0

[a] Number of vectors that have releases (transport to LWB) greater than one billionth of the 1-kg source released at center of waste panel.
[b] ^{230}ThA refers to Th released at the waste panel area. ^{230}Th refers to thorium resulting from ^{234}U decay.

Sensitivity analysis indicates that releases of ^{234}U in the partial-mining condition is associated with the VI oxidation state (Lowry and Kanney 2005; Kanney 2003). This result is reasonable because the matrix distribution coefficients for U in the IV state are much lower than for the VI state.

PA-8.4.4.2 Full Mining Results

Under full-mining conditions, only the ^{234}U species and its ^{230}Th decay product were transported to the LWB in any significant amount during the course of the 10,000-year simulation. More vectors resulted in releases greater than 10^{-9} kg for the full-mining scenario than were seen under partial-mining conditions. In addition, releases greater than 10^{-9} kg were calculated for all three replicates. Table PA-31 shows that 3 vectors in Replicate R1, 6 vectors in Replicate R2, and 3 vectors in Replicate R3 had ^{234}U releases greater than 10^{-9} kg. None of the 3 vectors in Replicate R1, 3 of the 6 in Replicate R2, and 1 of the 3 in Replicate R3 showed a

Table PA-31. Number of Realizations with Radionuclide Transport to the LWB Under Full-Mining Conditions[a,b]

Replicate	^{241}Am	^{239}Pu	^{234}U	^{230}Th	^{230}ThA
R1	0	0	3	0	0
R2	0	0	6	3	0
R3	0	0	3	1	0

[a] Number of vectors that have releases (transport to LWB) greater than one billionth of the 1-kg source released at center of waste panel.
[b] ^{230}ThA refers to Th released at the waste panel area. ^{230}Th refers to Th resulting from ^{234}U decay.

release of the ^{230}Th daughter product greater than 10^{-9} kg. These results are identical to the CRA-2004 PABC results.

Sensitivity analysis indicates that releases of ^{234}U in the full-mining condition is associated with the VI oxidation state (Lowry and Kanney 2005, Kanney 2003). This result is reasonable because the matrix distribution coefficients for U in the IV state are much lower than for the VI state.

PA-8.5 Direct Releases

Direct releases occur at the time of a drilling intrusion, and include cuttings and cavings, spallings, and DBRs. This section presents an analysis of the volume released by each mechanism.

Ismail (2008) provides additional information about the cuttings, cavings, and spallings releases calculated for the CRA-2009 PA. Clayton (2008b) provides a detailed analysis of DBRs in the CRA-2009 PA.

PA-8.5.1 Cuttings and Cavings

Cuttings and cavings are the solid waste material removed from the repository and carried to the surface by the drilling fluid during borehole drilling. Cuttings are the materials removed directly by the drill bit, and cavings are the material eroded from the walls of the borehole by shear stresses from the circulating drill fluid. The volume of cuttings and cavings material removed from a single drilling intrusion into the repository is assumed to be in the shape of a cylinder. The code CUTTINGS_S calculates the area of the base of this cylinder, and cuttings and cavings results in this section are reported in terms of these areas. The volumes of cuttings and cavings removed can be calculated by multiplying these areas with the initial repository height 3.96 m (BLOWOUT:HREPO).

Cuttings and cavings areas calculated for the CRA-2009 PA range between 0.076 m^2 and 0.86 m^2, with a mean area of 0.25 m^2 (Table PA-32). None of the changes implemented in the CRA-2009 PA affect the cuttings and cavings calculations, so the results are identical to the CRA-2004 PABC results (Ismail 2008).

Two uncertain sampled parameters affect the cavings calculations. The uncertainty in cavings areas arises primarily from the uncertainty in the shear strength of the waste (Ismail 2008). Lower shear strengths tend to result in larger cavings (Ismail 2008, Figure 1). The uncertainty in the drill string angular velocity has a smaller impact on the cavings results, but the combination of a low angular velocity and high shear strength can prohibit cavings from occurring (Figure PA-71). In fact, cavings did not occur in 10% of all vectors (Table PA-32).

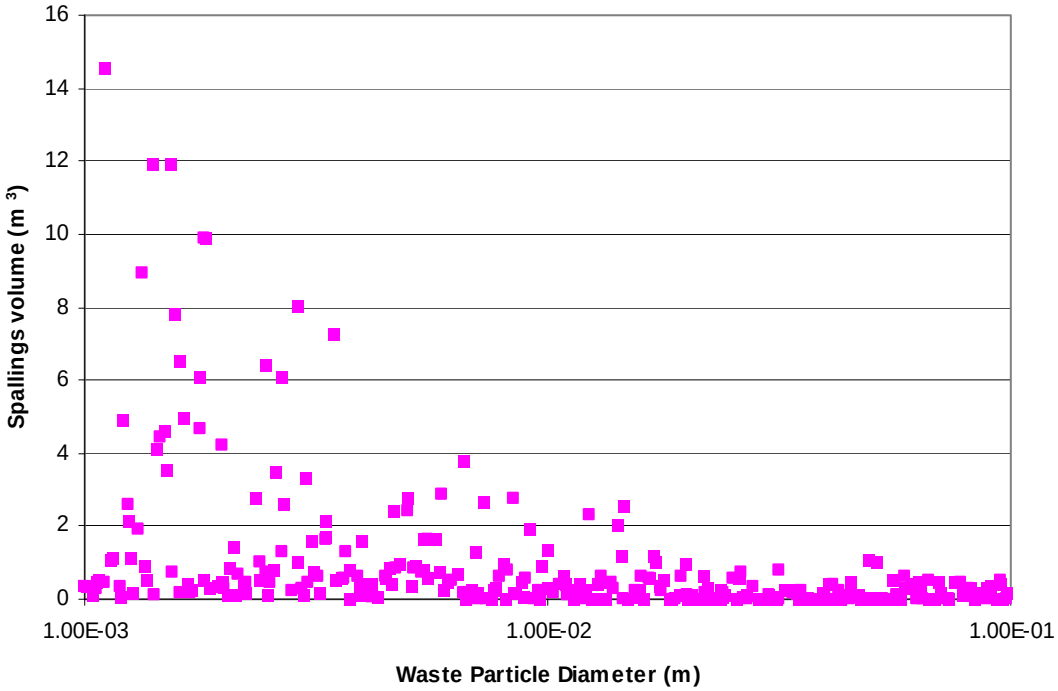


Figure PA-71. Scatterplot of Waste Particle Diameter Versus Spallings Volume, CRA-2009 PA

Table PA-32. CRA-2009 PA Cuttings and Cavings Area Statistics

Replicate	Minimum (m^2)	Maximum (m^2)	Mean (m^2)	Vectors Without Cavings
R1	0.076	0.82	0.25	9
R2	0.076	0.86	0.25	10
R3	0.076	0.83	0.25	11

PA-8.5.2 Spallings

Calculating the volume of solid waste material released to the surface due to spallings from a single drilling intrusion into the repository is a two-part procedure. The code DRSPALL calculates the spallings volumes from a single drilling intrusion at four values of repository pressure (10, 12, 14, and 14.8 MPa). Following this, spallings volumes from a single intrusion are calculated using the code CUTTINGS_S; this code linearly interpolates the spallings volumes calculated using DRSPALL, based on the pressure calculated by BRAGFLO. Results from both of these calculations are documented in this section.

PA-8.5.2.1 DRSPALL Results

None of the changes implemented in the CRA-2009 PA affect the DRSPALL calculations, so the results from the CRA-2004 PABC were used in the CRA-2009 PA. In the CRA-2004 PABC, the code DRSPALL was run for each of 100 vectors in 3 replicates and for 4 values of repository pressure (10, 12, 14, and 14.8 MPa, see Section PA-4.6.4). No spallings occurred at 10 MPa for any vector.

The uncertainty in the spallings volumes arises from four uncertain variables in the DRSPALL calculations: waste permeability, waste porosity, waste tensile strength, and waste particle diameter after tensile failure (Table PA-15). Figure PA-72 indicates that the largest spallings volumes occur when waste permeability is less than 1.0×10^{-13} m^2, but larger permeability values result in a higher frequency of nonzero spallings volumes. This observation can be explained as follows: the higher permeability values sampled result in smaller tensile stresses and less tensile failure, but promote fluidization. Lower permeability leads to greater tensile stresses and tensile failure, but failed material may not be able to fluidize at this low permeability.

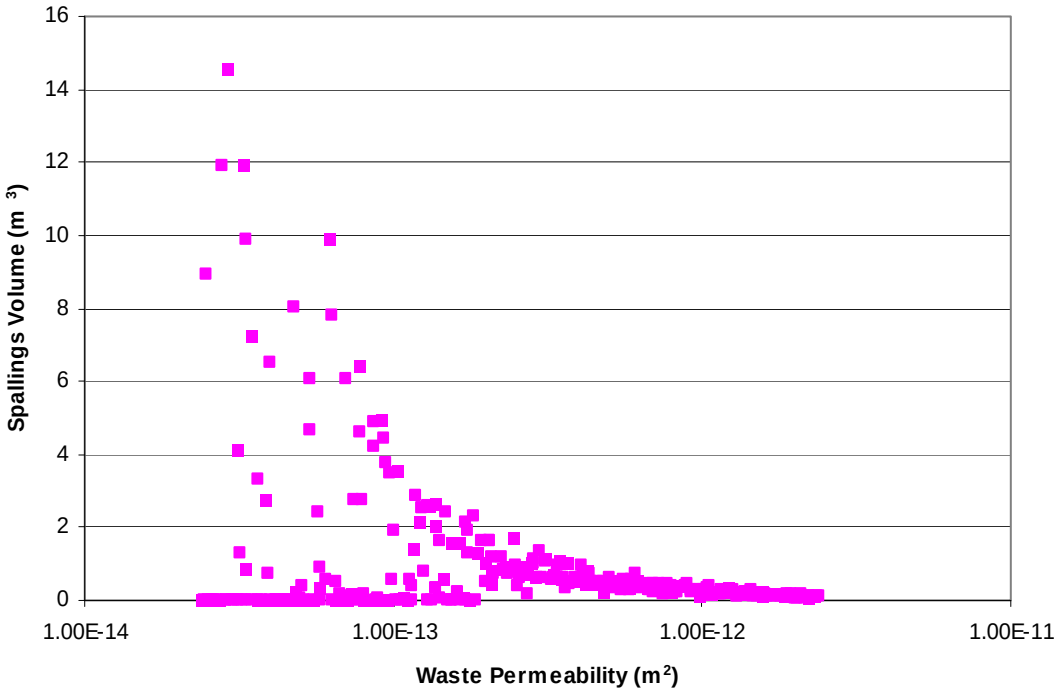


Figure PA-72. Scatterplot of Waste Permeability Versus Spallings Volume, CRA-2009 PA

Smaller particle diameter values (see Figure PA-71) tend to result in larger spallings volumes and a higher frequency of nonzero spallings volumes. The uncertainty in the spallings volumes from a single intrusion is largely determined by the uncertainty in these two parameters. Obvious correlations between spallings volumes and the other two parameters could not be established.

PA-8.5.2.2 CUTTINGS_S Results

Two factors directly affect the CUTTINGS_S calculation of spallings volumes for the drilling scenarios: the volumes calculated by DRSPALL and the repository pressures calculated by BRAGFLO.

Table PA-33 summarizes the statistics for the CRA-2009 PA spallings volumes. Of the 7,800 (26 intrusion time-scenario combinations × 3 drilling locations × 100 vectors) spallings volumes calculated per replicate, more than 92% of each replicate's calculations resulted in no spallings. Only about a third of the vectors in each replicate had spallings occur in at least one of the scenarios; therefore, spallings will not contribute to the total releases calculated for the other vectors.

Table PA-33. CRA-2009 PA Spallings Volume Statistics

Scenario	# of Calculations	Maximum Volume (m^3)			Average Volume (m)			Number of Nonzero Volumes		
		R1	R2	R3	R1	R2	R3	R1	R2	R3
S1	1,800	2.52	2.52	5.33	0.10	0.10	0.17	158	177	183
S2	1,500	8.31	2.87	6.32	0.14	0.12	0.12	120	135	122
S3	1,500	7.99	2.13	3.15	0.12	0.10	0.09	129	138	133
S4	1,500	1.67	2.40	1.99	0.04	0.07	0.04	69	64	56
S5	1,500	1.67	2.20	3.00	0.07	0.09	0.06	91	93	91
All	7,800	8.31	2.87	6.32	0.09	0.10	0.10	564	607	585

Scenarios S2 and S3 resulted in the largest maximum spallings volume, while Scenarios S1, S2, and S3 resulted in the largest average spallings volume. For the CRA-2009 PA, Scenarios S2 and S3 have the highest maximum pressures because in these scenarios, the drill bit intrudes into a pressurized brine pocket (Nemer and Clayton 2008). These higher pressures lead to larger spallings volumes. Scenarios S4 and S5 resulted in the lowest maximum and average volumes as, in general, these scenarios have the lowest pressure (see Section PA-8.3.1). Scenario S1 resulted in the largest number of nonzero spallings volumes per time intrusion. Without a prior intrusion creating a pathway for brine and gas flow to decrease the pressure, there are more vectors that result in pressures above 10 MPa and, hence, a nonzero spallings volume.

The frequency of nonzero spallings volumes increased for the CRA-2009 PA compared to the CRA-2004 PABC (see Ismail [2008, Table 8]). The maximum spallings volumes are similar between the two analyses, while the CRA-2009 PA average spallings volume increased compared with the CRA-2004 PABC results (see Ismail [2008, Table 8]). As the spallings volumes are calculated from BRAGFLO pressure and an increase in pressure was observed (see Section PA-7.1.1 and Section PA-8.3.1), an increase in the spallings releases is expected.

PA-8.5.3 DBRs

DBRs to the surface can occur during or shortly after a drilling intrusion. For each element of the Latin hypercube sample, the code BRAGFLO calculates volumes of brine released for a total of 78 combinations of intrusion time, intrusion location, and initial conditions (see Section PA-6.7.6). Initial conditions for the DBR calculations are obtained from the BRAGFLO Salado flow model results from Scenarios S1 through S5. Salado flow model results from the S1 scenario (Section PA-7.1) are used as initial conditions for DBR when modeling a first intrusion into the repository that may have a DBR. Salado flow model results from the S2 through S5 scenarios (Section PA-8.3) are used as initial conditions for DBR when modeling second or subsequent drilling intrusions that may have a DBR.

Summary statistics of the calculated DBR volumes for Replicate R1 of the CRA-2009 PA are shown in Table PA-34. As seen in Table PA-34, 1,001 of the 7,800 DBR calculations (100 vectors × 78 combinations) resulted in a nonzero DBR volume to the surface, the majority of which resulted from Scenarios S2 and S3. The maximum DBR volume is approximately 59 m^3, with an average volume of 0.9 m^3. Only intrusions into a lower panel (see Clayton [2008b, Section 6.2]) resulted in significant DBR volumes. In the S1 scenario, the lower panel represents an undisturbed panel at the south end of the repository. In the S2 and S3 scenarios, the lower panel represents any panel that has had a previous E1 intrusion; in the S4 and S5 scenarios, the lower panel represents any panel that has had a previous E2 intrusion. DBR volumes are larger and occur more frequently in the S2 and S3 scenarios, because the lower panel has a much higher saturation after an E1 intrusion.

Table PA-34. CRA-2009 PA DBR Volume Statistics

Scenario	Maximum Volume (m^3)	Average Volume (m^3)	Number of Nonzero Volumes
S1	19	0.1	122
S2	59	2.9	385
S3	44	1.5	317
S4	19	0.1	70
S5	21	0.1	107
All	59	0.9	1,001

The frequency of nonzero DBR volumes increased for the CRA-2009 PA compared to the CRA-2004 PABC (see Clayton [2008b, Table 6-1]). The maximum DBR volume is lower for the CRA-2009 PA (see Clayton [2008b, Table 6-1]). The CRA-2009 PA average DBR volume increased compared to the CRA-2004 PABC results (see Clayton [2008b, Table 6-2, Table 6-3, Table 6-4, and Table 6-5]). The increase in the frequency of nonzero and average DBR volume is due to the porosity correction, while the decrease in the maximum DBR volume is from the reduction in the maximum DBR duration parameter (Clayton 2008b).

Previous sensitivity analyses have determined that a DBR volume from a single intrusion is most sensitive to the initial pressure and brine saturation in the intruded panel. This analysis is

repeated below for Scenario S2 in the CRA-2009 PA. The initial pressure and brine saturation in the DBR calculations are transferred from the Salado flow calculations, as described above. Thus, the uncertain parameters that are most influential to the uncertainty in pressure and brine saturation in the Salado flow calculations (see Section PA-7.1 and Section PA-8.3) are also most influential to the uncertainty in DBR volumes.

The combination of relatively high pressure and brine saturation in the intruded panel is required for DBR to the surface. Figure PA-73 shows a scatterplot of pressure in the waste panel versus DBR volumes for scenario S2, lower intrusion, with symbols indicating the value of the mobile brine saturation (defined as brine saturation minus residual brine saturation in the waste). The figure clearly shows that there are no releases until pressures exceed about 8 MPa, as indicated by the vertical line. Above 8 MPa, a significant number of vectors have zero releases, but these vectors have mobile brine saturations less than zero, and thus no brine is available to be released. When mobile brine saturation approaches one, relative permeability of the gas becomes small enough that no gas flows into the well, and in these circumstances, DBR releases end after three days. Thus, in vectors with high mobile brine saturations, DBR releases increase proportionally with increases in pressure, as evidenced by the linear relationship between DBR volume and pressure for mobile brine saturation between 0.8 and 1.0. For vectors with mobile saturations between 0.2 and 0.8, both gas and brine can flow in the well, and the rate of gas flow can be high enough that the ending time of DBR releases may be as long as 4.5 days. Although brine may be flowing at slower rates in these vectors than in vectors with high mobile saturations, brine flow may continue longer and thus result in larger DBR volumes.

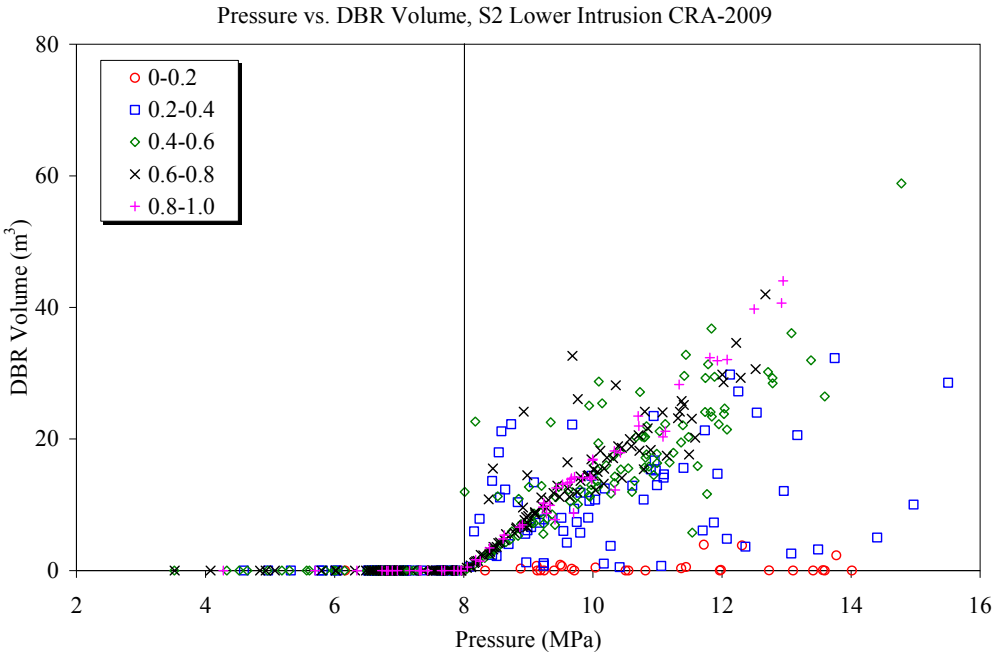


Figure PA-73. Sensitivity of DBR Volumes to Pressure and Mobile Brine Saturation, Replicate R1, Scenario S2, Lower Panel, CRA-2009 PA. (Symbols Indicate the Range of Mobile Brine Saturation Given in the Legend.)

PA-9.0 Normalized Releases

The radioactive waste disposal regulations of Part 191, Subparts B and C include containment requirements for radionuclides. The containment requirements of section 191.13 specify that releases from a disposal system to the accessible environment must not exceed the release limits set forth in 40 CFR Part 191, Appendix A, Table 1. As set forth in section 194.34, the results of PA are required to be expressed as CCDFs of total releases.

This section discusses each of the four categories of releases that constitute the total release: cuttings and cavings, spallings, DBRs, and transport releases, followed by the total normalized releases for the CRA-2009 PA. A comparison between the CRA-2009 PA and the CRA-2004 PABC results is also presented. In summary, despite the changes and corrections made between the CRA-2004 PABC and the CRA-2009 PA, there were no major changes in the overall pattern of releases. Cuttings, cavings, and DBRs remain the most significant pathways for release of radioactive material to the land surface. Release by subsurface transport in the Salado or Culebra continue to make essentially no contribution to total releases. Finally, the resulting CCDFs of total normalized releases for the CRA-2009 PA are within the regulatory limits defined in section 191.13. Section PA-9.0 is taken from Clayton et al. (2008, Section 6.0).

Rank regression analysis was used to evaluate the sensitivity of the normalized releases to the sampled parameters. Scatterplots of the dependent versus independent rank-transformed variables resulting from the sensitivity analysis were examined to determine if there were any obvious nonmonotonic relationships. Obvious nonmonotonic relationships were not found, although there are cases where inputs are categorized as discrete variables (e.g., OXSTAT) and cases where large proportions of the vectors show no release (e.g., CULREL). Application of linear regression to such cases is somewhat problematic with respect to the assumptions of normally distributed residuals and homogeneous variance among the residuals. However, with respect to ranking the relative importance of the parameters, these issues are probably not significant. Details of the analysis can be found in Kirchner (2008b).

PA-9.1 Cuttings and Cavings

The overall mean CCDFs for cuttings and cavings releases from the CRA-2009 PA and the CRA-2004 PABC are shown in Figure PA-74. These resulting overall mean CCDFs are very similar, with only a slight increase in the CRA-2009 PA mean due to the increase in the drilling rate.

The rank regression analysis showed that the uncertainty in waste shear strength (WTAUFAIL in Table PA-19) contributes about 98% of the variability in mean cuttings and cavings releases in both the CRA-2009 PA and CRA-2004 PABC (Kirchner 2008b). Cuttings and caving releases are primarily controlled by the volume of cuttings and cavings produced, which in turn is a highly nonlinear function of the waste shear strength (Ismail 2008).

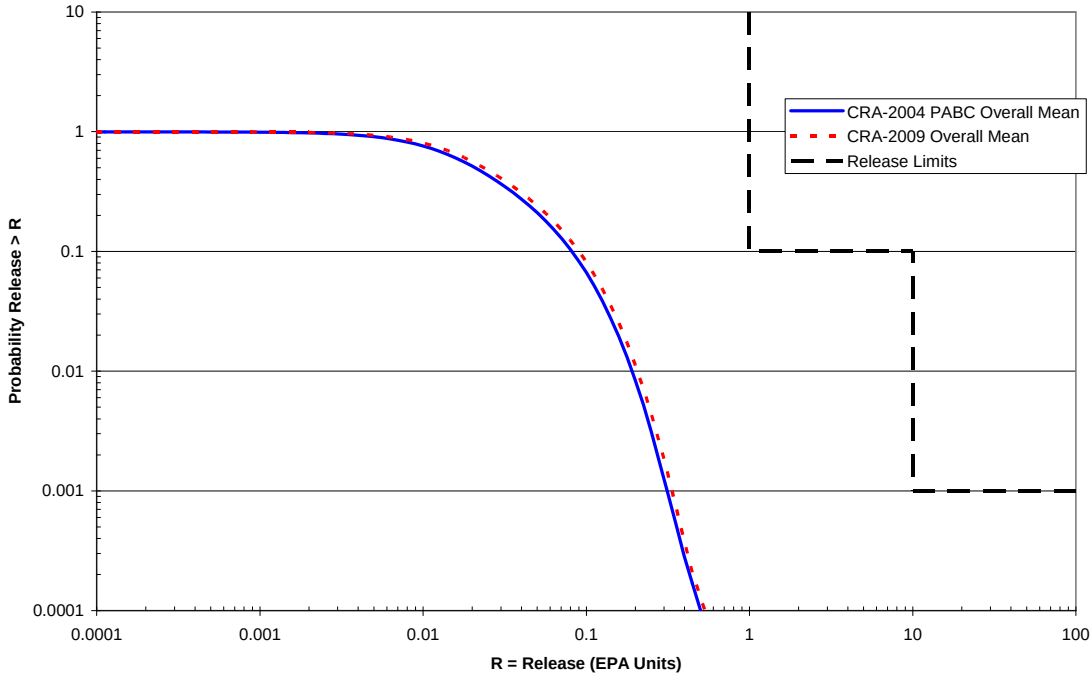


Figure PA-74. Overall Mean CCDFs for Cuttings and Cavings Releases: CRA-2009 PA and CRA-2004 PABC

PA-9.2 Spallings

Figure PA-75 shows the overall mean spallings release CCDFs from the CRA-2009 PA and the CRA-2004 PABC. This increase in overall mean spallings release values can be directly attributed to an increase in overall mean spallings volumes, with a small increase due to the increase in the drilling rate. The frequency of nonzero spallings volumes calculated by CUTTINGS_S increased. CUTTINGS_S calculates the spallings volume released from a single intrusion for the WIPP PA intrusion scenarios by interpolating the volumes calculated by DRSPALL using the repository pressures calculated by BRAGFLO. These increases are largely attributable to the increase in repository pressure resulting from the larger amounts of brine available (Ismail 2008).

The rank regression analysis indicates that the intact halite porosity (HALPOR in Table PA-19) is the dominant uncertain parameter with regard to the uncertainty in spallings releases in the CRA-2009 PA (Kirchner 2008b). Its higher ranking in the CRA-2009 PA analysis compared to the CRA-2004 PABC analysis is due to the increase in the maximum value of its distribution (Kirchner 2008b). Increases in halite porosity lead to increases in repository pressure (see Section PA-7.1.1 and Section PA-8.3.1) and thus to increases in spallings releases.

PA-9.3 Direct Brine

The overall mean CCDFs for DBRs from the CRA-2009 PA and the CRA-2004 PABC are shown in Figure PA-76. At all probabilities, the CRA-2009 PA mean DBRs increased from the

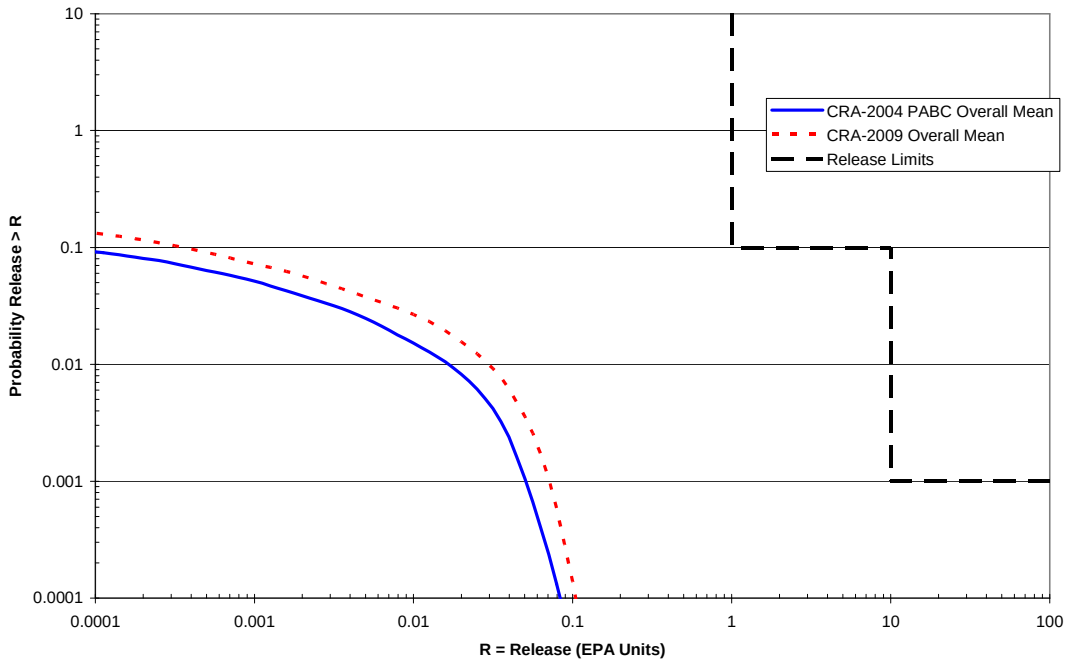


Figure PA-75. Overall Mean CCDFs for Spallings Releases: CRA-2009 PA and CRA 2004 PABC

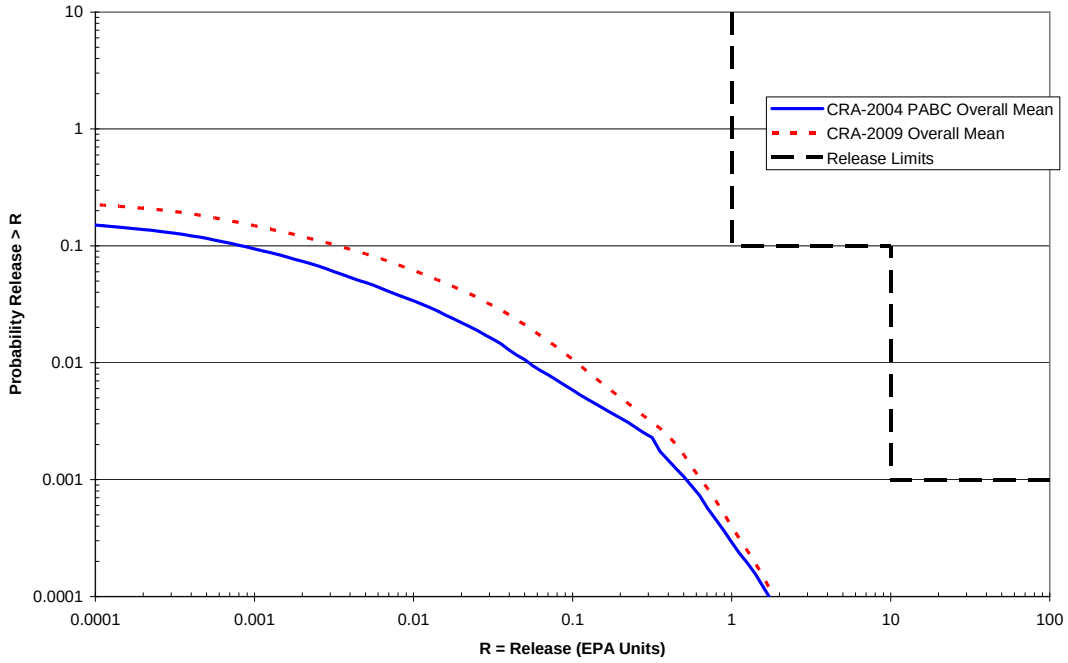


Figure PA-76. Overall Mean CCDFs for DBRs: CRA-2009 PA and CRA-2004 PABC

CRA-2004 PABC values, particularly at higher probabilities. In the CRA-2009 PA, at any level of release, the mean probability that DBRs exceed the release level is increased from the CRA-2004 PABC. This increase in the CCDFs for DBRs can be directly attributed to an increase in DBR volumes (Section PA-8.5.3), with a small increase due to the increase in the drilling rate (Clayton 2008a). The frequency of nonzero DBR volumes also increased (Section PA-8.5.3). The frequency and volume of the DBR are strongly correlated to the repository pressure. These increases are largely attributable to the increase in repository pressure resulting from of the larger amounts of brine available. The increase of the brine in the repository is due to higher intact halite porosities for higher probabilities and drilling rate at lower probabilities (Clayton 2008b).

The rank regression analysis shows that four variables, the "solubility multiplier" representing solubility uncertainty for all actinides in the III oxidation state (WSOLVAR3 in Table PA-19), the initial brine pore pressure in the Castile (BPINTPRS in Table PA-19), the inundated corrosion rate for steel (WGRCOR in Table PA-19), and the frequency with which Castile brine intrudes the repository as a result of a drilling event (BPPROB in Table PA-19), account for more than 50% of the uncertainty in DBRs for the CRA-2009 PA (Kirchner 2008b). These variables are also important in the CRA-2004 PABC analysis, although the third- and fourth-ranked variables are in reverse order relative to the CRA-2009 PA (Kirchner 2008b).

The solubility of actinides defines the concentration in DBRs. The corrosion of Fe is expected to produce gas, but at the same time it consumes water. When the repository is flooded with brine from the intrusion of a brine pocket, the influence on DBR would likely be positive, because the production of H_2 would outweigh the minimal impact of the consumption of water. However, a negative correlation is observed between the ranked variables, suggesting that the corrosion of steel has its strongest influence when the repository is not saturated and DBRs are expected to be small. The frequency with which Castile brine intrudes the repository as a result of a drilling event and the initial pressure of that brine affect the pressure in the repository. As DBR volumes are a strong function of pressure, a positive correlation is expected and shown (Kirchner 2008b).

PA-9.4 Groundwater Transport

Figure PA-77 shows the mean CCDFs for normalized releases due to transport through the Culebra for Replicate R2 of the CRA-2009 PA and the CRA-2004 PABC. No transport releases larger than 10^{-6} EPA units occurred in Replicates R1 and R3. Normalized transport releases for the CRA-2009 PA are qualitatively similar to the CRA-2004 PABC results, in that only one replicate (R2) exhibits releases that are significantly larger than the numerical error inherent in the transport calculations. Overall, the mean releases for Replicate R2 of the two analyses are quite similar and the numbers of vectors that had releases are identical, with only a slight increase in the CRA-2009 PA due to the increase in the drilling rate (Dunagan 2008).

A Culebra release represents the potential release of radioactivity from the Culebra at the LWB over 10,000 years. Analyzing sensitivity of Culebra releases to the input parameters using linear regression is problematic (Kirchner 2008b). In the CRA-2009 PA and the CRA-2004 PABC, ~83% of the vectors had Culebra releases of zero (Ismail and Garner 2008). Releases of zero are found across the entire range of every parameter. This is undoubtedly due, for the most part, to

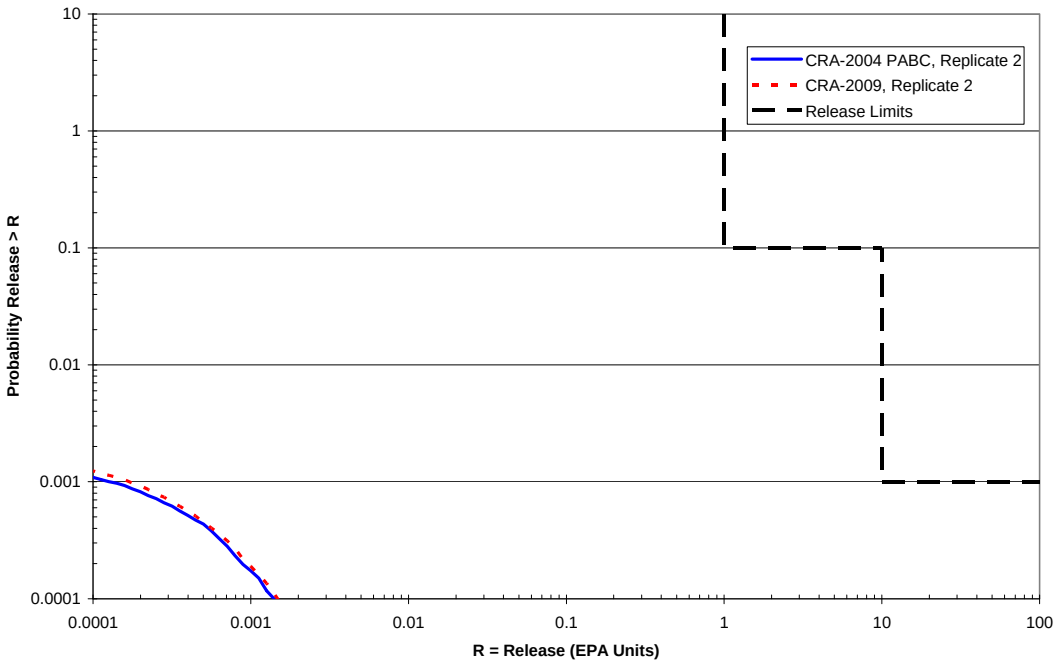


Figure PA-77. Mean CCDFs for Releases from the Culebra for Replicate R2: CRA-2009 PA and CRA-2004 PABC

transport rates frequently being too small to enable contaminants to reach the boundary within the 10,000-year simulation period. Thus, the release data are strongly skewed. The times of the intrusions giving rise to flows to the Culebra are also likely to influence whether or not such releases occur. These times are not represented in the sampled input parameters, and thus cannot be associated with the releases. In addition, the preponderance of zero values tends to negate the assumption of linear regression that errors (residuals) are normally distributed. In many cases, it appears that it is the distribution of zeros along the independent axis that determines whether a positive or negative correlation is observed. For example, Figure PA-78 shows the ranks of releases from the Culebra versus the ranks of the parameter CFRACPOR(CULEBRA:APOROS) for Replicate 1. The average rank of the zero values was 42 and was assigned to all cases where no release was observed. Because releases of zero were associated with high values of CFRACPOR, as well as low values, and because there were no nonzero releases for the futures having the highest values of CFRACPOR, the arrangement of the data would lead to a negative correlation. Because of these issues, the linear ranked regression analysis is unlikely to yield a definitive identification of the sensitivity of Culebra releases to the sampled parameters, and most of the variability in Culebra releases remains unexplained by the regression model (Kirchner 2008b).

PA-9.5 Total Normalized Releases

Total releases are calculated by totaling the releases from each release pathway: cuttings and cavings releases, spallings releases, DBRs, and transport releases (there were no undisturbed releases to contribute to total release). Figure PA-79 shows the 300 CCDFs for total releases in

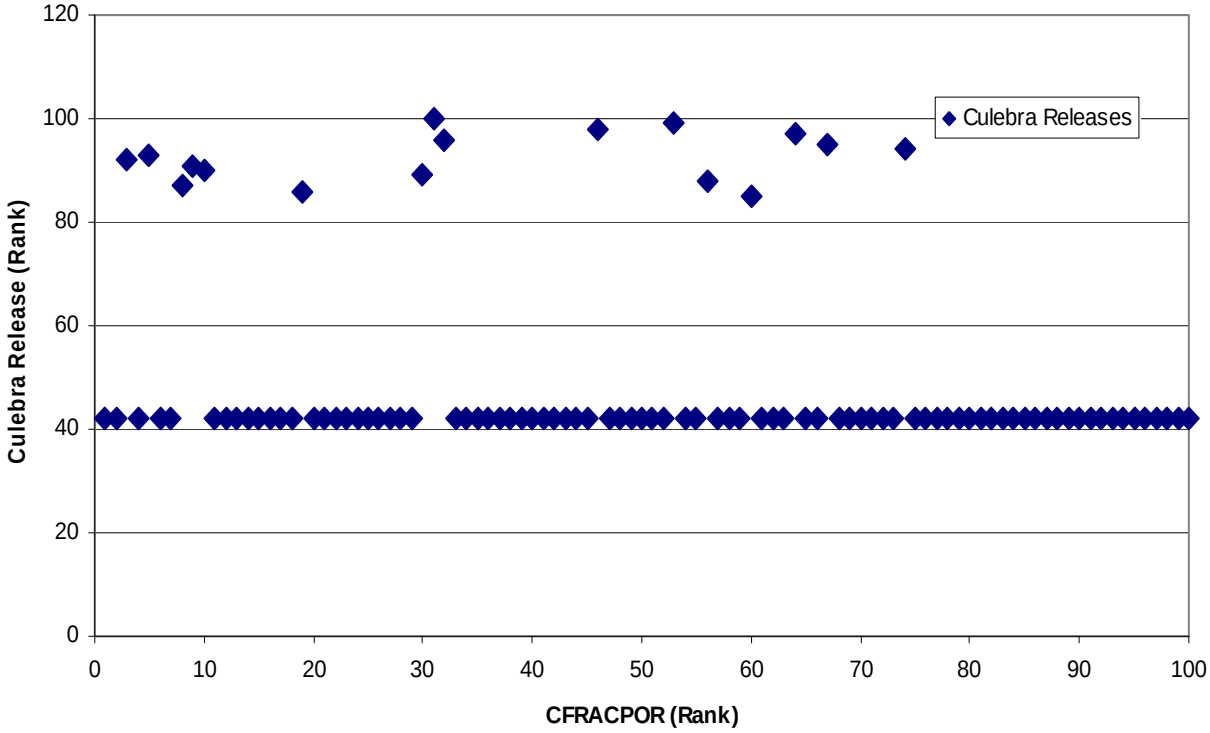


Figure PA-78. The Preponderance and Distribution of Zeros Can Control the Regression

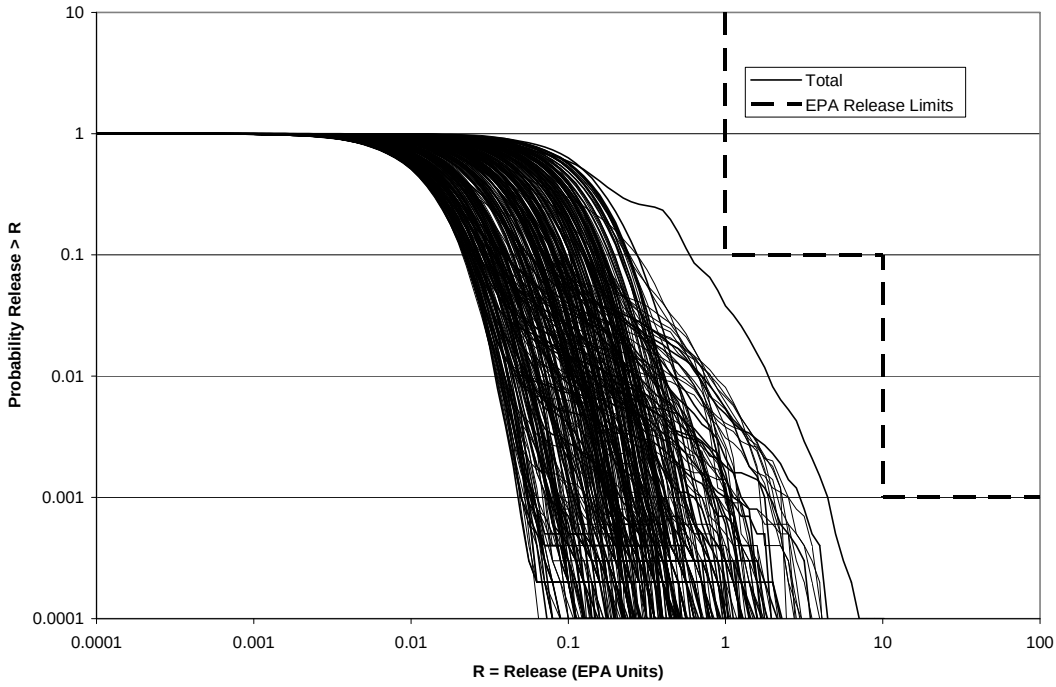


Figure PA-79. Total Normalized Releases, Replicates R1, R2, and R3, CRA-2009 PA

Replicates R1, R2, and R3 of the CRA-2009 PA. As seen in Figure PA-79, all of the CCDFs lie below and to the left of the limits specified in section 191.13(a).

The overall mean CCDF is computed as the arithmetic mean of the mean CCDFs from each replicate. To quantitatively determine the sufficiency of the sample size, a confidence interval is computed about the overall mean CCDF using the Student's t-distribution and the mean CCDFs from each replicate. Figure PA-80 shows 95% confidence intervals about the overall mean. The CCDF and confidences intervals lie below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of Part 191.

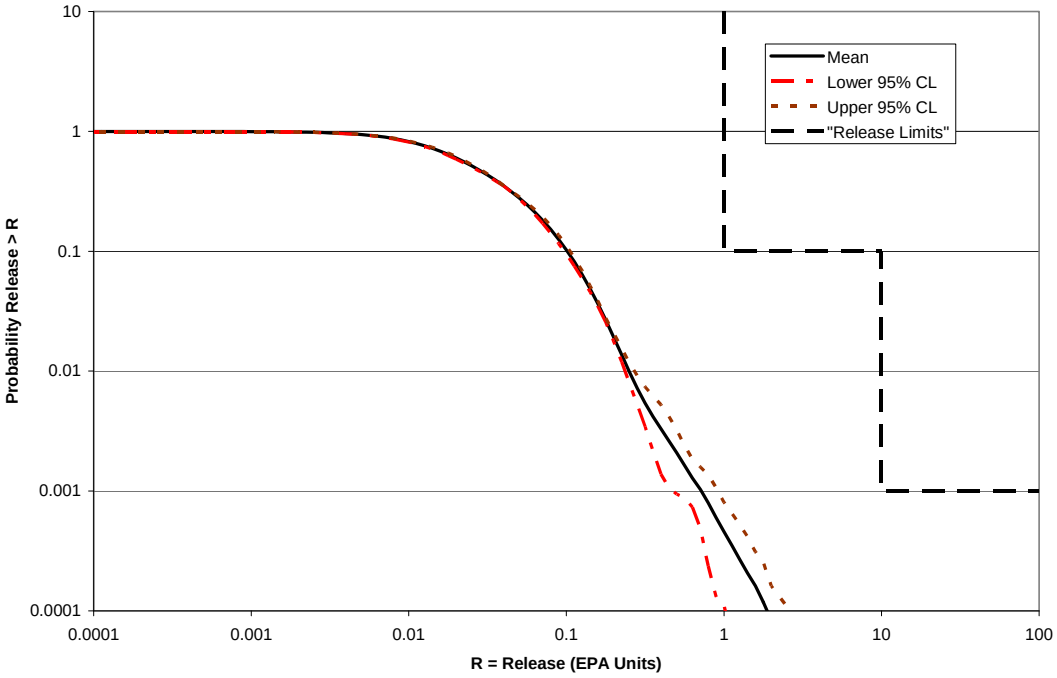


Figure PA-80. Confidence Interval on Overall Mean CCDF for Total Normalized Releases, CRA-2009 PA

Figure PA-81, Figure PA-82, and Figure PA-83 show the mean CCDFs for each component of total releases for Replicates R1, R2, and R3 of the CRA-2009 PA, respectively. The contributions to total releases for each release pathway in the CRA-2009 PA are the same as those observed in the CRA-2004 PABC (Dunagan 2008).

Figure PA-84 provides a comparison between the CRA-2009 PA and the CRA-2004 PABC. At any level of release, the overall mean probability that total releases exceed the release level is similar between the two analyses. A small increase in the probability is mainly due to the change in the drilling rate parameter (Dunagan 2008).

Table PA-35 shows the level of release at the probability of 0.1 and 0.001 from the overall mean CCDF. The CCDF value of the upper and lower 95% confidence levels on the mean CCDF at

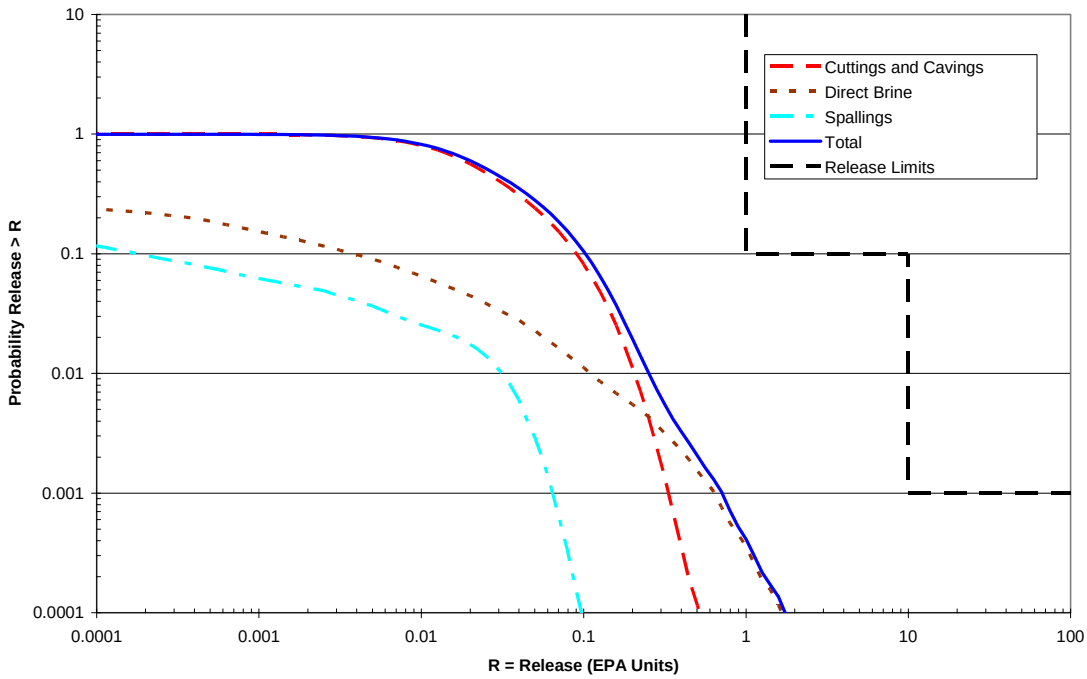


Figure PA-81. Mean CCDFs for Components of Total Normalized Releases, Replicate R1, CRA-2009 PA

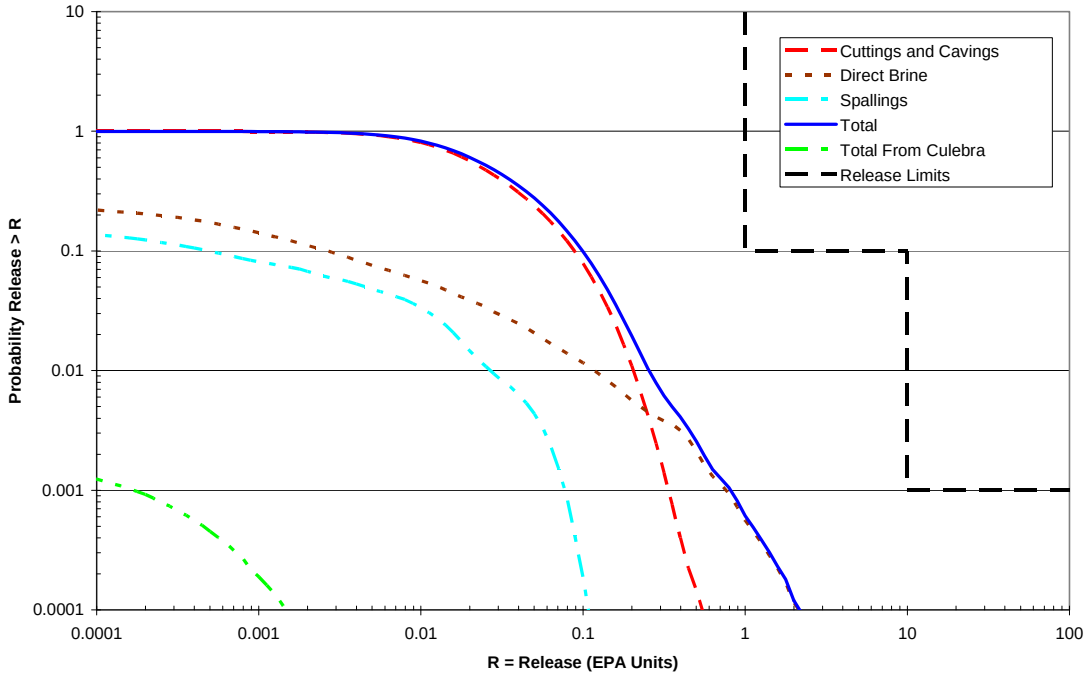


Figure PA-82. Mean CCDFs for Components of Total Normalized Releases, Replicate R2, CRA-2009 PA

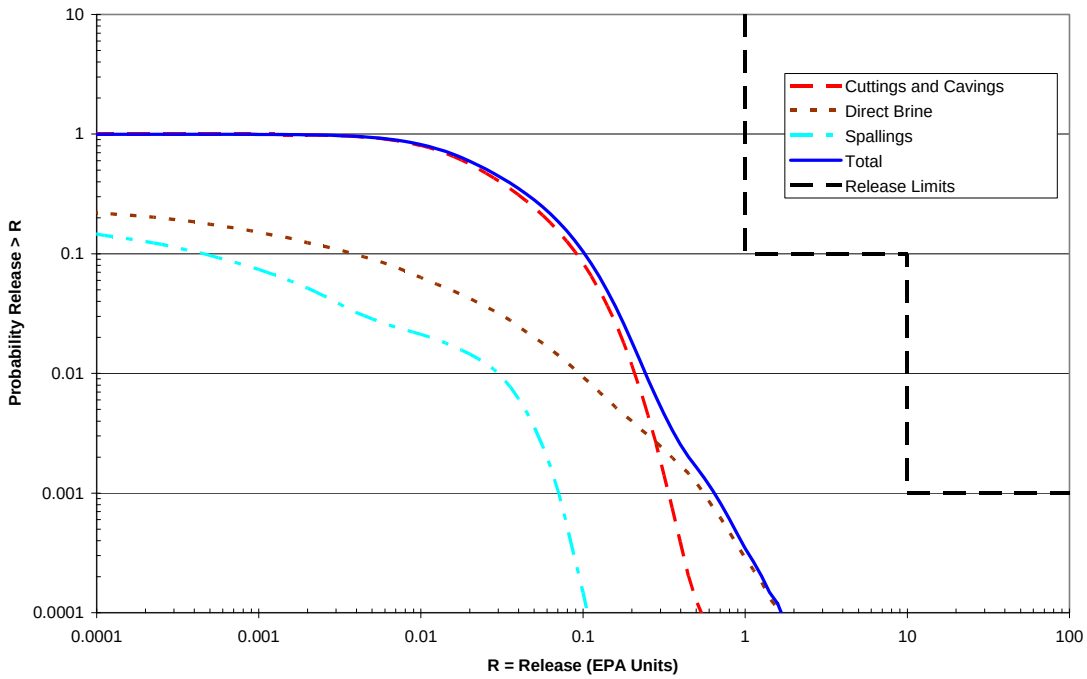


Figure PA-83. Mean CCDFs for Components of Total Normalized Releases, Replicate R3, CRA-2009 PA

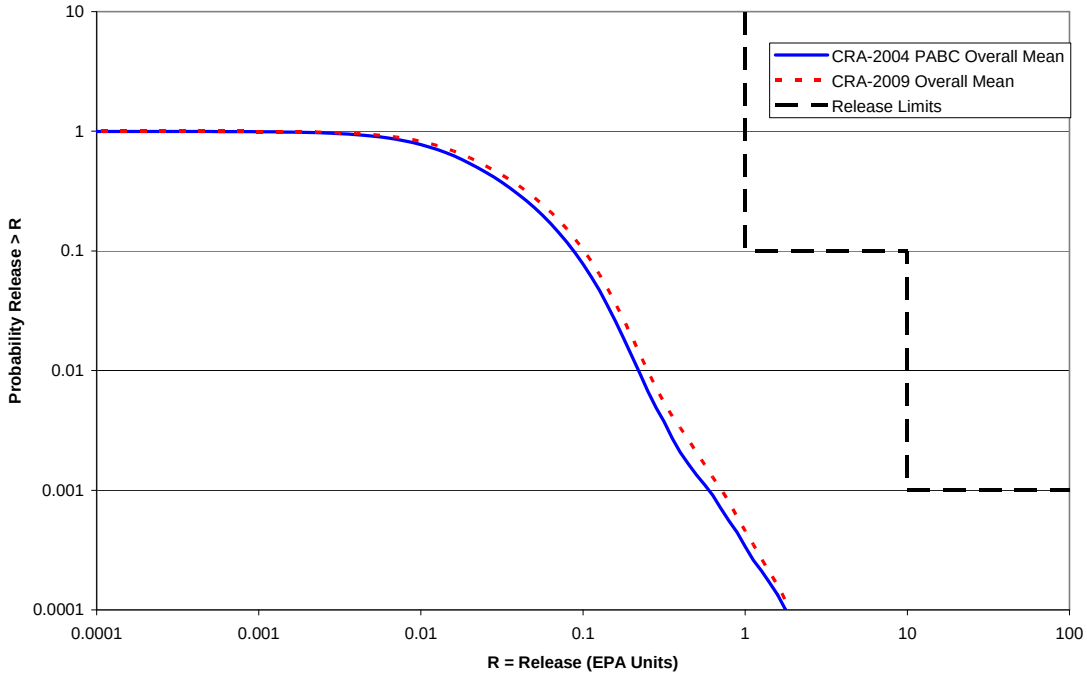


Figure PA-84. Overall Mean CCDFs for Total Normalized Releases: CRA-2009 PA and CRA-2004 PABC

Table PA-35. CRA-2009 PA and CRA-2004 PABC[a] Statistics on the Overall Mean for Total Normalized Releases in EPA Units at Probabilities of 0.1 and 0.001

Probability	Analysis	Mean Total Release	Lower 95% CL	Upper 95% CL	Release Limit
0.1	CRA-2004 PABC	0.09	0.08	0.09	1
	CRA-2009 PA	0.10	0.10	0.11	1
0.001	CRA-2004 PABC	0.60	0.52	0.68	10
	CRA-2009 PA	0.72	0.48	0.92	10

[a] CRA-2004 PABC data was initially reported in Vugrin and Dunagan (2005).

the 0.1 and 0.001 probability, along with the release limit, are also included. The overall mean total release CCDFs differ by ~0.01 EPA units at a probability of 0.1 and by ~0.1 EPA units at a probability of 0.001 (Table PA-35). These increases in the total releases primarily result from the increase in the drilling rate parameter.

There are some definite similarities between the CCDFs for the two analyses. First, for most probabilities, cuttings and cavings are the most significant pathways for release of radioactive material to the land surface. Second, release by spallings and subsurface transport in the Salado or Culebra make essentially no contribution to total releases. Finally, the resulting CCDFs of both analyses are within regulatory limits.

As in the CRA-2004 PABC, cuttings, cavings, and DBRs account for the majority of the total releases estimated in the CRA-2009 PA. As indicated in the rank regression analysis, in both the CRA-2009 PA and the CRA-2004 PABC, the uncertainty in waste shear strength (WTAUFAIL in Table PA-19) contributes to a large portion of the uncertainty in total normalized releases (Kirchner 2008b). The volumes of cuttings and cavings are primarily controlled by shear strength (Kirchner 2008b). The "solubility multiplier," which represents uncertainty in solubilities for all actinides in the III oxidation state (WSOLVAR3 in Table PA-19), remained the second-most dominant parameter contributing to variability in total releases in all replicates (Kirchner 2008b). Solubility of actinides defines the concentration in DBRs. The variability in total releases explained by the waste shear strength in the CRA-2009 PA dropped from previous levels. The waste shear strength only accounts for about 81% of the total variability in total releases in the CRA-2009 PA, whereas in the CRA-2004 PABC it accounted for 88% of the variability (Kirchner 2008b). This decrease is due to the relative increase in the DBR contribution to total releases.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix PORSURF-2009
Porosity Surface

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix PORSURF-2009
Porosity Surface

Table of Contents

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Acronyms and Abbreviations

CCA	Compliance Certification Application
CRA	Compliance Recertification Application
K	Kelvin
mol	mole
PA	Performance Assessment
WIPP	Waste Isolation Pilot Plant

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PORSURF-1.0 Introduction

Both creep closure of the salt and the presence of either brine or gas in the waste disposal region influence time-dependent changes in void volume in the waste disposal area. As a consequence, these processes influence two-phase fluid flow of brine and gases through the disposal area and its capacity for storing fluids. For performance assessment (PA), a porosity surface method is used to indirectly couple mechanical closure with two-phase fluid flow calculations implemented in the BRAGFLO code (see Appendix PA-2009, Section PA-4.2). The porosity surface approach is used because current codes are not capable of fully coupling creep closure, waste consolidation, brine availability, and gas production and migration. The porosity surface method incorporates the results of closure calculations obtained from the SANTOS code, a quasistatic, large-deformation, finite-element structural analysis code (Stone 1997a). The adequacy of the method is documented in Freeze (1996), who concludes that the approximation is valid so long as the rate of room pressurization in final calculations is bounded by the room pressurization history used to develop the porosity surface.

The porosity surface used in the 2009 Compliance Recertification Application (CRA-2009) PA is the same surface used for the Compliance Certification Application (CCA) (U.S. Department of Energy 1996) and the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004). Consequently, the models and parameters used to calculate this surface are unchanged from the CCA PA. For information on the porosity surface used in the CCA PA, see the CCA, Appendix PORSURF.

A separate analysis considered the potential effects on repository performance of uncertainty in the porosity surface (Appendix MASS-2009, Section MASS-21.0). Uncertainty in the porosity surface can arise from heterogeneity in the rigidity of waste packages and from uncertain spatial arrangements of waste in the repository. The analysis considered four porosity surfaces, including the surface from the CCA, which represented various bounding combinations of waste package rigidity and waste initial porosity. The analysis concluded that uncertainty in the porosity surface did not have significant effects on repository performance, and recommended the continued use of the CCA porosity surface in PA.

PORSURF-2.0 Creep Closure Method

Creep closure is accounted for in BRAGFLO by changing the porosity of the waste disposal area according to a table of porosity values, termed the porosity surface. The porosity surface is generated using SANTOS, a nonlinear finite element code. Disposal room porosity is calculated over time, for different rates of gas generation and gas production potential, to construct a three-dimensional porosity surface representing changes in porosity as a function of pressure and time over the 10,000-year simulation period.

The completed porosity surface is compiled in tabular form and is used in the solution of the gas and brine mass balance equations presented in Appendix PA-2009, Section PA-4.2.1. Porosity is interpolated from the porosity surface corresponding to the calculated gas pressure at time step t_n. This is done iteratively, as decreases in the porosity will increase the pressure. The closure data provided by SANTOS can be viewed as a series of surfaces, with any gas generation history computed by BRAGFLO constrained to fall on this surface. Various techniques described in Freeze, Larson, and Davies (1995) were used to check the validity of this approach, and it was found to be a reasonable representation of the behavior observed in the complex models.

In SANTOS, the gas pressure in the disposal room at time t_n is computed from the ideal gas law by the following relationship:

$$p_g = \frac{NRT}{V}$$

where N is the number of moles of gas at time t_n, R is the universal gas constant (8.31 m^3·Pa/mol·K), T is the absolute temperature in degrees Kelvin (constant at 300 K), and V is the free volume of the room at time t_n. The number of moles of gas is computed as

$$N_t = N_{t-1} + N_{drums} \times f \times r(t) \times (t_n - t_{n-1})$$

where $r(t)$ is the gas generation rate (mol/drum/yr) at time t for the scaling factor f and N_{drums} is the number of drums of waste in the room (6804 drums/room). The base gas generation rate in SANTOS is

$$r(t) = \begin{cases} 2\ mol/drum/yr, & 0 \le t \le 550\ yr \\ 1\ mol/drum/yr, & 550\ yr < t \le 1050\ yr \\ 0\ mol/drum/yr, & 1050\ yr < t \end{cases}$$

The base gas generation rate $r(t)$ is representative of relatively high gas production rates from both microbial degradation of cellulosic, plastic, and rubber materials and from anoxic corrosion of Fe-base metals (Appendix PA-2009, Section PA-4.2.5; Butcher 1997a). To provide a range of SANTOS results that spans the possible range of pressure computed by BRAGFLO, the gas generation rate is varied by the scaling factor f. Thirteen values of f are used to construct the porosity surface: f = 0.0, 0.025, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.6, and 2.0. The condition f = 0 represents the state of the repository when no gas is produced; f = 2 represents twice the base gas generation rate.

In SANTOS, gas generation is included to introduce a range of values for gas pressure during room closure, thereby capturing the effects of gas pressure on room closure; the use of the scaling factor *f* ensures that SANTOS results span a wide range of possible gas generation rates and potentials.

PORSURF-3.0 Conceptual Model for Porosity Surface

The ability of salt to deform with time, eliminate voids, and create an impermeable barrier around the waste was one of the principal reasons for locating the Waste Isolation Pilot Plant (WIPP) repository in a bedded salt formation (National Academy of Sciences-National Research Council 1957, pp. 4–5). The creep closure process is a complex and interdependent series of events starting after a region within the repository is excavated. Immediately upon excavation, the equilibrium state of the rock surrounding the repository is disturbed, and the rock begins to deform and return to equilibrium. Eventually, at equilibrium, deformation ceases, as the waste region has undergone as much compaction as is possible under the prevailing lithostatic stress field and the differential stresses in the salt approach zero.

Creep closure of a room begins immediately upon excavation and causes the volume of the cavity to decrease. If the room were empty, rather than partially filled with waste, closure would proceed until the void volume created by the excavation is eliminated; the surrounding halite would then return to its undisturbed, uniform stress state. In a waste-filled room, the rock will contact the waste and the rate of closure will decrease as the waste compacts and stiffens; eventually, closure will cease when the waste can take the full overburden load without further deformation. Initially, unconsolidated waste can support only small loads, but as the room continues to close after contact with the waste, the waste will consolidate and support a greater portion of the overburden load.

The presence of gas in the room will retard the closure process due to pressure buildup. As the waste consolidates, pore volume is reduced and pore pressure increases (using the ideal gas law). In this process, the waste can be considered to be a skeleton structure immersed in a pore fluid (the gas). As the pore pressure increases, less overburden weight is carried by the skeleton, and more support is provided by the gas. If the gas pressure increases to lithostatic pressure, the pore pressure alone is sufficient to support the overburden.

PORSURF-4.0 SANTOS Numerical Analyses

Computing repository creep closure is a particularly challenging structural engineering problem because the rock surrounding the repository continually deforms with time until equilibrium is reached. Not only is the deformation of the salt inelastic, but it also involves larger deformations that are not customarily addressed with conventional structural deformation codes. In addition, the formation surrounding the repository is inhomogeneous in composition, containing various parting planes and interbeds with different properties than the salt.

Waste deformation is also nonlinear, with large strains, and the response of a waste-filled room is complicated by the presence of gas. These complex characteristics of the materials making up the repository and its surroundings require the use of highly specialized constitutive models. Appropriate models have been built into the SANTOS code over a number of years. Principal components of these models include the following:

1. Disposal Room Configuration and Idealized Stratigraphy. Disposal room dimensions, computational configuration, and idealized stratigraphy are defined in the CCA, Appendix PORSURF, Attachment 1. The idealized stratigraphy is reproduced in Figure PORSURF-1.

2. Discretized Finite Element Model. A two-dimensional plane strain model, shown in Figure PORSURF-2, is used for the SANTOS analyses. The discretized model represents the room as one of an infinite number of rooms located at the repository horizon. The model contains 1,680 quadrilateral uniform-strain elements and 1,805 nodal points. Contact surfaces between the emplaced waste and the surfaces of the room are addressed. The justification for this model and additional detail on initial and boundary conditions are provided in the CCA, Appendix PORSURF, Attachment 1.

3. Geomechanical Model. Mechanical material response models and their corresponding property values are assigned to each region of the configuration. These models include:

   A. A combined transient-secondary creep constitutive model for clean and argillaceous halite

   B. An inelastic constitutive model for anhydrite

   C. A volumetric plasticity model for the emplaced waste

   Material properties are provided in the CCA, Appendix PORSURF, Attachment 1.

The results of the SANTOS calculations are illustrated in Figure PORSURF-3 and Figure PORSURF-4. Figure PORSURF-3 shows disposal room porosity as a function of time for various values of the gas generation scaling factor *f*. Figure PORSURF-4 shows disposal room pressure as a function of time for various values of *f*. When $f = 0$, no gas is present in the disposal room; thus, disposal room pressure is identically zero for all times. This pressure curve is omitted from Figure PORSURF-4.

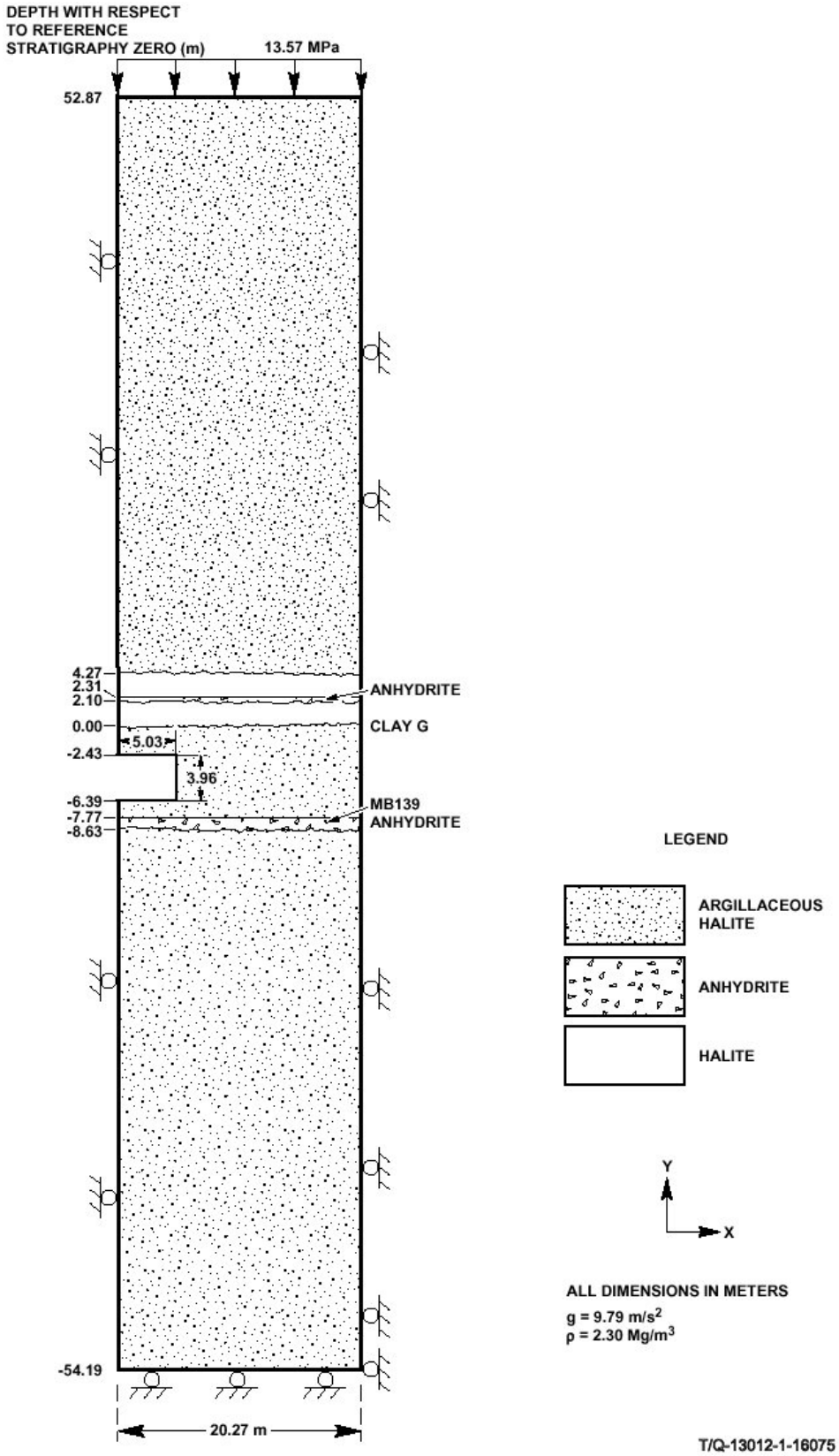

Figure PORSURF-1. Stratigraphy Used for the Porosity Surface Calculations

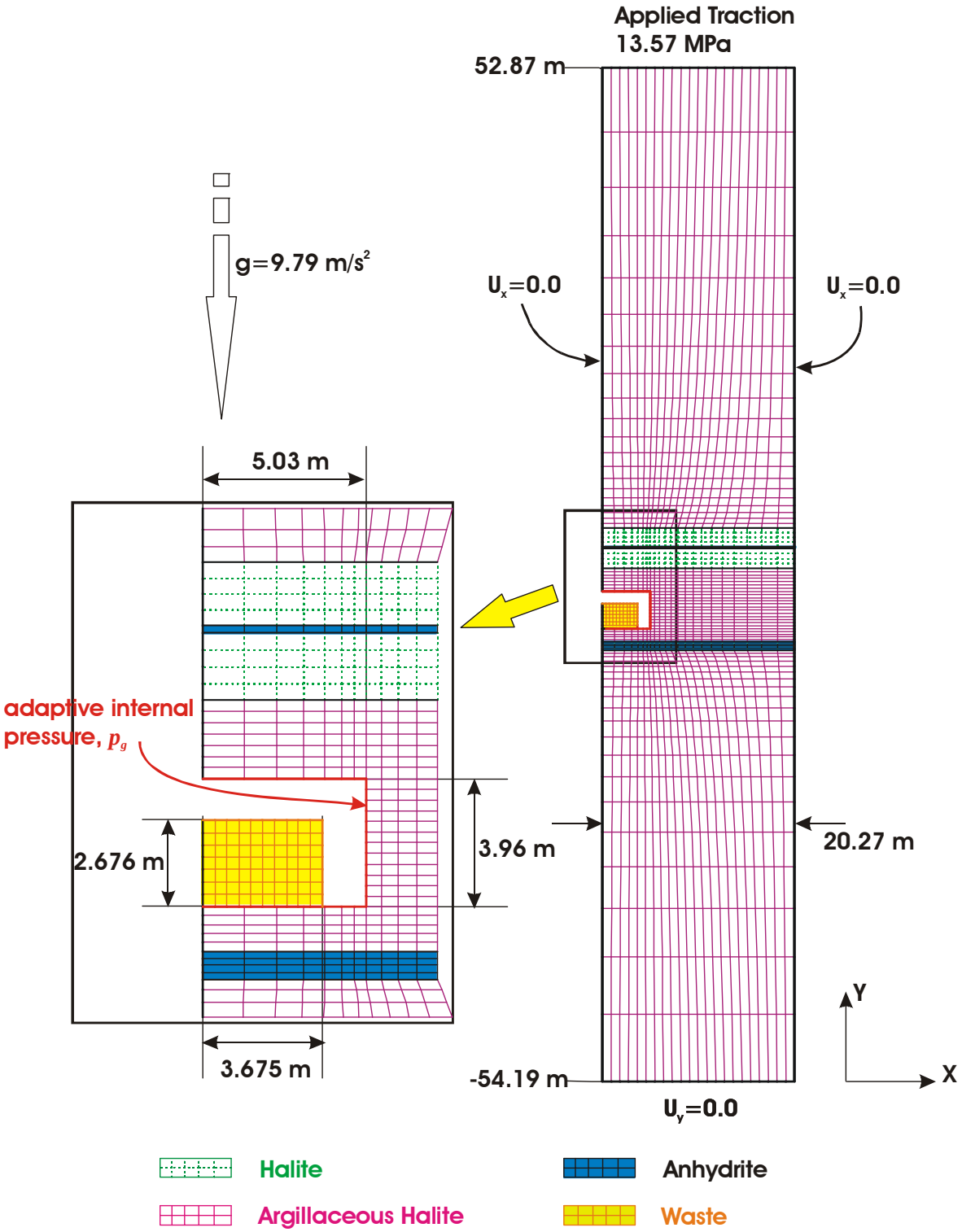

Figure PORSURF-2. Mesh Discretization and Boundary Conditions Used for the Porosity Surface Calculations

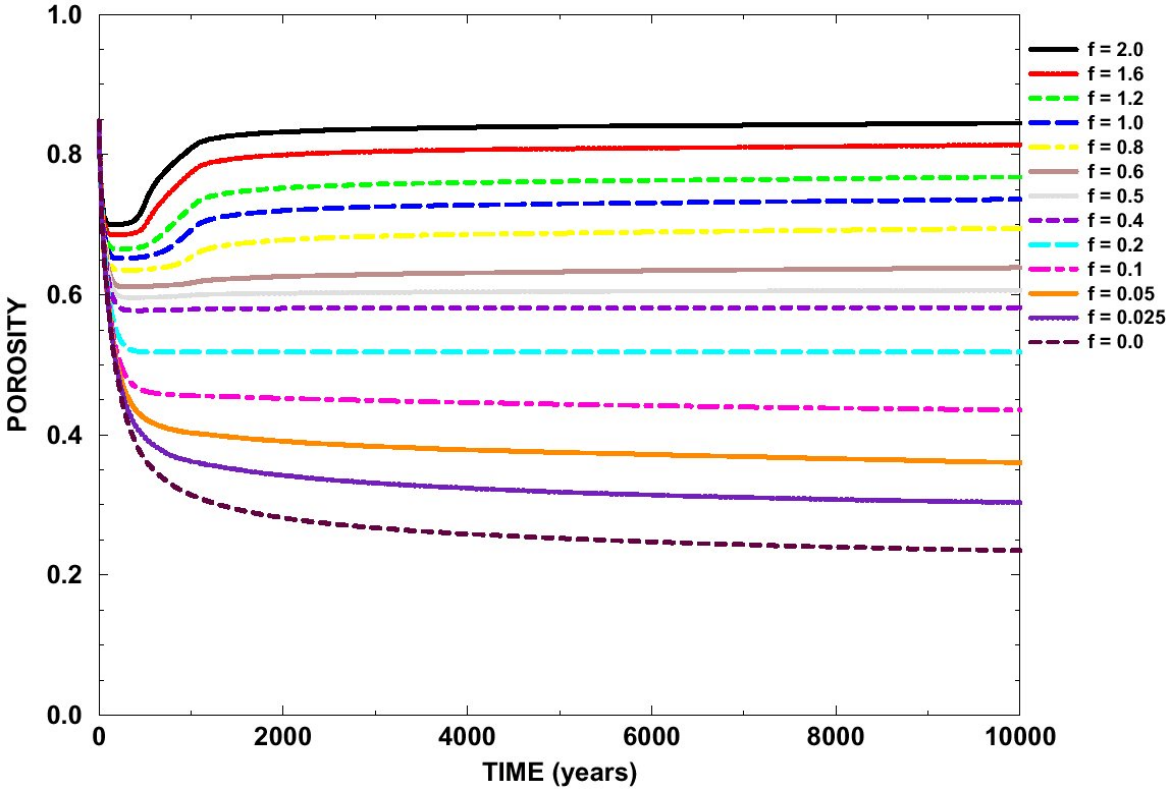

Figure PORSURF-3. Disposal Room Porosity for Various Values of the Scaling Factor *f*

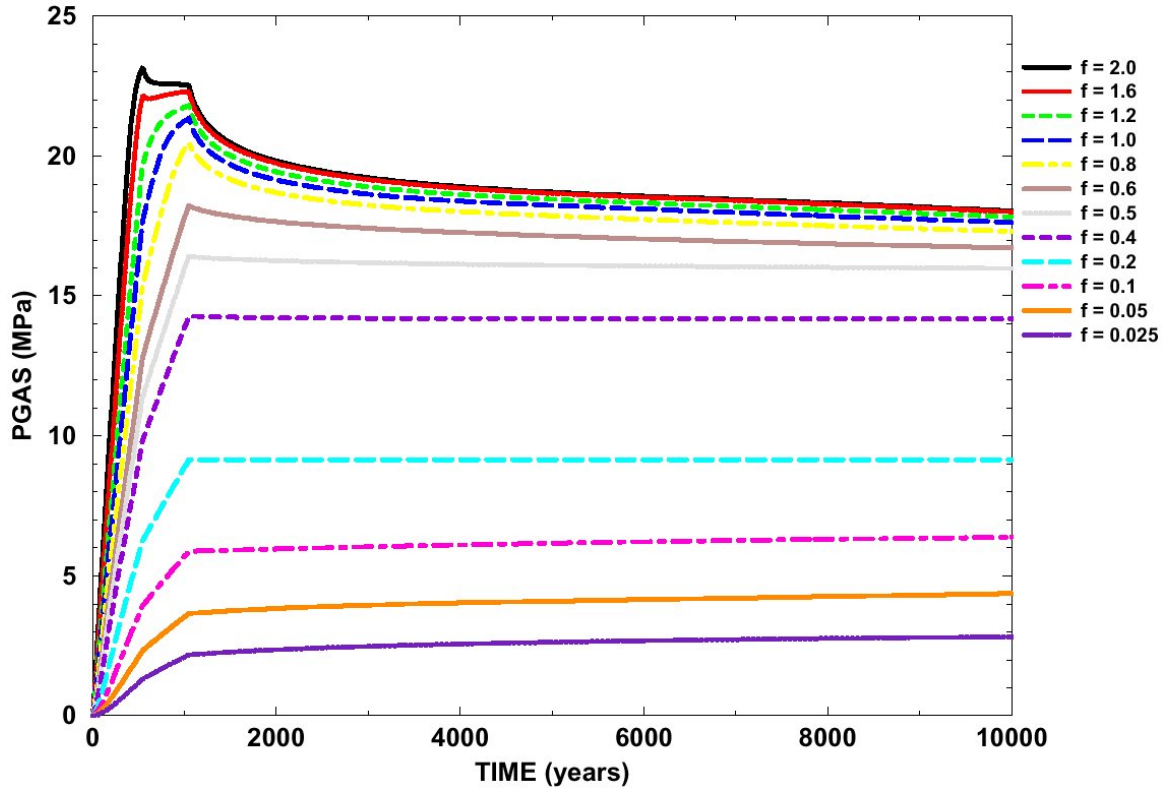

Figure PORSURF-4. Disposal Room Pressure for Various Values of the Scaling Factor *f*

PORSURF-5.0 Implementation of Porosity Surface in BRAGFLO

As outlined above, the SANTOS program is used to calculate time-dependent porosities and pressures in the repository for a range of gas generation rates determined by the scaling factor *f*. Calculation with each value of *f* results in the porosity and pressure curves in Figure PORSURF-3 and Figure PORSURF-4.

The porosity calculated by SANTOS is the intrinsic, or true, porosity, which is defined as the ratio of the void volume to the current volume of a (deformable) element of waste. In contrast, porosity in BRAGFLO is defined as the ratio of void volume to the original volume of an element of waste. Mathematically, the BRAGFLO porosity, ϕ_B, and the intrinsic porosity in SANTOS, ϕ, are defined as

$$\phi_B = \frac{V_{void}}{V_0}$$

$$\phi = \frac{V_{void}}{V}$$

where V_{void} is the current void volume, V_0 is the original (total) volume, and V is the current (total) volume of a waste element.

The porosities shown in Figure PORSURF-3 are the porosities calculated by SANTOS to be used in BRAGFLO. The BRAGFLO porosities are related to the porosities calculated by SANTOS by correcting for deformation of the waste during repository closure. The relationship between ϕ_B and ϕ is given by

$$\phi_B = \frac{1-\phi_0}{1-\phi}\phi$$

where ϕ_0 is the initial porosity of the waste. Note that the values of ϕ_B and ϕ are equal at the initial porosity before the waste starts to compact.

Brine pressures $p_b(t)$ obtained in the waste disposal regions are used in conjunction with the results in Figure PORSURF-3 and Figure PORSURF-4 to estimate porosity in the waste-filled regions for the BRAGFLO calculations. In the CRA-2009 PA, brine pressure and gas pressure are set as equal in the waste-filled regions, i.e. capillary pressure is not included (see Appendix PA-2009, Section PA-4.2). This is unchanged from the CCA and CRA-2004 PAs.

Given a value for $p(t)$, BRAGFLO looks at the porosity surface to find indices for times in the porosity table so that

$$t_1 \le t \le t_2$$

Next, BRAGFLO determines whether the current pressure is above the pressure curve in the interpolation table corresponding to the maximum *f* value or corresponding to the minimum *f*

value in the table. If p lies above the curve formed by the points $(t_1, p(t_1, f_{\max}))$ and $(t_2, p(t_2, f_{\max}))$, the porosity is calculated by interpolation using the following formula:

$$\phi = \phi(t_1, f_{\max}) + \frac{\phi(t_2, f_{\max}) - \phi(t_1, f_{\max})}{t_2 - t_1}(t - t_1)$$

Similarly, if p lies below the curve formed by the points $(t_1, p(t_1, f_{\min}))$ and $(t_2, p(t_2, f_{\min}))$, the porosity is calculated by interpolation using the following formula:

$$\phi = \phi(t_1, f_{\min}) + \frac{\phi(t_2, f_{\min}) - \phi(t_1, f_{\min})}{t_2 - t_1}(t - t_1)$$

For values of p that do not lie above or below the maximum and minimum $p(t, f)$ curves in the interpolation table, BRAGFLO finds f values f_1 and f_2 so that the point (t, p) lies between two curves $(t, p(t, f_1))$ and $(t, p(t, f_2))$. This is illustrated in Figure PORSURF-5.

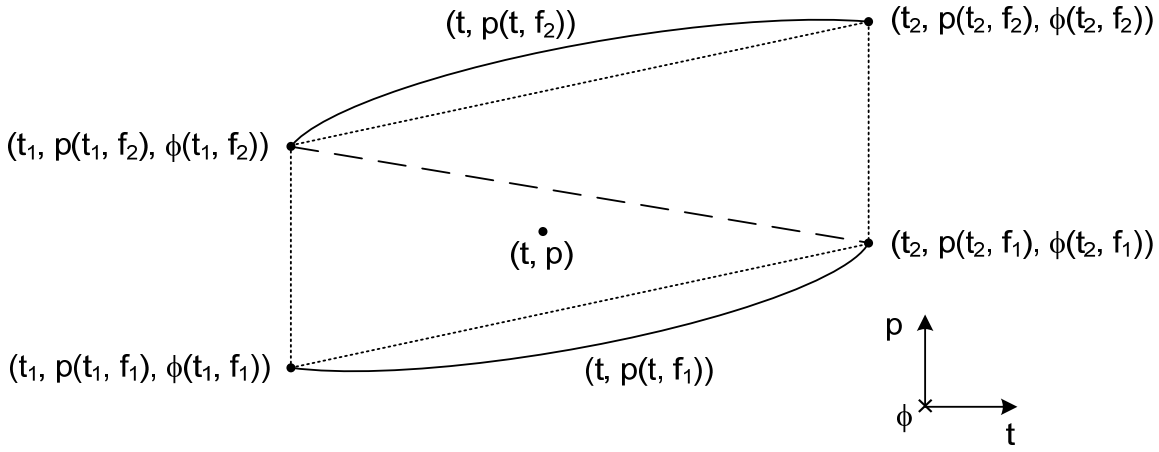

Figure PORSURF-5. Location of Points in Porosity Table around Point (*t*, *p*)

Interpolation is performed on the triangle formed by the set of points that encloses the point (t, p). For example, in Figure PORSURF-5, the points constituting the lower triangle would be used for interpolation. Interpolation on the triangle is calculated from the areas of the three triangles in the plane of t and p that can be formed from the point (t, p) and the vertices of the enclosing triangle, as illustrated in Figure PORSURF-6. The porosity is then calculated from

$$\phi(t, p) = \frac{A_1}{A}\phi(t_1, f_2) + \frac{A_2}{A}\phi(t_1, f_1) + \frac{A_3}{A}\phi(t_2, f_1)$$

where A is the total area of the triangles ($A_1 + A_2 + A_3$) in Figure PORSURF-6.

At $t = 0$ (i.e., immediately after the operational period; see Appendix PA-2009, Section PA-4.2), interpolation is performed using the points $(t_1, p(t_1, f_1), \phi(t_1, f_1))$, $(t_2, p(t_2, f_1), \phi(t_2, f_1))$, and

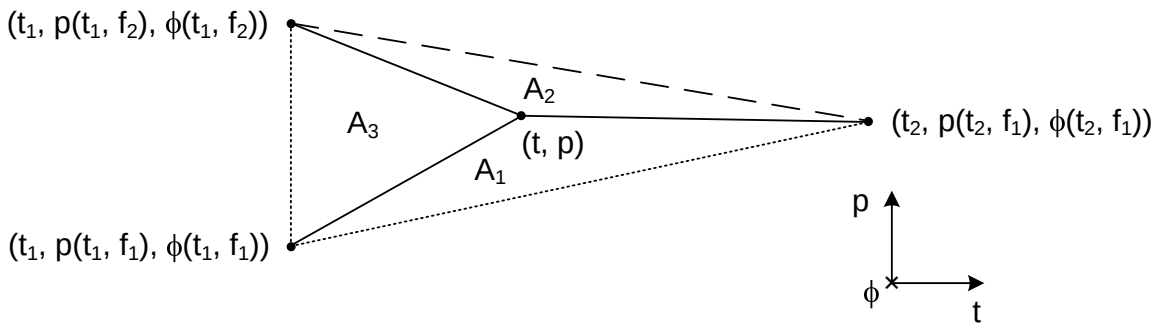

Figure PORSURF-6. Triangular Interpolation to Determine the Porosity at (*t, p*)

$(t_2, p(t_2, f_2), \phi(t_2, f_2))$. This is because at $t = 0$, the two points vertically separated in Figure PORSURF-6 at t_1 are equal (the porosity is equal to the initial value at $t = 0$ for all values of f).

PORSURF-6.0 Dynamic Closure of the North End and Hallways

The porosity surface method is not used to model the north end of the repository occupied by the experimental and operational regions. During development of the CCA PA, a supporting analysis compared brine and gas flow results for two models for closure of the north end of the repository: a dynamic closure model and a baseline model, in which the porosity and permeability of these regions were held constant (Vaughn, Lord, and MacKinnon 1995). The study examined the effect of these two approaches on brine releases to the accessible environment for both disturbed and undisturbed conditions, as well as the effects on brine pressures and brine saturations in the modeled regions. The study concluded that the baseline case (assuming constant low porosity and high permeability) consistently led to either similar or more conservative brine pressures and brine saturations, thereby overestimating potential releases relative to the dynamic consolidation case. Consequently, PA uses the simplifying case of constant porosity and permeability in the north end of the repository, rather than modeling dynamic closure of these areas.

PORSURF-7.0 Additional Information

The following attachments were included in the CCA, Appendix PORSURF to document additional details of the porosity surface method:

1. The CCA, Appendix PORSURF, Attachment 1, *Proposed Model for the Final Porosity Surface Calculations*. This memo documents preliminary configuration and constitutive property values for the final porosity surface calculations. Tables in the memo include elastic and creep properties for clean halite and argillaceous halite, volumetric strain data and material constants used in the volumetric-plasticity model for waste, and elastic and Drucker-Prager constants assigned to anhydrite Marker Bed 139. This attachment was supplemented and updated subsequent to the CCA by Butcher (1997a and 1997b).

2. The CCA, Appendix PORSURF, Attachment 2, *Baseline Inventory Assumptions for the Final Porosity Surface Calculations*. This memo discusses the effect of changes in the Transuranic Waste Baseline Inventory Report on the SANTOS analyses.

3. The CCA, Appendix PORSURF, Attachment 3, *Corrosion and Microbial Gas Generation Potentials*. This memo discusses the rationale for the base gas production potentials of 1,050 mol per drum for corrosion and 550 mol per drum for microbial decay in the SANTOS analyses.

4. The CCA, Appendix PORSURF, Attachment 4, *Resolution of Remaining Issues for the Final Disposal Room Calculations*. This memo provides additional detail on the disposal room elevation, determination of plastic constants for transuranic waste, and determination of SANTOS input constants for clean halite, argillaceous halite, and anhydrite.

5. The CCA, Appendix PORSURF, Attachment 5, *Sample SANTOS Input File for Disposal Room Analysis*. A representative sample input file is provided in this attachment. The only difference between this input file and the file used in the CCA calculations (see Stone 1997b) is a subroutine modifying the gas generation variable.

6. The CCA, Appendix PORSURF, Attachment 6, *Final Porosity Surface Data*. This attachment provides SANTOS results for selected gas generation scaling factors $f = 0.5$, 1.0, and 2.0. This attachment was updated and published as a formal SAND report (Stone 1997b) subsequent to submittal of the CCA.

7. The CCA, Appendix PORSURF, Attachment 7, *SANTOS – A Two-Dimensional Finite Element Program for the Quasistatic, Large Deformation, Inelastic Response of Solids*. This report documents the SANTOS code.

PORSURF-8.0 References

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Title 40 CFR Part 191
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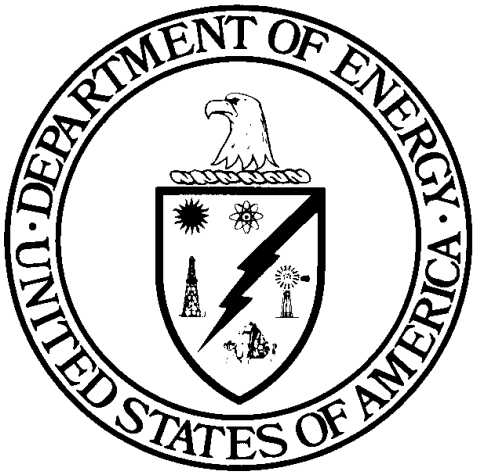
Appendix QAPD-2009
Quality Assurance Program Document



United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix QAPD-2009
Quality Assurance Program Document

U.S. DEPARTMENT OF ENERGY

CARLSBAD FIELD OFFICE

QUALITY ASSURANCE PROGRAM DOCUMENT

DOE/CBFO-94-1012

REVISION 9

Prepared by: *//signature on file//* **Date:** 11/20/2007

QA Manager, CBFO

Approved by: *//signature on file//* **Date:** 11/20/2007

Manager, CBFO

POLICY STATEMENT

The mission of the Carlsbad Field Office (CBFO) is to protect human health and the environment by operating the Waste Isolation Pilot Plant (WIPP) for safe disposal of transuranic (TRU) waste and by establishing an effective system for management of TRU waste from generation to disposal.

To help fulfill this mission and to ensure that the risks and environmental impacts are identified and minimized and that safety, reliability, and performance are optimized, it is the policy of the CBFO to establish, implement, and maintain an effective quality assurance (QA) program that supports compliance with applicable Federal, State, and local regulations and U.S. Department of Energy (DOE) orders and requirements.

Further, it is the intent of the CBFO to establish a culture and work environment that encourages setting and maintaining effective standards, identifying and resolving problems, emphasizing a continual pursuit of improvement, and fostering mutual respect and effective communication within the CBFO and among its participants, their suppliers, the public, and other stakeholders.

The *CBFO Quality Assurance Program Document* (QAPD) establishes QA program requirements for all quality-affecting programs, projects, and activities sponsored by the CBFO. The CBFO and organizations supporting the CBFO shall implement the applicable requirements of this QAPD within their systems for management and control of these activities.

It is the responsibility of all personnel assigned to CBFO-sponsored activities to achieve quality, identify problems, and recommend improvements. CBFO organizations define and achieve quality, recommend and promote improvements in the quality of items and processes, and identify, document, and resolve problems. CBFO quality assurance organizations verify the achievement of quality. CBFO management establishes and cultivates principles and practices that integrate QA program requirements and performance standards into their management approach and control systems. Additionally, CBFO management provides personnel who perform work with the proper qualifications, training, resources, oversight, and support to achieve the CBFO organizational and mission objectives.

The CBFO QA program requirements, as described in this QAPD, have my full endorsement and complete support. Implementation of the applicable QAPD requirements, responsibilities, and authorities is mandatory for all CBFO personnel.

In support of this policy statement, all CBFO personnel are expected to demonstrate their personal commitment to the achievement of quality through their active involvement in the implementation of the CBFO QA program.

David C. Moody
Manager, Carlsbad Field Office

Date

CHANGE HISTORY

Revision:	Changes to the QAPD
Rev 1	The QAPD has been substantially rewritten, the structure has been reorganized, and the content has been supplemented to broaden its scope from a CAO internal requirements and participant guidance document to a CAO program-wide requirements document. The document elements that defined the extent of applicability regarding specific QA program requirements have been clarified through the identification of "general" and "additional" requirements. Requirements for the grading of management controls have been clarified and more fully developed. The requirement for Sandia National Laboratories (SNL) and Westinghouse Waste Isolation Division (WID) QAPDs was deleted. A requirement was added for each organization to prepare, submit for review, and maintain a QA implementing procedures matrix. Revisions were made to incorporate all the requirements of 40 CFR Part 194, ANSI/NCSL Z540-1, and stakeholder comments. The use of the terms "will" and "shall" are interchangeable and denote requirements. Editorial changes were made throughout.
Rev 2	The section describing the organization and responsibilities for CAO personnel have been deleted from section QAPD-1.0 and incorporated into a policy statement (Attachment A and Attachment B). The QA program document hierarchy (Table QAPD-1), has been updated to reflect current regulatory requirements commitment and guidance documents. Requirements have been clarified in the areas of 1) grading, 2) the control of conditions adverse to quality, and 3) the preparation and maintenance of document review comments. Section QAPD-7.0, *Software,* has been rewritten to include both general and additional requirements. Definitions in the glossary have been added, deleted, and clarified. Editorial changes have been made throughout the document.
Rev 3	Changes in Revision 3 have been limited to those necessary to achieve full compliance with the Waste Analysis Plan (WAP) in the WIPP Hazardous Waste Facility Permit and to incorporate certain TRU waste QA requirements contained in the CAO QAPP, which is to be inactivated. Refer to the following list of pages affected by Revision 3.

List of Pages Affected by QAPD Revision 3

Change History	iv to v
Table of Contents	vi to xii
List of Acronyms	xiii to xiv
Introduction	I-1 to I-2
Section I - Management	1-1 to 1-23
Appendix A - Glossary	A-1 to A-10
Appendix B - References	B-1
Appendix C - CAO Organization	C-1 to C-2
Appendix D - CAO QA Manager Responsibilities	D-1 to D-2
Appendix E - TRU Sites Organization	E-1 to E-4

The pages in Revision 3 that are not listed above (Sections 2.0 through 6.0) remain effective.

Rev 4 The changes in Revision 4 were made to incorporate the DOE name change from the Carlsbad Area Office (CAO) to the Carlsbad Field Office (CBFO) and reflect current CBFO organization titles and responsibilities, rewrite the Quality Improvement section, update the source requirements documents listed in Table I-1, make changes to capture the wording used in the requirements documents, add more specific detail to the QA functional responsibilities of the CBFO management, and eliminate divisions between "general requirements" and "additional requirements." Editorial, formatting, and paragraph number changes have been made throughout the document. Change markings are present for those revisions that affect content. Changes related to editorial and formatting revisions are not marked. Technical revisions were made to the following specific sections:

	List of Acronyms and Abbreviations	ix - x
Table I-1	QA Program Source Documents	xii
1.1.1	Organization	1-1
1.1.1.4.B	Interface Responsibilities	1-4
1.1.2.2	Procedures Matrix	1-5
1.1.2.3	Applicability of QAPD Requirements	1-5
1.1.2.4	Grading Items and Activities and Applying Management Controls	1-6
1.2.1	Qualification Requirements	1-8
1.2.2	Training Requirements	1-8
1.3	Quality Improvement	1-9 to 1-15
1.4.B	Documents	1-15
1.5.2	Generating QA Records	1-17 to 1-18
1.5.4	Classifying QA Records	1-19 to 1-20
1.5.6.1	Records Classification and Disposition	1-22
2.1.3.A	Item Identification and Control	2-2
2.2	Design Control	2-5
2.2.9	Design Change	2-11

2.3.5.A	Procurement Document Review and Approval	2-14
2.3.7.1	Source Verification	2-16
2.3.7.4	Supplier Certificate of Conformance	2-17
2.3.9	Commercial Grade Items	2-18
2.4.2	Qualification of Nondestructive Examination Personnel	2-21
3.2.A	Independent Assessment	3-1
3.2.2.8.B	Reporting Audit Results	3-8 to 3-9
5.4	Qualification of Existing Data	5-4 to 5-6
5.5	Quality Assurance Compliance Data (new section)	5-6
Appendix A	Glossary	A-1 to A-2, A-5 to A-7, A-9 to A-10
Appendix C	CBFO Organization, Responsibilities, and Interfaces	C-1
Appendix D	CBFO Quality Assurance Manager Responsibilities	D-1 to D-2
Appendix E	TRU Waste Characterization and Certification Organizational and Individual Responsibilities	E-1

Rev 5 The changes in revision 5 were made to address an EPA finding from the annual EPA QA audit conducted on January 7 – 9, 2003. This finding concerned the language in the QAPD regarding the responsibilities for achievement and verification of quality not matching the requirements from NQA-1. In addition to the change made to address the EPA finding, the following changes were made:

- The requirement for program participants to maintain a QAPD procedures matrix has been deleted; because this matrix is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement for organizations receiving records to return a receipt acknowledgment to the sender has been deleted, because this also is not required by NQA-1, 2, or 3, or other regulatory document.
- The requirement that CBFO and participant organization ensure that they comply with the Federal Acquisition Regulations was deleted because the QAPD is not the appropriate document to specify this requirement.
- The requirement to maintain records related to the characterization of the mixed transuranic waste form as lifetime QA records was deleted. Records classification of mixed waste characterization records is specified in the Hazardous Waste Facility Permit.
- The requirement to maintain audit and surveillance checklists as QA records was deleted, because this is not a requirement of NQA-1, 2, or 3, or other regulatory document.
- The requirement for calibration laboratories to comply with ANSI/NCSL Z540-1 was deleted because this is not a requirement of NQA-1, 2, or 3, or

other regulatory document.

- The safety analysis report for the HalfPACT shipping package was added as a regulatory source document to Table QAPD-1
- Section 5.5 was deleted. The requirements for data quality evaluation during scientific investigation planning are addressed in Section 5.1.G of the QAPD. Section 5.5 was redundant and specified requirements for the content of compliance applications, which was not appropriate for the QAPD.
- Changes were also made to correct typographical errors and incorrect section references.

Technical revisions were made to the following specific sections:

Section	Section Title
	Policy Statement
	Introduction
1.1.1	Organization
1.1.1.1.D	Management
1.1.1.3	Quality Assurance Management
1.1.2.2	Procedures Matrix (deleted)
1.2.1	Qualification Requirements
1.3.2.5	Disposition of Nonconforming Items or Data
1.5.4.B and E	Classifying QA Records
1.5.6.A	Storage, Preservation, Safekeeping, and Disposition of QA Records
2.1.B	Work Processes
2.3	Procurement
2.3.4	Procurement Document Requirements
2.4.6	Use and Control of M&TE
2.4.7	Calibration
3.2.2.10	Audit Records
Appendix C	CBFO Organization, Responsibilities, and Interfaces
Appendix D	CBFO Quality Assurance Manager Responsibilities

Rev. 6 The changes in Revision 6 were made to implement the new CBFO organization chart that was approved on May 15, 2004.

Revisions were made to the following specific sections

	List of Acronyms and Abbreviations
	Introduction
Appendix C	CBFO Organization, Responsibilities, and Interfaces
Appendix D	CBFO Quality Assurance Manager Responsibilities
Appendix E	TRU Waste Characterization and Certification Organizational and Individual Responsibilities

Rev. 7 The changes in Revision 7 were the direct result of DOE EM 3-2 comments relative to compliance with DOE O 414.1B.

Revisions were made to the following specific sections:

	Policy Statement
	List of Acronyms and Abbreviations
	Section 1.3
	Section 2.3
	Program Source Documents
	Appendices C and D

Rev. 8 The changes in Revision 8 were made to address thirteen minor findings and one concern from an EPA inspection of CBFO's QA program (Ref: Letter from Gitlin to Moody dated April 18, 2006). Document citations were added to include remote-handled waste packaging. The exemption of NEPA-related software from the requirements of the QAPD was deleted. The applicability of software QA to safety software was clarified. Editorial changes related to the June 26, 2006 reorganization of the CBFO were also incorporated.

Revisions were made to the following specific sections:

	List of Acronyms and Abbreviations
	Introduction
1.1.2.1	Quality Assurance Program Documents
1.2.2	Training Requirements
1.3.2.3	Reporting Nonconformances
1.5.3	Indexing QA Records
1.5.6	Storage, Preservation, Safekeeping, and Disposition of QA Records
1.5.6.1	Records Disposition
2.3.1	Procurement Planning Requirements
2.3.7	Acceptance of Items or Services
2.3.8	Control of Supplier Nonconformances
2.4.2	Qualification of Nondestructive Examination Personnel
2.4.7	Calibration
3.2.2.1	Scheduling Audits
6.1	Applicability
6.6.2.4	Testing Phase
6.7.3	Validation
Appendix A	Glossary
Appendix B	References
Appendix C	CBFO Organization, Responsibilities, and Interfaces
Appendix D	CBFO Quality Assurance Manager Responsibilities

Appendix E	TRU Waste Characterization and Certification Organizational and Individual Responsibilities

Rev. 9

The QAPD was revised to clarify that reliance on administrative controls alone is not sufficient for differentiating between waste that is acceptable for shipment to WIPP and waste that does not meet the WIPP waste acceptance criteria. The classification of conditions adverse to quality related to the Hazardous Waste Facility Permit was also clarified. The language regarding reporting nonconformances was revised to comport with the November 16, 2006 Permit Modification. The requirements for records disposition were revised to comport with the Class 1 Permit Modification that was approved by NMED on September 13, 2007.

Revisions were made to the following specific sections:

1.3.2.3	Reporting Nonconformances
1.3.2.4	Segregating Nonconforming Items
1.3.3.2	Classification of Conditions Adverse to Quality
1.3.3.5	Corrective Action Planning
1.5.6.1	Records Disposition

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Acronyms and Abbreviations

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society of Nondestructive Testing
ASTM	American Society for Testing and Materials
CAP	Corrective Action Plan
CAQ	Condition Adverse to Quality
CATS	Corrective Action Tracking System
CBFO	Carlsbad Field Office
CFR	Code of Federal Regulations
DQO	Data Quality Objective
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
HWFP	Hazardous Waste Facility Permit
M&DC	Monitoring and Data Collection Equipment
M&TE	Measuring and Test Equipment
M&O	Management and Operating Contractor
NARA	National Archives and Records Administration
NDE	Nondestructive Examination
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NMED	New Mexico Environment Department
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NTP	National TRU Program
NUREG	Nuclear Regulatory Commission Report designation
OD	Office Director
QA	Quality Assurance
QAPD	Quality Assurance Program Document
QAPjP	Quality Assurance Project Plan
QAPP	Transuranic Waste Characterization Quality Assurance Program Plan (CAO-94-1010)

QC	Quality Control
RIDS	Records Inventory and Disposition Schedule
SCAQ	Significant Condition Adverse to Quality
SNL	Sandia National Laboratories
SQA	Software Quality Assurance
TRAMPAC	TRUPACT-II Authorization Methods for Payload Control
TRU	Transuranic
TRUPACT-II	Transuranic Package Transporter, Model II
UL	Underwriter's Laboratory
WAP	Waste Analysis Plan
WID	Westinghouse Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WTS	Washington TRU Solutions

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QAPD-1.0 Introduction

The Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) is the document that describes and establishes the CBFO Quality Assurance (QA) program. The provisions of this QAPD apply to all programs and projects managed by the CBFO which require a QA program, including activities related to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the Waste Isolation Pilot Plant (WIPP) facility. This document identifies the sources of all applicable QA program requirements. The subject requirements are based on criteria contained, or incorporated by reference, in source documents listed in Table QAPD-1. These documents have been placed into one of three categories:

1. Regulatory documents, including those incorporated by reference, that define the requirements necessary for the WIPP to be granted a certificate of compliance by the Federal Government and permit(s) by State governmental agencies to dispose of transuranic (TRU) and mixed TRU wastes in the WIPP repository, or that define requirements applicable to the management of the WIPP as a U.S. Department of Energy (DOE) non-reactor nuclear facility

2. Commitment documents that are imposed by DOE management

3. Guidance documents that provide additional information that is useful in developing and implementing the CBFO QA program

The purpose of the QAPD is to describe the applicability and requirements of the CBFO QA program as applied within the CBFO management infrastructure. In this context, the management infrastructure includes all CBFO program participants (e.g., Sandia National Laboratories [SNL] as Science Advisor; Washington TRU Solution [WTS] as the Management and Operating [M&O] contractor of the WIPP, and various DOE organizations and contractors performing work under the direction of the CBFO). This program is developed and maintained through an ongoing process that selectively applies the varied QA program criteria. This process provides due consideration to the extent of source requirement applicability, a graded-approach, available guidance, and the current foreseeable activities expected to be performed under the direction of CBFO.

The requirements in this QAPD are based on the principle that work shall be planned, documented, performed under controlled conditions, and periodically assessed to establish work item quality and process effectiveness and to promote improvement. Management, line personnel, and organizations are responsible for planning and achieving quality and for promoting continuous improvement. Quality assurance organizations and personnel are responsible for the verification of the achievement of quality. This QAPD further delineates the quality contributions expected of all personnel and encourages their active participation in implementing the CBFO QA program.

Table QAPD-1. QA Program Source Documents

MAJOR REGULATORY REQUIREMENTS DOCUMENTS	TITLE
40 CFR Part 191	Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes
40 CFR Part 194	Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations
10 CFR Part 830	Nuclear Safety Management
10 CFR Part 71	Packaging and Transportation of Radioactive Material
10 CFR Part 21	Reporting of Defects and Nonconformances
ASME NQA-1-1989 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Requirements for Nuclear Facilities
ASME NQA-2a-1990 addenda, Part 2.7 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Requirements of Computer Software for Nuclear Facility Applications
ASME NQA-3-1989 excluding Section 2.1(b) and (c) and Section 17.1 (incorporated by reference in 40 CFR Part 194)	Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories
NM 48901 39088 – TSDF/WIPP	WIPP Hazardous Waste Facility Permit
NRC Certificate Number 9212	RH-TRU 72-B Certificate of Compliance
NRC Certificate Number 9218	TRUPACT-II Certificate of Compliance
NRC Certificate Number 9279	HalfPACT Certificate of Compliance
NRC Certificate Number 9204	10-160B Certificate of Compliance
NUREG-1297 (1988) (incorporated by reference in 40 CFR Part 194)	Peer Review for High-Level Nuclear Waste Repositories
COMMITMENT DOCUMENTS	**TITLE**
DOE O 414.1C	Quality Assurance
DOE O 226.1	Implementation of Department of Energy Oversight Policy
SNT-TC-1A-1980	American Society of Nondestructive Testing (ASNT) "Recommended Practice No. l SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing," August 1980
GUIDANCE DOCUMENTS	**TITLE**
DOE, G-414.1-2A	Quality Assurance Management System Guide for Use with 10 CFR Part 830.120 and DOE O 414.1
NUREG/BR-0167 (1993)	Software Quality Assurance Program and Guidelines

QAPD-2.0 Management Requirements

This section describes the fundamental elements related to the organization and management of the CBFO QA program, as well as the fundamentals to be applied in managing the work of the program.

QAPD-2.1 Organization and Quality Assurance Program

This section describes the requirement for the organizational structure, primary interfaces, functional responsibilities, and levels of authority required to implement the CBFO QA program. In addition, this section describes the basic elements of the QA program and their applicability.

QAPD-2.1.1 Organization

Effective implementation of the CBFO QA program is dependent on the efforts at all levels of the program participants. The organizational structures and the responsibility assignments of program participants shall be such that those organizations that have been assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and supporting the workers in pursuit of quality. QA organizations of the program participants are responsible for verifying the achievement of quality in the implementation of the CBFO QA program. CBFO organizational and individual responsibilities are addressed in Attachment A and B. Organizational and individual responsibilities for TRU waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility are addressed in Section QAPD-2.3.3.1.

QAPD-2.1.1.1 Management

1. Management has overall responsibility for successfully accomplishing activities subject to this QAPD. Management provides the necessary planning, organization, direction, control, resources, and support to achieve their defined objectives. Management is responsible for planning, performing, and improving the work.

2. Management is responsible for establishing and implementing policies, plans, and procedures that control the quality of work, consistent with the provisions of this QAPD.

3. Management quality responsibilities include:

   A. Ensuring that adequate technical and QA training is provided for personnel performing activities subject to this QAPD

   B. Ensuring compliance with all applicable regulations, DOE orders and requirements, and applicable Federal, State, and local laws

   C. Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records

D. Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations

E. Developing, implementing, and maintaining plans, policies, and procedures that implement this QAPD

F. Identifying, investigating, reporting, and correcting quality problems

4. Quality achievement is the responsibility of those performing the work. Line organizations are responsible for achieving quality in their areas.

5. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

QAPD-2.1.1.2 Employees

Each program participant employee is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

QAPD-2.1.1.3 QA Management

An organization's QA management has the authority and overall responsibility to independently assess the organization's effective implementation of the QA program to verify the achievement of quality.

1. QA management shall:

A. Schedule and conduct QA assessments

B. Maintain liaison with participant QA organizations and other affected organizations

C. Ensure preparation, review, and issuance of QA plans and procedures that implement the provisions of this QAPD

D. Review and approve supplier and subcontractor QA plans

E. Track or perform trend analysis of quality problems, and report quality problem areas

F. Provide for the administrative processing of documentation concerning conditions adverse to quality

G. Have direct access to responsible management at a level where appropriate action can be effected

H. Be sufficiently independent from cost and schedule considerations

I. Have the organizational freedom to communicate with management

J. Have no assigned responsibilities unrelated to the QA program that would prevent appropriate attention to QA matters

K. Develop, establish, and interpret QA policy and ensure effective implementation

L. Interface, as appropriate, with the CBFO staff, participants, and other stakeholders on QA matters

M. Assist subordinate organizations with quality planning, documentation, quality measurement, and problem identification and resolution

N. Provide guidance to all applicable subordinate organizations concerning identification, control, and protection of QA records

2. The QA organization shall have sufficient authority, access to work areas, and organizational freedom to:

A. Identify quality problems

B. Recommend solutions

C. Verify implementation of solutions

D. Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

QAPD-2.1.1.4 Communication and Interface Responsibilities

1. Communication Responsibilities

Participating organizations at all management levels shall establish communication channels that provide timely and wide dissemination of information pertinent to quality performance, such as:

A. The status of development and implementation of the QA program

B. The status and resolution of significant quality problems

C. The lessons learned from significant quality problems and adverse conditions

D. Quality management practices and improvements

E. Trend analysis results

2. Interface Responsibilities

A. Where more than one organization is involved in the execution of activities covered by this QAPD, the responsibility and authority of each organization shall be clearly established, defined, and documented. The external interfaces between organizations, the internal interfaces between organizational units, and interface changes shall be

documented. Interface responsibilities shall be defined and documented and shall include the requirements for management, performance, and assessment.

B. CBFO-sponsored activities, performed by organizations external to the CBFO, include, but are not limited to, compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. Responsible CBFO organizations shall ensure the effective implementation of the CBFO QA program.

QAPD-2.1.1.5 Delegation of Work

Individuals or organizations responsible for establishing, planning, accomplishing, and assessing the work may delegate work to other individuals or organizations. However, the individuals or organizations making the delegation shall retain overall responsibility for the delegated work.

QAPD-2.1.1.6 Resolution of Disputes

Differences of opinion involving the definition and implementation of QA program requirements will be brought to the attention of the appropriate QA manager and the responsible manager. If not resolved, the issues will be elevated progressively to successively higher levels of management as necessary.

QAPD-2.1.2 Implementation of the CBFO QA Program

QAPD-2.1.2.1 Quality Assurance Program Documents

Program participants shall develop and follow plans and procedures that effectively implement the requirements described in this QAPD along with those requirements contained within the Resource Conservation and Recovery Act (RCRA) Permit Waste Analysis Plan (WAP), Quality Assurance Project Plans (QAPjPs), Certification QA Plans, Waste Acceptance Criteria (WAC), and Certificates of Compliance for NRC licensed nuclear packaging, as applicable.

QAPD-2.1.2.2 Applicability of QAPD Requirements

The terminology "items or activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility" is used generically throughout this QAPD to refer to the following:

1. WIPP site activities or operations that process or store radioactive liquid or solid waste, perform waste management activities involving radioactive materials, or design, manufacture, or assemble items for use with radioactive materials in such a form and quantity that a nuclear hazard exists

2. Waste characterization activities

3. Environmental monitoring, monitoring the performance of the disposal system, and sampling and analysis activities

4. Field measurements of geological factors, ground water, meteorology, and topography

5. Computations, codes, models, and methods used to demonstrate compliance with disposal regulations

6. Expert judgment elicitation to support applications for recertification or determination of compliance

7. Design of the disposal system and actions taken to ensure compliance with design specifications

8. The collection of data and information used to support compliance application(s) and/or any modifications to the compliance application

9. Other systems, structures, components, and activities important to the isolation of waste in the disposal system

10. Those items and activities related to Nuclear Regulatory Commission (NRC) licensed packaging (e.g., Transuranic Package Transporter Model II [**TRUPACT-II**], **RH-72B**, CNS 10-160B), design, purchase, fabrication, handling, shipping, storage, cleaning, assembly, inspection, testing, operation, maintenance, repair, and modification or components of packaging that are important to safety

QAPD-2.1.2.3 Grading Items and Activities and Applying Management Controls

1. The graded approach is the process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with the following factors:

   A. The importance of an item or activity with respect to safety, waste isolation, and regulatory compliance

   B. The importance of the data to be generated

   C. The need to demonstrate compliance with specific regulatory design and QA requirements

   D. The impact on the results of performance assessments and engineering analyses

   E. The magnitude of a hazard or the consequences of failure

   F. The life-cycle stage of a facility or item

   G. The programmatic mission of a facility

H. The particular characteristics of a facility, item, or activity (e.g., complexity, uniqueness, history, or the necessity for special controls or processes)

I. The relative importance of radiological and non-radiological hazards

2. The extent of management and QA controls applied to an item or activity will vary as a function of the degree of confidence needed to achieve the desired quality of the item or activity. The grading process provides the flexibility to design and implement controls that best suit the facility or activity. Each organization should develop their own method to determine that the defined grading process is effective. The use of the graded approach shall determine the appropriate level of controls necessary to manage the items, systems, and activities necessary to ship TRU waste to WIPP.

3. Grading methods for each organization shall provide for:

A. The assignment of management and QA control levels

B. The definitive criteria used in selecting those levels

C. Detailed descriptions of the management and QA control provisions corresponding to those levels, based on the above requirements

4. Program participant procedures that establish and implement a graded approach for items and activities under the cognizance of the CBFO shall be submitted to the CBFO QA Manager for approval for use in CBFO programs.

QAPD-2.1.2.4 Planning Work

Planning shall be performed and documented to ensure that work is accomplished under suitably controlled conditions. As appropriate, planning elements shall include:

1. Definition of work scope, objectives, and a listing of the primary tasks involved

2. Identification of scientific approaches or technical methods used to collect, analyze, or study results of applicable work

3. Identification of field and laboratory testing standards and quality criteria

4. Identification of applicable implementation documents (appropriate nationally recognized standards shall be used whenever possible)

5. Identification of field and laboratory testing equipment or other equipment

6. Identification of, or provisions for the identification of, required records and the recording of objective evidence of the results of the work performed

7. Identification of prerequisites, special controls, specific environmental conditions, processes, or skills

8. Identification of computer software

QAPD-2.1.2.5 Peer Reviews

Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes. Peer reviews of the following activities shall be conducted in a manner consistent with NUREG-1297, *Generic Technical Position on Peer Review for High-Level Nuclear Waste Repositories:*

1. Conceptual models selected and developed by the DOE

2. Waste characterization analysis as required in 40 CFR § 194.24(b)

3. Engineered barrier evaluation as required in 40 CFR § 194.44

QAPD-2.2 Personnel Qualification and Training

Personnel shall be trained and qualified to ensure they are capable of performing their assigned tasks and to ensure that job proficiency is maintained.

QAPD-2.2.1 Qualification Requirements

Qualification requirements for CBFO and participant positions or job functions shall be established for activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility. The evaluation shall be documented. At a minimum, these positions include managers, designers, scientists, independent assessment personnel, operators, maintenance personnel, technicians, and inspectors.

The responsible organization shall:

1. Analyze each job position to determine the task responsibilities of the position subject to the QAPD. The analysis shall identify minimum education, experience, and training prerequisites for each position involved in the planning, performance, or verification of activities subject to the QAPD, commensurate with the scope, complexity, and nature of the work.

2. Ensure that personnel selected to perform or verify activities subject to the QAPD have education, experience, and training commensurate with the minimum requirements specified. The qualification of an individual shall be based upon evaluation of education and experience, which is compared to the established requirements for the position.

QAPD-2.2.2 Training Requirements

CBFO and participant personnel performing activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility shall receive related training in accordance with the following requirements. Training shall

emphasize the correct performance of work, describe why the applicable quality and nuclear safety requirements exist, and describe the fundamentals of the work and the context. Training shall be subject to ongoing review to determine instruction and training program effectiveness and shall be upgraded whenever needed improvements or enhancements are identified. Management shall:

1. Ensure that personnel receive indoctrination and training, including on-the-job and hands-on training, as needed, to achieve initial proficiency; maintain proficiency; and adapt to changes in technology, methods, job responsibilities and authority, and quality assurance implementing procedures, prior to performing any tasks subject to the QAPD.

2. Ensure that personnel receive indoctrination in the following:

   A. General criteria, including applicable QA plans, codes, regulations, and standards

   B. Specific criteria, including applicable QAPjPs and implementing procedures

3. Ensure that records generated during qualification, general indoctrination and training, or specific skill training activities are collected and maintained as QA records.

QAPD-2.3 Quality Improvement

Quality improvement is a management process carried out to improve items, services, products, or processes. All aspects of work that affect quality and the management system are subject to continuous improvement through assessment and feedback processes.

For findings identified by the organizations listed in DOE O 414.1C, Attachment 4, Paragraph 1, the implementation process described in DOE G 450.4-1B, Appendix G will be invoked. The CBFO Office Director, Office of Disposal, is responsible for the management of the identified issues as required by the DOE Corrective Action Tracking System (CATS) User's Guide. This function is applicable only to safety issues identified at the CBFO. The waste generator sites are required to implement the process of the Corrective Action Management Program as directed by the appropriate site office.

Quality-related program deficiencies are addressed as indicated in Section QAPD-2.3.3.3.

QAPD-2.3.1 Quality-Affecting Problems

Quality-affecting problems and items, services, and processes that do not meet established requirements shall be identified, documented, reported, controlled, and corrected. Quality problems may be identified by the organization or by an external source.

QAPD-2.3.1.1 Problem Identification

All personnel shall be responsible for identifying quality problems and shall be encouraged by management to suggest improvements. CBFO and participant organizations foster a "no-fault" attitude for quality problems and prioritize and focus resources on preventive actions and on those quality problems that have the greatest potential for:

1. Posing adverse risks to the environment and human health
2. Adversely impacting the quality, safety, and reliability of waste operations
3. Affecting the ability to meet quality requirements

QAPD-2.3.1.2 Problem Types

Quality-affecting problems may involve:

1. Noncompliance with a QA program requirement. A noncompliance is classified as a Condition Adverse to Quality (CAQ) or Significant Condition Adverse to Quality (SCAQ)
2. Nonconforming items, including suspect/counterfeit items or data, that do not conform to specified requirements.

QAPD-2.3.2 Nonconformances

Items or data that do not conform to established requirements shall be controlled to prevent inadvertent installation or use.

QAPD-2.3.2.1 Documenting and Evaluating Nonconforming Items

The documentation and evaluation of nonconforming items shall be accomplished by:

1. Clearly identifying and describing the characteristics that do not conform to specified criteria
2. Reviewing nonconformance documentation and proposed recommended disposition of the nonconforming item or data. The review shall include a determination of the need for corrective action in accordance with the requirements of Section QAPD-2.3.3, *Corrective Action*. In addition, organizations affected by the nonconformance shall be notified.
3. Evaluating and approving of recommended dispositions
4. Ensuring that personnel performing evaluation or recommending disposition have demonstrated competence in the specific area they are evaluating or dispositioning, and have an adequate understanding of the requirements
5. Implementing procedures that specify the responsibility and authority for reviewing, evaluating, approving the disposition, and closure of the nonconformance

QAPD-2.3.2.2 Identifying Nonconforming Items or Data

1. Nonconforming items shall be physically identified by marking, tagging, segregation, or other methods that do not adversely affect the end use. The identification shall be legible and easily recognizable, and shall be traceable to the reporting documentation.

2. If physical identification of each nonconforming item is not practical, the container, package, or segregated storage area, as appropriate, shall be physically identified as in A above.

QAPD-2.3.2.3 Reporting Nonconformances

Organizations affected by a nonconformance shall be notified. The CBFO shall be notified in writing within 5 calendar days of identification of any non-administrative nonconformance related to applicable requirements specified in the WIPP Hazardous Waste Facility Permit (HWFP) Waste Analysis Plan (WAP), which is first identified at the site project manager's signature release level (i.e., a failure to meet a data quality objective [DQO]). Notification is also required if the results sampling and analysis specified in Permit Attachment B are inconsistent with acceptable knowledge documentation. The nonconformance report shall be submitted to CBFO within 30 calendar days of identification of the deficiency.

Nonconformances related to defects or failure to comply with requirements applicable to NRC licensed packaging (e.g., TRUPACT II, RH 72-B) shall be reported to the CBFO Office of the National TRU Program. The WIPP M&O contractor will evaluate issues and nonconformances for reporting to the NRC under 10CFR Part 21 or Part 71 and provide the results of this evaluation to CBFO.

QAPD-2.3.2.4 Segregating Nonconforming Items

1. Further processing, delivery, installation, or use of nonconforming items shall be controlled pending the evaluation and approval of the disposition.

2. Nonconforming items shall be segregated, when practical, by placing them in a clearly identified and designated hold area until properly dispositioned.

3. If segregation is impractical or impossible due to physical condition, other precautions shall be employed to preclude inadvertent use.

4. Reliance solely on other precautions (i.e., administrative controls) to differentiate waste containers that are acceptable for shipment to WIPP from those containers that do not meet the WIPP acceptance criteria is not allowed.

QAPD-2.3.2.5 Disposition of Nonconforming Items or Data

The disposition of nonconforming characteristics shall be accomplished as follows:

1. The nonconformance characteristics shall be reviewed, and recommended dispositions of nonconforming items or data shall be proposed and approved in accordance with documented procedures. Personnel performing evaluations to determine a disposition shall have demonstrated competence in the specific area they are evaluating, have adequate understanding of the requirements, and have access to pertinent background information.

2. The dispositions "use-as-is," "reject," "repair," or "rework" for nonconforming items or data shall be identified and documented.

3. The technical justification for the acceptability of a nonconforming item or data that has been dispositioned "use-as-is" or "repair" shall be documented.

4. Items that do not meet original design requirements that are dispositioned "use-as-is" or "repair" shall be subject to design control measures commensurate with those applied to the original design, and

   A. If changes to the specifying document are required to reflect the as-built condition, then the disposition shall require action to change the specifying document to reflect the accepted nonconformance.

   B. Any document or QA record change required by the disposition of the nonconformance shall be identified in the nonconformance documentation and, when a document or record is changed, the justification for the change shall reference the nonconformance documentation.

5. The disposition of an item to be reworked or repaired shall contain a requirement to re-examine (inspect, test, or examine by nondestructive examination) the item to verify acceptability. Repaired or reworked items shall be re-examined using the original process and acceptance criteria unless the nonconforming item disposition has established alternate acceptance criteria.

QAPD-2.3.2.6 Quality Trending of Nonconformances

Nonconformance documentation shall be periodically analyzed by the QA organization to identify quality trends in accordance with Section QAPD-2.3.3, *Corrective Action*.

QAPD-2.3.3 Corrective Action

QAPD-2.3.3.1 Identifying Conditions Adverse to Quality (CAQ)

A CAQ occurs when a QA requirement has not been met.

QAPD-2.3.3.2 Classification of Conditions Adverse to Quality

Classification of CAQs is based on the effect the CAQ has on compliance to regulatory requirements for safety, operability, TRU waste characterization, TRU waste site certification, TRU waste containment, and the effective implementation of the QAPD. Any CAQs that are determined to be noncompliant with an HWFP condition or requirement require corrective action plans (CAPs) that meet the requirements of Section QAPD-2.3.3.5.

QAPD-2.3.3.3 Conditions Adverse to Quality

1. CAQs shall be documented and reported to the appropriate levels of management responsible for the condition and to the QA organization for tracking.

2. Responsible management shall determine the extent and impact of the adverse condition and, at a minimum, complete remedial action as soon as practical.

QAPD-2.3.3.4 Significant Conditions Adverse to Quality

1. Implementing documents shall include criteria for determining if a condition adverse to quality is significant. These criteria shall be based on the criteria in the definition of conditions adverse to quality included in Section QAPD-8.0.

2. SCAQs shall be investigated, documented (including the extent of the condition and the impact on completed work), and reported to the management responsible for the condition, their senior management, and the QA organization for tracking.

3. Responsible management shall determine when an SCAQ related to the WIPP HWFP (i.e., a waste characterization process currently certified by the CBFO at a TRU waste site) requires accelerated corrective action. The required time interval for accelerated corrective action shall be established by the CBFO QA Manager.

QAPD-2.3.3.5 Corrective Action Planning

CAPs are required for all SCAQs. SCAQ CAPs shall address:

1. Remedial Action: actions necessary to resolve the initial problem

2. Investigative Actions: assessment of the extent and impact of the SCAQ

3. Root Cause Determination: identification of the root cause of the SCAQ

4. Actions to Preclude Recurrence: actions necessary to prevent recurrence of the SCAQ

5. Schedule: milestones for completion of the CAP, including expected completion dates and identification of responsible individuals

QAPD-2.3.3.6 Work Suspension

If a work suspension condition has been identified, responsible management shall take appropriate action to lift and close the work suspension, based on the resolution of the related SCAQ. The QA organization shall verify and document the completion of applicable corrective actions prior to any management action releasing the work suspension.

QAPD-2.3.3.7 Corrective Action Follow-up

A system shall be established to verify the effective implementation of scheduled corrective actions and to complete corrective actions in a timely manner. The QA organization shall evaluate the adequacy of corrective actions planned, assign responsibility for follow-up verification, and perform and document verification results. If results of verification are unsatisfactory, the CAP shall be revised appropriately, and corrective actions and verification performed.

QAPD-2.3.3.8 Recurring Conditions Adverse to Quality

For recurring CAQs, management shall:

1. Determine the events leading up to the occurrences
2. Develop an understanding of the technical and work activities associated with the CAQ
3. Ascertain and identify any generic implications and impacts on completed work
4. Determine the extent to which similar quality problems, or precursors to the problem, have been identified
5. Determine the effectiveness of corrective actions that have been taken
6. Consider suspending work associated with the applicable activity, as appropriate
7. Suggest actions that can be taken by the responsible organization to preclude recurrence, as appropriate

QAPD-2.3.3.9 Quality Trending

The need for quality improvement is accomplished through quality analysis and trending. To provide reliable trending information, the following activities shall be performed:

1. Quality performance data shall be identified, collected, and routinely analyzed to identify opportunities to improve items, services, activities, and processes. This analysis shall consider information from external sources and not be limited to one type of work or to one organization.
2. The analyses shall be performed semi-annually to provide for prompt identification of trends adverse to quality. Reports of CAQs, including those identified during quality assurance audits as Corrected During the Audit/Surveillance (CDAs/CDSs), shall be evaluated to identify adverse quality trends and root causes, with results reported to the organization responsible for corrective actions.
3. Program participants will report trending information to responsible management and to the applicable organization.

QAPD-2.4 Documents

1. Documents shall be prepared, reviewed, approved, issued, used, and revised to prescribe processes, specify requirements, or establish design.
2. Documents that specify requirements, prescribe processes, or establish design important to the compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, such as instructions, procedures, drawings,

test plans, management plans, technical reports, performance reports, and test reports, shall be controlled according to the requirements listed below to ensure that the correct documents are being used.

QAPD-2.4.1 Document Preparation, Review, Approval, and Issuance

1. Documents shall be reviewed for adequacy, correctness, and completeness prior to approval and issuance. Program participants shall identify the individuals or organizations responsible for the preparation, review, approval, and issuance of controlled documents.

2. Documents shall be controlled during the review and approval phase in accordance with approved procedures.

3. The requesting organization shall identify the applicable criteria for the review. These criteria shall consider technical adequacy, accuracy, completeness, and compliance with established requirements.

4. Pertinent background information or data shall be made available by the organization requesting the review if the information is not readily available to the reviewer.

5. The review will be performed by individuals other than the originator.

6. Reviewers will be technically competent in the subject area being reviewed.

7. The organization or technical discipline affected by the document shall review the document according to the established review criteria.

8. The appropriate quality assurance organization shall review documents that translate CBFO QAPD or other CBFO requirements.

9. Review comment documentation shall be resolved in accordance with approved procedures. Evidence of review comment resolution shall be maintained by the originating organization.

10. Documents shall be approved for release by authorities designated in accordance with approved procedures.

11. Documents shall be issued by designated individuals or organizations in accordance with approved procedures.

QAPD-2.4.2 Document Distribution and Use

The distribution and use of controlled documents and forms that document or prescribe work, including changes and editorial corrections to documents, shall be controlled to meet the following requirements:

1. Documents shall be distributed to affected personnel and used at the work location.

2. Effective dates shall be established and identified on the approved documents.

3. The disposition of obsolete or superseded documents and forms shall be controlled to avoid their inadvertent use.

4. Controls shall be established and maintained to identify the current status or revision of controlled documents and forms.

5. Controls shall provide for identification of documents to be controlled and their distribution.

QAPD-2.4.3 Document Changes

1. Changes to documents, other than those defined below as editorial changes, shall be reviewed and approved by the same organizations that performed the original review and approval, unless other organizations are specifically designated in accordance with approved procedures.

2. Document changes shall be:

   A. Reviewed by the organizations or technical disciplines affected

   B. Clearly indicated in the changed document

3. Editorial or minor changes may be made without the same level of review and approval as the original or otherwise changed document. The following items are considered editorial or minor changes:

   A. Correcting grammar or spelling (the meaning has not changed)

   B. Renumbering sections or attachments

   C. Updating organizational titles

   D. Changes to non-quality affecting schedules

   E. Revising or reformatting forms, providing the original intent of the form has not been altered

   F. Attachments marked “Example,” or “Sample,” or exhibits that are clearly intended to be representative only

   G. Clarification changes that do not affect the purpose of the document

4. A change in an organizational title accompanied by a change in responsibilities is not considered an editorial change.

5. The organization responsible for preparing the document shall identify and approve editorial changes.

QAPD-2.5 Records

1. Records shall be specified, prepared, reviewed, approved, and maintained.

2. A "QA record" is an authenticated record that provides objective evidence of the quality of items or activities. QA records shall be controlled in accordance with the following requirements.

QAPD-2.5.1 Records System

1. A QA records system shall be established by the responsible organization at the earliest practical time, consistent with the schedule for accomplishing work activities. The QA records system shall be defined, implemented, and enforced in accordance with written procedures, instructions, or other documentation.

2. This does not prohibit the management of QA records within a general records system, nor does this require a separate records system for QA records, as long as the applicable provisions of this section are satisfied for the control of QA records.

QAPD-2.5.2 Generating QA Records

1. Prior to conducting a work activity, the responsible organization shall:

   A. Identify those documents that shall become QA records

   B. Identify the organization responsible for submitting the QA records to the records system

2. QA records shall be legible, accurate, and completed appropriate to the work accomplished.

3. Individuals handling documents intended to become QA records shall provide reasonable protection for the records from damage or loss until the records are submitted to the records system (this includes documents generated during field operations).

4. Documents shall be considered valid QA records only if stamped, initialed, or signed and dated by authorized personnel, or otherwise authenticated. If the nature of the record (such as magnetic or optical media) precludes stamping or signing, then other means of authentication by authorized personnel are required. This authentication represents a certification as to the content of the record by those individuals with knowledge of the related facts, whether by direct personal knowledge or through the direct reports of others. The authentication should not be confused with any subsequent reviews of the content.

5. Once authenticated, QA records shall be submitted to the records system as prescribed by approved procedures. Upon completion of a project or other discrete task or activity, responsible management shall verify that the contents of the applicable QA records package are stored in the records system.

6. QA records may be originals or reproducible copies unless otherwise required.

7. Documents referenced by final reports, except readily available references such as encyclopedias, dictionaries, engineering handbooks, and national codes and standards, shall be retrievable from records files. Preparers of such records shall ensure that the documents are entered into the records system.

QAPD-2.5.3 Indexing QA Records

The records system shall provide for the indexing of QA records according to the following requirements:

1. An individual or organization shall be assigned the responsibility of indexing and maintaining QA records.

2. The indexing system shall include, at a minimum, record retention times and the location of the record within the records system. These and other features of the records system shall facilitate the disposition of scheduled QA records and ensure the retrievability of any QA records entered in accordance with planned retrieval times based upon the record type.

3. Records and/or indexing system(s) shall provide sufficient information to permit identification between the record and the item(s) to which it applies.

QAPD-2.5.4 Classifying QA Records

1. QA records shall be classified as either "post-closure," "lifetime," or "nonpermanent." Post-closure QA records may be required to be maintained for periods of several hundred years and in a manner that will permit future generations to maintain them longer, if desired, using reasonably available technology. Records that fall into one or more of the following categories shall be classified as "post-closure" QA records:

   A. Records assisting prevention of actions that could impair the long-term isolation of the waste

   B. Records preserving information that would prevent inadvertent human intrusion, such as the nature and hazard of the waste and the locations of the geologic repository operations area, the underground facility, boreholes and shafts, and boundaries of the controlled area

   C. Records providing information relevant to post-closure monitoring and assessment of performance of the repository system

   D. Records preserving for future generations information regarding the geologic setting relevant to mitigation of releases of radioactive materials

   E. Records of significant value in exercising the retrieval option for waste packages after decommissioning and closure of the repository

2. Records not falling into the categories listed above, but falling into one or more of the following categories, shall be classified as "lifetime" QA records:

A. Records used for repository permitting or certification

B. Records used to identify and assess the performance capabilities of those engineered and natural barriers important to waste isolation

C. Records of computer programs and mathematical models needed to perform ongoing correlations between performance assessment predictions and actual tests and data analyses

D. Records of significant value in demonstrating the capability for safe operation of the WIPP repository or in determining the cause of an accident or a malfunction of an item in the WIPP repository

E. Records of significant value in maintaining, reworking, repairing, replacing, or modifying WIPP repository systems, components, or structures

F. Records needed during decommissioning and closure of the repository

G. Records relating to site characterization samples and data

H. Records relating to data used in performance assessment of the WIPP facility

I. Records documenting regulatory compliance

J. Records providing required baseline data for in-service inspections

3. Lifetime QA records are required to be retained and preserved in an acceptable condition for the operating life of the repository (i.e., until termination of the repository permit). Prior to destruction of any lifetime record, it shall be evaluated for upgrade to a post-closure record

4. Records that provide objective evidence that the QA program has been properly implemented, but that do not meet the above criteria for post-closure or lifetime records shall be classified as "nonpermanent" QA records. The retention period for nonpermanent records shall be established in writing.

5. Records shall be classified in accordance with the requirements of the major regulatory requirements documents listed in Table QAPD-1. In the case of conflicts between the records requirements contained in these documents, the most stringent requirements shall be used in determining the records classification.

QAPD-2.5.5 Receiving QA Records

Each organization responsible for the receipt of QA records shall designate the person or organization responsible for receiving the records. The designee shall be responsible for organizing and implementing a system of controls for the receipt of QA records for permanent and temporary storage. At a minimum, the receipt control system shall include:

1. Provisions to permit a current and accurate assessment of the status of QA records

2. A method for identifying the records required to be included in the records system

3. A method for identifying the records that have been received

4. Procedures for the receipt and inspection of incoming records, including verification that the QA records received are in agreement with the transmittal document and that the records are legible

5. Provisions to control and protect the records from damage or loss during the receiving processes

6. A method for submittal of completed records to the storage facility without unnecessary delay

QAPD-2.5.6 Storage, Preservation, Safekeeping, and Disposition of QA Records

1. QA records shall be stored and preserved in predetermined storage facilities in accordance with approved QA implementing procedures that provide :

   A. A description of the storage facility

   B. A description of the filing and indexing systems used

   C. For records submitted to the WIPP Records Center for final storage, provisions for providing a receipt acknowledgement to the sender.

   D. A description of controls governing QA records access, retrieval, and removal

   E. A method for filing supplemental information and documenting the authorization for corrections

2. The records storage arrangements shall provide adequate protection of records, including special processed records (such as radiographs, photographs, negatives, microfilm, and magnetic media) to preclude damage from:

   A. Natural disasters such as winds, floods, or fires

   B. Environmental conditions such as high and low temperatures and humidity

   C. Infestation of insects, mold, or rodents

3. Records shall be firmly attached in binders or placed in folders or envelopes in steel file cabinets or on shelving in containers.

4. Records that require special processing and control, such as software and related documentation or information on high density media or optical disks, or hardware and

software required to maintain and access records, shall be controlled to ensure that the records are useable.

QAPD-2.5.6.1 Records Disposition

1. Lifetime QA records shall be retained and preserved in an acceptable condition for the operating life of the WIPP repository (i.e., until termination of the operating permits), or for the particular item while it is installed in the repository or is being stored for future use. Lifetime records shall be evaluated for the need to be upgraded to post-closure records prior to their destruction.

2. Waste characterization data and related QA/Quality Control (QC) records in the generator/storage site project files for TRU waste to be shipped to the WIPP facility are designated as either lifetime records or non-permanent records as specified in Attachment B of the WIPP Hazardous Waste Facility Permit. Records that are designated as lifetime records shall be maintained for the life of the waste characterization program at a participating generator/storage site plus six years, or transferred for permanent archival storage to the WIPP Records Archive facility. Waste characterization records designated as non-permanent records shall be maintained for ten years from the date of (record) generation at the participating generator/storage site, or at the WIPP Records Archive facility and then dispositioned according to their approved records inventory and disposition schedule (RIDS). If a generator/storage site ceases to operate, records shall be transferred before closeout for management at the WIPP Records Archive facility.

3. Records relevant to an enforcement action under the WIPP Hazardous Waste Permit, regardless of assigned dispositions, shall be maintained at the TRU waste site until the NMED determines that they are no longer needed for enforcement actions, and then dispositioned as required.

4. Waste characterization data for each TRU mixed waste container transmitted to WIPP shall be maintained by CBFO for the active life of the WIPP facility plus two years. The active life of the WIPP facility is defined as the period from the initial receipt of TRU mixed waste at the facility until NMED receives certification of final closure of the facility. After their active life, records shall be retired to the WIPP Records Archive facility and maintained for 30 years.

5. Design and construction of a single records storage facility shall meet the applicable requirements of NQA-1-1989, NQA-3-1989, 10 CFR 71, and current requirements of the National Archives and Records Administration (NARA).

6. The construction details shall be reviewed by a person who is competent in the technical field of fire protection and fire extinguishing to determine the adequacy of protection of contents. If the facility is located within a building or structure, the environments and construction of that building can provide a portion or all of these criteria.

7. The following criteria are acceptable alternatives to the current NARA requirements and NQA-1-1989 criteria for a single storage facility:

A. Two-hour fire-rated vault meeting the National Fire Protection Association (NFPA) 232-1986, *Standards for the Protection of Records,* or NFPA 232AM-1986, or both

B. Two-hour fire-rated Class B file containers meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both

C. Two-hour fire-rated file room meeting the requirements of NFPA 232-1986, or NFPA 232AM-1986, or both, with the following additional provisions:

i. Early warning fire detection and automatic fire suppression capability with electronic supervision at a constantly attended central station

ii. Records storage in fully enclosed metal cabinets

iii. Adequate access and aisle ways

iv. Prohibition in the room of work not directly associated with record storage or retrieval

v. Prohibition of smoking, eating, or drinking

vi. Two-hour fire-rated dampers or doors in all boundary penetrations

8. If storage at dual facilities for each record is provided, the facilities shall be at locations sufficiently remote from each other to eliminate the chance of exposure to a simultaneous hazard. Each facility is not required to satisfy the requirements of paragraphs 5, 6, or 7 above, but shall meet all other records storage requirements prescribed in this QAPD.

9. When temporary storage of records (such as for processing, review, or use) is required by an organization's procedures, the records shall be stored in a 1-hour fire-rated container. The procedures shall specify the maximum allowable time limit for temporary storage. The container shall bear a UL label (or equivalent) certifying one-hour fire protection, or be certified by a person competent in fire protection.

10. Access to storage facilities shall be controlled. A list designating personnel who are permitted access to the QA records shall be maintained and posted. Measures shall be established to preclude the entry of unauthorized personnel into the storage area. These measures shall guard against theft and vandalism.

11. Measures shall be taken to provide for replacement, restoration, or substitution of lost or damaged records.

12. QA records shall not be destroyed until the following conditions are met:

A. The appropriately assigned NARA authorized disposition specifies destruction

B. Regulatory requirements are satisfied

C. Operational status permits the disposal of such records

D. The related contractual requirements have been satisfied

E. In cases of conflicting requirements concerning records retention requirements, the most stringent requirements shall be used in determining the final disposition.

QAPD-2.5.7 Correcting Information in QA Records

1. Corrections to records will include the initials or signature of the authorized person making the correction and the date the correction was made.

2. Corrections to QA records shall be authorized by the originating organization.

3. Corrections to QA records should be made using a single line through and shall not obliterate the prior entry. QA records shall not be corrected with correction fluids or tapes.

QAPD-3.0 Performance Requirements

QAPD-3.1 Work Processes

1. Work shall be performed in accordance with established technical standards and administrative controls. Work shall be performed under controlled conditions using approved instructions, procedures, or other appropriate means. Items shall be identified and controlled to ensure their proper use. Items shall be maintained to prevent their damage, loss, or deterioration. Equipment used for process monitoring or data collection shall be calibrated and maintained.

2. The intent of this section is to establish the policy that those who have been assigned responsibility for performing work are responsible for achieving and maintaining quality. Those performing work have the goal of doing work correctly the first time. To ensure that those doing the work achieve that goal, management is responsible for establishing processes and procedures to ensure that all work is planned and performed under controlled conditions by personnel who are knowledgeable of the work requirements, and that these individuals are capable of accomplishing the work in accordance with the requirements of this QAPD.

3. This section further establishes management involvement in the work processes through their interactions with personnel performing the work and through their review and assessment of ongoing and completed work. This helps to ensure that the definition of "acceptable work performance" is clearly communicated and that personnel are provided the necessary training, resources, and administrative controls to properly accomplish their tasks.

QAPD-3.1.1 Work

1. Personnel performing work are responsible for the quality of their work. Because the individual worker is the first line in ensuring quality, personnel will be knowledgeable of requirements for work they perform and the capability of the tools and processes they use.

2. Line managers will ensure that personnel working under their supervision are qualified and are provided the necessary training, resources, and administrative controls to accomplish assigned tasks. Criteria describing acceptable work performance shall be defined for the worker.

3. Line managers will review work and related information to ensure that the desired quality is achieved and to identify areas needing improvement.

4. Work shall be planned, authorized, and accomplished under controlled conditions using technical standards, QA requirements, and implementing procedures commensurate with applicable control levels.

QAPD-3.1.2 Implementing Procedures

1. Implementing procedures shall be developed, reviewed, and approved by technically competent personnel.

2. Implementing procedures shall include the following information, as appropriate to the work to be performed:

   A. Responsibilities of the organizations affected by the document

   B. Technical, regulatory, quality assurance, or other program requirements

   C. Sequential description of the work to be performed, including any allowance for out-of-sequence processing

   D. Quantitative or qualitative acceptance criteria sufficient for determining that activities were satisfactorily accomplished

   E. Prerequisites, limits, precautions, process parameters, and environmental conditions

   F. Special qualification and training requirements

   G. Verification points and hold points

   H. Methods for demonstrating that the work was performed as required (such as provisions for recording inspection and test results, check-off lists, or sign-off blocks)

   I. Identification and classification of QA records to be generated by the implementing procedure

3. Individuals performing work shall comply with implementing procedures; however, when work cannot be accomplished as described in the implementing procedure or accomplishment of such work would result in an undesirable situation, a condition adverse to quality, or an unacceptable safety risk, the work shall be suspended until the appropriate procedure change provisions are implemented.

QAPD-3.1.3 Item Identification and Control

1. Processes shall be established and maintained to identify, control, and maintain items to prevent their damage, loss, or deterioration. The identification of items shall be maintained to ensure appropriate traceability. Traceability requirements shall be specified in design documents or implementing procedures. Processes shall be established and implemented to control consumables and items with limited operating or shelf life and to prevent the use of incorrect or defective items.

2. The following controls shall be established to ensure that only correct and accepted items are used or installed:

   A. Items shall be identified and traced from the time of receipt, up to and including installation or end use. Records shall be maintained to ensure that the item can be traced at all times, from its source through installation or end use.

B. Item identification methods shall include physical markings. If physical markings are either impractical or insufficient, other appropriate means shall be employed (such as physical separation, labels or tags attached to containers, or procedural controls). When used, physical markings shall:

i. Be applied using materials and methods that provide clear, permanent, and legible identification

ii. Not be detrimental to the function or service life of the item

iii. Be transferred to each part of an identified item when the item is subdivided

iv. Not be obliterated or hidden by surface treatments, coatings, or installation unless other means of identification are substituted

C. If codes, standards, or specifications include specific identification or traceability requirements (such as identification or traceability of the item to applicable specification or grade of material; heat, batch, lot, part, or serial number; or specified inspection, test, or other record(s)), then identification and traceability methods shall be implemented to ensure the special requirements are met.

D. Item identification control system records shall provide the inspection, test, and operating status of items. Items that have satisfactorily passed the required inspections and tests shall be identified. The identification methods shall preclude the inadvertent installation, use, or operation of items that have not passed required inspections and tests.

E. The status of inspections and tests shall be identified either on the items or in documents traceable to the items. Status shall be maintained through the use of status indicators (such as tags, markings, labels, or stamps) or other means (such as inspection or test records), and the authority for applying and removing status indicators shall be specified.

QAPD-3.1.4 Special Processes

1. Processes shall be considered as special processes if they meet any one or a combination of the following criteria:

A. The results are highly dependent on the control of the process

B. The results are highly dependent on the skill of the operator

C. The quality of the results cannot be readily determined by inspection or test of the product

2. Implementing procedures shall be developed and implemented to ensure that special process parameters are controlled and specified environmental conditions are maintained. In addition to the requirements provided in Section QAPD-3.1.2, special process implementing procedures shall include or reference:

A. The requirements for training/qualification of personnel and quality processes/equipment

B. The conditions necessary for completion of the special process, including equipment, statistical process control, controlled parameters of the process, and calibration requirements

QAPD-3.1.5 Handling, Storage, and Shipping

1. Handling, storage, cleaning, shipping, and other means of preserving, transporting, and packaging of items shall be conducted in accordance with established work and inspection procedures, shipping instructions, or other specified documents.

2. If required for critical, sensitive, perishable, or high-value articles, specific implementing procedures for handling, storage, cleaning, packaging, shipping, and other preservation shall be prepared and used.

3. Measures shall be established and implemented for the marking and labeling of items for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the item. Markings and labels shall indicate the presence of special environments or the need for special controls, as necessary, and shall be applied and removed by authorized personnel.

4. If required for protection or maintenance of particular items, special equipment (such as containers, shock absorbers, and accelerometers) and special protective environments (such as inert gas and specific moisture and temperature levels) shall be specified, planned for, and provided.

   A. If special protective equipment and environments are used, provisions shall be made for verifying their adequacy.

   B. Special handling tools and equipment shall be used and controlled, as necessary, to ensure safe and adequate handling.

   C. Special handling tools and equipment shall be inspected and tested at specified intervals and in accordance with implementing procedures to verify that the tools and equipment are adequately maintained.

   D. Operators of special handling and lifting equipment shall be sufficiently experienced and trained to use the equipment.

5. If storage of items is required, methods shall be established for the control of item identification records that are commensurate with the planned duration and conditions of storage. These methods shall provide for, as applicable:

   A. Maintenance or replacement of markings and identification tags damaged during handling or aging

B. Protection of identification markings that are subject to excessive deterioration due to environmental exposure

C. Update of related identification records and documentation

6. Status indicators, such as tagging valves and switches to prevent inadvertent operation, shall be used to indicate the operating status of items. Status indicators, such as lockout tags, shall also be used where appropriate and shall be applied and removed by authorized personnel.

QAPD-3.2 Design Control

1. Items and processes shall be designed using sound engineering and scientific principles and appropriate standards. Design work, including changes, shall incorporate appropriate requirements, such as general design criteria and design bases. Design interfaces shall be identified and controlled.

2. The adequacy of design products shall be verified by individuals or groups other than those who performed the design work. Required verification and validation shall be completed before approval and implementation of the design.

3. Designs (from conceptual through final) shall be defined, controlled, and verified. In establishing design controls, management is responsible for ensuring that design inputs are technically correct; that design interfaces are identified; that authorities, responsibilities, and lines of communication are clearly defined; and that the design processes clearly define the acceptance criteria for the product.

QAPD-3.2.1 Design Input

Applicable design inputs such as design bases, conceptual design reports, performance requirements, regulatory requirements, codes, and standards shall be controlled by those responsible for the design in accordance with the following requirements:

1. Design inputs shall be identified and documented and their selection reviewed and approved by those responsible for the design.

2. Design inputs shall be specified and approved on a timely basis to the level of detail necessary to permit the design work to be carried out correctly in a manner that provides a consistent basis for making design decisions, accomplishing design verification, and evaluating design changes.

3. Changes from approved design inputs and reasons for the changes shall be identified, approved, documented, and controlled.

4. Design inputs based on assumptions that require reverification shall be identified and controlled.

QAPD-3.2.2 Design Process

The design process shall be controlled according to the following requirements:

1. Appropriate standards shall be identified and documented and their selection reviewed and approved. Changes from specified standards, including the reasons for the change, shall be identified, approved, documented, and controlled.

2. Design work shall be prescribed and documented on a timely basis and to the level of detail necessary to permit the design process to be carried out correctly.

3. Design documents shall be adequate to support design, fabrication, construction, and operation.

4. Design documents shall be sufficiently detailed as to purpose, method, assumptions, design input, references, and units such that a person technically qualified in the subject can understand the documents and verify their adequacy without recourse to the originator.

5. Controls for identifying assemblies or components that are part of the item being designed shall be established. If a commercial grade assembly or component is modified or selected by special inspection or testing to meet requirements that are more restrictive than the supplier's published product description, then the assembly or component shall be represented as different from the commercial grade item in a manner traceable to a documented definition of the difference.

6. Controls for selecting and reviewing design methods, materials, parts, equipment, and processes essential to the function of an item shall be established.

7. Drawings, specifications, and other design output documents shall contain appropriate inspection and testing acceptance criteria.

QAPD-3.2.3 Design Analyses

1. Design analyses shall be planned, controlled, and documented.

2. Documentation of design analyses shall include

   A. Definition of the objective of the analyses

   B. Definition of design inputs and their sources

   C. Results of literature searches or other applicable background data

   D. Identification of assumptions and designation of those assumptions that shall be verified as the design proceeds

E. Identification of any computer calculations, including computer type, computer software name, revision identification, inputs, outputs, and the bases (or reference thereto) supporting application of the software to the specific physical problem.

F. Identification of the reviewer and the approver

3. Calculations shall be identifiable by subject (including structure, system, or component to which the calculation applies), originator, reviewer, and date, or by other designator such that the calculations are traceable.

4. Computer software used to perform design analyses shall be developed, qualified, and used according to the requirements of QAPD-7.0.

QAPD-3.2.4 Design Interface

1. Design interfaces shall be identified, documented, and controlled so that efforts are coordinated among participating organizations.

2. Design interface controls shall including the assignment of responsibility and the establishment of implementing procedures among participating design organizations for the review, approval, release, distribution, and revision of documents involving design interfaces

3. Design information transmitted across interfaces shall be documented and controlled.

4. The status of the design information or issued design documents shall be identified in transmittals. Where necessary, incomplete designs that require further evaluation, review, or approval shall be identified.

QAPD-3.2.5 Design Verification

The acceptability of design work and documents, including design inputs, processes, outputs, and changes, shall be verified. The following design control requirements shall be applied to verify the adequacy of design:

1. Design verification shall be performed using one or a combination of the following methods:

A. Design review

B. Alternate calculations

C. Qualification testing

2. The particular design verification method shall be identified and its use justified.

3. The results of design verification shall be clearly documented, including the identification of the verifier.

4. Design verification shall be performed by competent individuals or groups other than those who performed the original design (but they may be from the same organization). If necessary, this design verification may be performed by the originator's supervisor, provided that:

   A. The supervisor did not specify a singular design approach or rule out certain design considerations and did not establish the design inputs used in the design.

   B. The supervisor is the only individual in the organization competent to perform the verification.

   C. The determination to use the supervisor is documented and approved in advance.

5. Design verification shall be performed at appropriate times during the design process.

   A. Verification shall be performed before release for procurement, manufacture, construction, or release to another organization for use in other design work.

   B. Design verification shall be completed before relying on an item to perform its function.

6. The extent of the design verification required shall be based on the complexity, risk, uniqueness of design, complexity of design, degree of standardization, state of the art, and similarity to previously proven designs. When the design has been subjected to a verification process in accordance with this QAPD, the verification process need not be duplicated for identical designs.

7. Use of previously proven designs shall be controlled according to the following requirements:

   A. The applicability of standardized or previously proven designs shall be verified with respect to meeting pertinent design inputs for each application.

   B. Known problems affecting standard or previously proven designs and their effects on other features shall be considered.

   C. The original design and associated verification measures shall be adequately documented and referenced in the files of subsequent application of the design.

   D. Changes in previously verified designs shall require reverification. Such reverifications shall include the evaluation of the effects of those changes on the overall previously verified design and on any design analyses upon which the design is based.

QAPD-3.2.6 Design Reviews

1. Design reviews shall be controlled, documented, and performed, and shall consider the following:

   A. Design inputs were correctly selected and incorporated.

B. Assumptions necessary to perform the design work were adequately described, reasonable, and reverified as necessary.

C. Appropriate design methods were used.

D. Design output is reasonable compared to design inputs.

E. The necessary design input and verification requirements for interfacing organizations were specified in the design documents or in supporting implementing procedures.

2. Disposition of design review comments shall be documented.

QAPD-3.2.7 Alternative Calculations

Alternative calculations are calculations or analyses that are made using alternate methods to verify correctness of the original calculations or analyses. The appropriateness of any assumptions, the input data used, any computer programs, or other calculation methods used, shall be evaluated.

QAPD-3.2.8 Qualification Testing

If design adequacy is to be verified by qualification tests, the tests shall be pre-identified. When qualification testing is used, the following requirements shall apply:

1. The test configuration shall be defined and documented.

2. Testing shall demonstrate the adequacy of performance under conditions that simulate the most adverse design conditions. Operating modes and environmental conditions in which the item must perform satisfactorily shall be considered in determining the most adverse conditions.

3. If the tests verify only specific design features, the other features of the design shall be verified by other means.

4. Test results shall be documented and evaluated by the responsible design organization to ensure that test requirements have been met.

5. If qualification testing indicates that a modification to an item is necessary to obtain acceptable performance, the modification shall be documented and the modified item retested or otherwise verified to ensure satisfactory performance.

6. Scaling laws shall be established and verified when tests are being performed on models or mockups.

7. The results of model test work shall be subject to error analysis, where applicable, before the results are used in final design work.

QAPD-3.2.9 Design Change

Design changes shall be controlled in accordance with the following requirements:

1. Changes to final designs, field changes, and nonconforming items dispositioned "use as is" or "repair" shall be justified and shall be subject to design control measures commensurate with those applied to the original design.

2. Design control measures for changes shall include provisions to ensure that the design analyses for the item are still valid.

3. Changes shall be approved by the same groups or organizations that reviewed and approved the original design documents, with the following considerations:

   A. If an organization that originally was responsible for approving a particular design document is no longer responsible, the new responsible organization shall be designated.

   B. The cognizant design organization shall have demonstrated competence in the specific design area of interest and have an adequate understanding of the requirements and intent of the original design.

4. When a design change is approved other than by revision to the affected design documents, measures shall be established to incorporate the change into these documents, where such incorporation is appropriate.

5. If a significant design change becomes necessary because of an incorrect original design, the design process and design verification methods and implementing procedures shall be reviewed and modified as appropriate. These design deficiencies shall be documented according to the requirements provided in Section QAPD-2.3.2.

6. Field changes shall be incorporated into the applicable design documents.

7. Design changes that affect related implementing procedures or training programs shall be communicated to the appropriate organizations.

QAPD-3.3 Procurement

CBFO and participant organizations shall ensure that procured items and services meet established technical and QA requirements, and that they perform as specified. Prospective suppliers shall be evaluated and selected on the basis of documented criteria. The responsible organization shall verify that approved suppliers continue to provide acceptable items and services.

QAPD-3.3.1 Procurement Planning Requirements

The processes for procurement and design control described in this QAPD are sufficient to implement the requirements associated with Suspect/Counterfeit Items (S/CI) Prevention described in DOE O 414.1C, Attachment 3. The process of this section is consistent with the

CBFO activity hazards and mission impact. The CBFO Program Participant in Procurement and Engineering Managers are responsible for compliance with the applicable requirements.

The waste generator sites are responsible for developing a S/CI Prevention program/process in accordance with DOE O 414.1C, Attachment 3, as directed by the appropriate site office.

Procurement activities shall be planned as early as possible. At a minimum, the activities shall be planned no later than the start of those procurement activities that are required to be controlled. Procurement planning shall be documented to ensure a systematic approach to the procurement process. Procurement planning shall:

1. Identify procurement methods and organizational responsibilities, including the appropriate QA organization

2. Identify and document the sequence of actions and milestones needed to effectively complete the procurement

3. Provide for the integration of the following activities:

    A. Procurement document preparation, review, and change control

    B. Selection of procurement sources

    C. Proposal or bid evaluation and award

    D. Purchaser evaluation of supplier performance

    E. Purchaser verifications including any hold-point and witness-point notifications

    F. Control of nonconformances

    G. Corrective action

    H. Acceptance of the item or service

    I. Identification of QA records

QAPD-3.3.2 Supplier Selection

1. Supplier selection shall be based on evaluation of the supplier's capability to provide items or services in accordance with procurement document requirements

2. Organizations responsible for supplier source selection shall be identified and shall include the appropriate QA organization.

3. Measures for selecting procurement sources shall include one or more of the following elements:

A. An evaluation of the supplier's history for providing an identical or similar product that performs satisfactorily in actual use

B. An evaluation of the supplier's current QA documentation, supported by any documented qualitative and quantitative information

C. An evaluation of the supplier's technical and QA capability, based on an evaluation of the supplier's facilities, personnel, and quality program implementation

4. D. The results of procurement source selection shall be documented.

QAPD-3.3.3 Proposal/Bid Evaluation

1. The proposal or bid evaluation process shall include a determination of the extent of conformance to the procurement document requirements. This evaluation shall be performed by designated, technically qualified personnel, including the quality assurance organization, and shall include, at a minimum, the following:

A. Technical considerations

B. QA program requirements

C. Supplier personnel skills

D. Supplier production capabilities

E. Supplier past performance

F. Alternatives proposed by the supplier

G. Exceptions taken by the supplier

2. Before the contract is awarded, the purchaser shall resolve, or obtain commitments to resolve, deficiencies identified during the proposal or bid evaluation.

3. Supplier QA provisions shall be accepted by the purchaser QA management before the supplier is authorized to start work.

QAPD-3.3.4 Procurement Document Requirements

Procurement documents shall include the following, as applicable to the item or service being procured:

1. The scope of work

2. Technical requirements, including the following:

A. Design bases shall be identified or referenced.

B. Specific documents (such as drawings, codes, standards, regulations, DOE orders, procedures, or instructions) that describe the technical requirements of the items or services to be furnished shall be identified. The revision level or change status of these documents shall also be identified.

C. Tests, inspections, hold points, or acceptance criteria that the purchaser shall use to monitor and evaluate the performance of the supplier shall be specified.

3. QA provisions specified by the purchaser QA organization shall include:

A. The requisite QA and documentation requirements, depending on the control level of the item or service being procured

B. The pass-down requirements that the supplier shall incorporate into any sub-tier procurement document

C. When deemed appropriate, the purchaser may permit some or all supplier work to be performed under the purchaser QA program, provided that the requirements are adequately implemented. In these cases, procurement documents shall specify that the purchaser's QA implementing procedures are applicable to the supplier and that the purchaser shall provide these applicable documents to the supplier.

D. Right of access to supplier facilities and records for inspection and audit by the purchaser, CBFO, or other designee authorized by the purchaser

E. The requirements of Section QAPD-2.5 and provisions for disposition, if the supplier is required to maintain QA records

F. Requirements for the supplier to report nonconformances and obtain purchaser approval of supplier-recommended dispositions

G. Spare and replacement parts or assemblies and the appropriate technical and QA requirements for ordering

QAPD-3.3.5 Procurement Document Review and Approval

1. A review of the procurement documents and any changes thereto shall be made to verify that documents include appropriate provisions to ensure that items or services meet the prescribed requirements. Procurement document changes shall be subject to the same degree of control as the original documents.

2. Procurement document reviews shall be performed and documented prior to the document being issued to the supplier.

3. Reviews shall be performed by personnel who have access to pertinent information and who have adequate understanding of the requirements and scope of the procurement.

4. Procurement document reviews shall include representatives from the technical and QA organizations and shall be approved by responsible management.

QAPD-3.3.6 Supplier Performance Evaluation

The purchaser of items and services shall establish measures to interface with the supplier and to verify supplier performance, as deemed necessary by the purchaser. The measures shall include:

1. Establishing an understanding between the purchaser and supplier of the requirements and specifications identified in the procurement documents

2. Requiring the supplier to identify planning techniques and processes to be used in fulfilling procurement document requirements

3. Reviewing supplier documents that are prepared or processed during work performed to fulfill procurement requirements

4. Identifying and processing necessary change information

5. Establishing the method to be used to document information exchanges between purchaser and supplier

6. Establishing the extent of assessment activities and inspection

QAPD-3.3.7 Acceptance of Items or Services

1. Methods shall be established for the acceptance of an item or service being furnished by a supplier.

2. Prior to offering an item or service for acceptance, the supplier shall verify that the item or service complies with the procurement requirements.

QAPD-3.3.7.1 Source Verification

1. The purchaser may accept an item or service by monitoring, auditing, surveilling, witnessing, or observing activities performed by the supplier. This method of acceptance is called source verification.

2. The extent of source verification shall be a function of the relative importance, complexity, and quantity of items or services being procured, as well as the supplier's quality of performance. Source verifications shall be accomplished as early as possible, but prior to the start of those activities that are required to be controlled, and shall include the active involvement of the purchaser's QA organization. In addition:

    A. Source verification shall be accomplished consistent with the supplier's planned inspections, examinations, or tests and performed at intervals consistent with the importance and complexity of the item.

B. Documented evidence of acceptance of source-verified items or services shall be furnished to the party receiving the item, to the purchaser, and to the supplier.

C. Source verification shall be performed by qualified personnel.

3. For procurement of services only (such as third party inspection, engineering and consulting services), and installation, repair, overhaul, or maintenance work, the purchaser shall accept the service by any or all of the following methods:

A. Technical verification of data produced

B. Surveillance and/or audit of the activity

C. Review of objective evidence for conformance to the procurement document requirements such as certifications or test reports

QAPD-3.3.7.2 Receiving Inspection

When a receiving inspection is used to accept an item:

1. The inspection shall include consideration of source assessments, verifications and audits and the demonstrated quality performance of the supplier.

2. The inspection shall be performed in accordance with established inspection procedures or instructions.

3. The inspection shall verify, as applicable, proper configuration; identification; dimensional, physical, and other characteristics; freedom from shipping damage; and cleanliness.

4. The inspection shall be planned and executed in accordance with the applicable requirements of Section QAPD-3.4.

5. Receiving inspection shall include a review of the adequacy and completeness of any required supplier documentation.

QAPD-3.3.7.3 Post-Installation Testing

When post-installation testing is used as a method of acceptance, post-installation test requirements and acceptance documentation shall be mutually established and agreed upon by the purchaser and supplier.

QAPD-3.3.7.4 Supplier Certificate of Conformance

When a certificate of conformance is used, the following, at a minimum, shall be met:

1. The certificate shall identify the purchased material or equipment, including the purchase order and item number or other identification that is traceable to the requirements of the procurement document.

2. The certificate shall identify the specific procurement requirements met by the purchased material or equipment, such as codes, standards, and other specifications. The procurement requirements identified shall include any approved changes, waivers, or deviations applicable to the subject material or equipment.

3. The certificate shall identify any procurement requirements that have not been met, together with an explanation and the means for resolving the nonconformances.

4. The certificate shall be signed or otherwise authenticated by an official of the supplier organization, whose function and position are described in the supplier's QA program.

5. The certification system, including the procedures to be followed in filling out a certificate and the administrative procedures for review and approval of the certificate, shall be described in the purchaser or supplier QA program.

6. Means shall be provided to verify the validity of supplier certificates and the effectiveness of the certification system, such as during the performance of audits of the supplier or independent inspection or test of the items. Such verification shall be conducted by the purchaser at intervals commensurate with the supplier's past quality performance.

QAPD-3.3.8 Control of Supplier Nonconformances

The purchaser and supplier shall establish and document the process for dispositioning items and services that do not meet procurement document requirements in accordance with the following:

1. The supplier shall submit a report of nonconformance to the purchaser that includes supplier-recommended disposition (for example, "use as is" or "repair") and provide technical justification for such disposition.

2. Reports of nonconformances to procurement document requirements or documents approved by the purchaser shall be submitted to the purchaser for approval. Examples of conditions requiring a report of nonconformance include:

    A. Failure to meet technical or material requirements

    B. Failure to meet a requirement in supplier documents that have been approved by the purchaser

    C. The nonconformance cannot be corrected by continuation of the original manufacturing process or by rework

    D. The item does not conform to the original requirement even though the item can be restored to a condition such that its capability to function is unimpaired (i.e., a waiver is requested)

3. The purchaser shall evaluate the supplier-recommended disposition.

4. The purchaser shall verify implementation of the disposition.

QAPD-3.3.8.1 Commercial Grade Items

Where the design specifies the use of commercial grade items, the following requirements are an acceptable alternative to other requirements of this section.

1. The commercial grade item shall be identified in an approved design output document, such as a drawing, specification, or other document translated from a design input document. An alternative commercial grade item may be applied as long as the responsible design organization provides verification that the alternative commercial grade item performs the intended function and meets design requirements that are applicable to both the replaced item and its application.

2. Source evaluation and selection, where determined necessary by the purchaser based on complexity and importance to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP facility, shall be in accordance with Section QAPD-3.3.2.

3. Commercial grade items shall be identified in the procurement document by the manufacturer's published product description.

4. After receipt of a commercial grade item, the purchaser shall ensure that:

   A. Damage was not sustained during shipment

   B. The item received was the item ordered

   C. Inspection or testing is accomplished, to the extent determined by the purchaser, to ensure conformance with the manufacturer's published requirements

   D. Documentation, as applicable to the item, was received and is acceptable

QAPD-3.4 Inspection and Testing

1. Inspections and testing shall be performed in accordance with approved implementing procedures. An essential part of the work planning process is to identify the items and processes to be inspected or tested, the parameters or characteristics to be evaluated, the techniques to be used, the acceptance criteria, any hold points, and the organizations responsible for performing the tests and inspections. Inspection for acceptance shall be performed by personnel other than those who performed or directly supervised the work being inspected. Inspection and testing of specified items and processes shall be conducted using established acceptance and performance criteria. The acceptance of items and processes shall be made by and documented by qualified and authorized personnel. Equipment used for inspections and tests shall be calibrated and maintained.

2. Inspection and testing activities shall be conducted in accordance with the following requirements, as applicable.

QAPD-3.4.1 Qualification of Inspection and Test Personnel

This section provides amplified requirements for the qualification of personnel who perform inspection and testing to verify conformance to specified requirements for the purpose of acceptability. The requirements of this section do not apply to the qualification of personnel for performance of nondestructive examination. Qualification of personnel for nondestructive examination is addressed in Section QAPD-3.4.2.

1. The responsible organization shall designate those activities that require qualified inspection and test personnel and the minimum requirements for such personnel. Further, the responsible organization shall establish written procedures for the qualification of inspection and test personnel and for the assurance that only those personnel who meet the requirements of this section are permitted to perform applicable inspection and test activities.

2. When a single inspection or test requires implementation by a team or a group, personnel not meeting the requirements of this section may be used in data-taking assignments or in plant or equipment operation, provided they are supervised or overseen by a qualified individual.

3. Personnel selected for performing inspection and test activities shall have the experience or training commensurate with the scope, complexity, or special nature of the activities.

4. Provisions shall be made for the indoctrination of personnel to the technical objectives and requirements of the applicable codes and standards and the QA program controls that are to be employed.

5. The need for a formal training program shall be determined, and such training activities shall be conducted as required to qualify personnel that perform such inspections and tests. On-the-job training shall also be included in the program, as appropriate, with emphasis on first-hand experience gained through actual performance of inspections and tests.

6. The capabilities of a candidate for certification shall be initially determined by a suitable evaluation of the candidate's previous education, experience, training, and either test results or capability demonstration.

7. The job performance of inspection and test personnel shall be reevaluated for capability at periodic intervals, not to exceed three years. Reevaluation shall be by evidence of continued satisfactory performance or redetermination of capability in accordance with the above requirements. If, during this evaluation or at any other time, it is determined by the responsible organization that the capabilities of an individual are not in accordance with the qualification requirements specified for the job, that person shall be removed from that activity until such time as the required capability has been demonstrated. Any person who has not performed inspection or testing activities in their qualified area for a period of one year shall be reevaluated for the required capability in accordance with the above requirements.

8. The qualification of personnel shall be certified in writing in an appropriate form and shall include the following information:

A. Employer's name

B. Identification of person being certified

C. Activities certified to perform

D. Basis used for certification, including such factors as: (1) education, experience, indoctrination, and training; (2) test results, where applicable; and (3) results of capability demonstration

E. Results of periodic evaluation

F. Results of physical examinations, when required

G. Signature of the employer's designated representative responsible for such certification

H. The date of certification and date of certification expiration

9. The responsible organization shall identify any special physical characteristics needed in the performance of each activity, including the need for initial and subsequent physical examination.

10. Records of personnel qualification shall be established and maintained by the employer. These records shall include the information required above for certification.

QAPD-3.4.2 Qualification of Nondestructive Examination Personnel

This section identifies the requirements for the qualification of personnel who perform nondestructive examination (NDE) (radiographic, magnetic particle, ultrasonic, liquid penetrant, eddy current, neutron radiographic, leak testing, and visual testing) to verify conformance to specified requirements, for nondestructive examination activities.

1. The American Society of Nondestructive Testing (ASNT) Recommended Practice No. SNT-TC-1A, June 1980 Edition, and its applicable supplements, shall apply as requirements for personnel performing the above methods of NDE. Later editions of SNT-TC-1A may be used as the basis for the qualification of NDE personnel, as long as the minimum requirements of the June 1980 edition are met.

2. The responsible organization shall establish written procedures for the control and administration of the training, examination, and certification of NDE personnel.

3. Records of personnel qualification shall be established and maintained by the employer.

QAPD-3.4.3 Inspection

QAPD-3.4.3.1 Inspection Planning

1. Inspection planning shall be performed and documented and shall include:

A. Identification of work operations where inspections are necessary

B. Identification of the characteristics to be inspected and when during the work process inspections are to be performed

C. Identification of inspection or process monitoring methods to be employed

D. Identification of acceptance criteria

E. Identification of sampling requirements

F. Methods to record inspection results

G. Selection and identification of the measuring and test equipment (M&TE) to be used to perform the inspection

H. Process used to ensure that the equipment being utilized for inspection or testing is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

2. When statistical sampling is to be used to verify the acceptability of a group of items, the sampling method shall be based on recognized standard practices.

QAPD-3.4.3.2 Inspection Hold Points

Hold points are used to control work that is not to proceed without the specific consent of the organization placing the hold point. The specific hold points shall be indicated in appropriate documents. Only the organization responsible for the hold point may waive the hold point. Approval to waive specified hold points shall be documented before continuing work beyond the designated hold point.

QAPD-3.4.3.3 In-Process Inspections and Monitoring

1. Items in process shall be inspected as necessary to verify quality. If inspection of processed items is impossible or disadvantageous, indirect control by monitoring of processing methods, equipment, and personnel shall be provided. Both inspection and process monitoring shall be conducted when control is deemed inadequate, using only one of these methods.

2. When a combination of inspection and process monitoring methods is used, monitoring shall be performed systematically to ensure that the specified requirements for control of the process and the quality of the item are met throughout the duration of the process.

3. Controls shall be established and documented for the coordination and sequencing of the work at established inspection points during successive stages of the process.

QAPD-3.4.3.4 Final Inspections

1. Final inspections shall include a review of the results and the verification of the resolution of all nonconformances identified by earlier inspections.

2. Finished items shall be inspected for completeness, markings, calibration, protection from damage, or other characteristics, as required to verify the quality and conformance of the item to the applicable requirements.

3. Records review shall be performed to ensure adequacy and completeness.

4. Item modifications, repairs, or replacements that are performed subsequent to final inspection shall require reinspection or retest, as appropriate, to verify acceptability.

QAPD-3.4.3.5 In-service Inspections

1. Required in-service inspection or surveillance of structures, systems, or components shall be planned and executed by or for the organization responsible for their operation.

2. Inspection methods shall be established and executed to verify that the characteristics of an item continue to remain within specified limits.

3. Inspection methods shall include evaluations of performance capability of essential emergency and safety systems and equipment, verification of calibration and integrity of instruments and instrument systems, and verification of maintenance, as appropriate.

QAPD-3.4.3.6 Inspection Documentation

Inspection documentation shall identify:

1. The item inspected and the date of the inspection

2. The name or unique identifier of the inspector who documented, evaluated, and determined acceptability

3. The method of inspection

4. The inspection criteria, sampling plan, or reference documents (including revision designation) used to determine acceptance

5. The results

6. The M&TE used during the inspection, including the identification number and the calibration due date

7. Reference to any information on actions taken in connection with nonconformances, as applicable

QAPD-3.4.4 Test Requirements

Testing shall be used to determine the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operating conditions. Examples of such tests include prototype qualification tests, production tests, proof tests prior to installation, construction tests, and pre-operational tests.

QAPD-3.4.4.1 Test Planning

Test planning shall include:

1. The identification of the implementing procedures to be developed to control and perform the test. In lieu of specially prepared written test procedures, appropriate sections of related documents such as American Society for Testing and Materials (ASTM) methods may be used. If used, they shall incorporate the information directly into the approved test implementing procedure, or shall be incorporated by reference.

2. The identification of the item to be tested and the test requirements and acceptance limit, including the required levels of precision and accuracy

3. The identification of the M&TE to be used to perform the test to ensure that the equipment being utilized is calibrated and is of the proper type, range, accuracy, and tolerance to accomplish the intended function

4. Any test prerequisites, including test equipment, instrumentation and software needs, personnel training and qualification, and suitably controlled environmental conditions

5. Any mandatory hold points

6. The methods to be used to record data and results

7. The provisions for ensuring that prerequisites for the given test have been met

QAPD-3.4.4.2 Test Documentation

Test documentation shall identify:

1. The applicable test requirements, plans, and procedures, including revisions

2. The item or work product tested

3. The date of the test

4. The name of the tester and data recorders

5. The type of observation and method of testing

6. The identification of test criteria or reference documents used to determine acceptance

7. The results and acceptability of the test

8. The actions taken in connection with any noted nonconformances

9. The name of the person evaluating the test results

10. The identification of the M&TE used during the test (including the identification number and calibration due date)

QAPD-3.4.4.3 Test Results

Test results shall be documented and their conformance with acceptance criteria shall be evaluated by a qualified individual within the responsible organization to ensure that all test requirements have been satisfied.

QAPD-3.4.5 Monitoring, Measuring, Testing, and Data Collection Equipment

The following sections establish requirements to ensure that equipment used for inspection and testing is properly controlled, calibrated, and maintained. Equipment discussed in the following sections includes inspection and test equipment, measuring and data collection equipment, equipment (either hand-held or installed) used for data indication, and other equipment used for data indication, collection, or evaluation. These are called M&TE.

Calibration and control measures may not be required for rulers, tape measures, levels, and other such devices, if normal commercial equipment provides adequate accuracy.

QAPD-3.4.6 Use and Control of M&TE

Each organization using M&TE shall:

1. Establish and document a system to control the use and calibration of M&TE

2. Have a program to recall for calibration, or remove from service, M&TE that has exceeded its calibration interval; has broken calibration seals; has been modified, repaired, or has had components replaced; or is suspected to be malfunctioning because of mishandling, misuse, or unusual results

3. Establish and maintain documented procedures to evaluate the adequacy of the calibration system and to ensure compliance with the requirements of this QAPD

4. Maintain records documenting that established M&TE schedules and procedures have been followed. These records shall include an individual record of calibration, or other means of control, providing:

    A. A description or identification of the item

    B. Calibration interval

C. Date calibrated

D. Identification of the calibration source

E. Calibration results (data and status)

F. Calibration action taken (e.g., adjusted, repaired, new value assigned, derated)

G. Evaluation and corrective action taken in response to out-of-calibration conditions

5. Label all M&TE to indicate the calibration status, the date calibrated, the calibration due date or usage equivalent, and the identification of any limitations. (When it is impractical to apply a label directly to an item, the label may be affixed to the instrument container or some other suitable means may be used to reflect calibration status.)

6. Evaluate the validity of previous inspection and test results and the acceptability of related items, data collected, and processes monitored, when M&TE is found to be out-of-calibration

7. Handle, store, and transport M&TE in a manner that does not adversely affect the accuracy of the equipment

8. Give due consideration to temperature, humidity, lighting, vibration, dust control, cleanliness, electromagnetic interference, and any other factors affecting the results of measurements. Where pertinent, these factors shall be monitored and recorded and, when appropriate, correcting compensations shall be applied to measurement results.

QAPD-3.4.7 Calibration

1. M&TE requiring calibration shall be calibrated at periodic intervals established and maintained to ensure acceptable reliability, where reliability is described as the probability that M&TE will remain in tolerance throughout the interval.

2. M&TE shall be calibrated to provide traceability of the calibration against certified equipment having known valid relationships to nationally recognized standards. If nationally recognized standards do not exist, the bases for calibration shall be documented.

3. Intervals shall be established for all M&TE requiring calibration unless the equipment is regularly monitored through the use of check standards in a documented measurement assurance process. Check standards must closely represent the item parameters normally tested in the process, and the check standard must be verified periodically.

4. Where intervals are used to ensure reliability, the interval setting system must be systematically applied and shall have stated reliability goals and a method of verifying that the goals are being attained.

5. Intervals may be based on usage or time since last calibration.

6. All exemptions from periodic calibration shall be approved and documented.

7. The recall system may provide for the temporary extension of the calibration due date for limited periods of time under specified conditions that do not unreasonably impair the satisfaction of task objectives.

8. If any M&TE is found to be significantly out-of-tolerance during the calibration process, the cognizant organization shall provide for the notification to the user and cognizant QA management of the out-of-tolerance condition, with the associated measurement data, so that appropriate action can be taken.

QAPD-4.0 Assessment Requirements

QAPD-4.1 Management Assessment

Managers at every level shall periodically assess the performance of their organization to determine the effectiveness of QA program provisions that enable the organization to meet customer requirements and expectations. This assessment shall emphasize the use of human and material resources to achieve organizational goals and objectives.

1. The management assessment should include an introspective evaluation to determine if the entire integrated management system effectively focuses on meeting strategic goals.

2. Managers shall retain overall responsibility for management assessments. Direct participation by senior management is essential to the success of the process because management is in the position to view the organization as a total system.

3. Management assessments should focus on the identification and resolution of both systemic and management issues and problems. Strengths and weaknesses affecting the achievement of organizational objectives should be identified so that meaningful action can be taken to improve quality.

4. Processes being assessed should also include strategic planning, organizational interfaces, cost control, use of performance indicators, staff training and qualifications, and supervisory oversight and support. Effective management assessments should evaluate such conditions as the state of employee knowledge, motivation, and morale; the amount of mutual trust and communication among workers and organizations; the existence of an atmosphere of creativity and improvement; and the adequacy of human and material resources.

5. Management assessments of the QA program shall be conducted regularly and reported at least annually to an identified senior management level with sufficient authority to effect corrective measures, as necessary.

6. Management assessment results should be used as input to the organizational continuous improvement process.

QAPD-4.2 Independent Assessment

1. Planned and periodic independent assessments shall be conducted to measure item and service quality, process effectiveness, and promote improvement. The organization performing assessments shall have sufficient authority and freedom from the activities being assessed to carry out its responsibilities. Persons conducting independent assessments shall be technically qualified and knowledgeable of the items and activities being assessed.

2. The types and frequencies of independent assessments shall be based upon the relevant control levels assigned to the items and activities under the cognizance of the organization.

3. The CBFO and participant organizations responsible for the performance of activities important to compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, and management and operation of the WIPP site shall implement a program of surveillance and audits. The program shall be planned and documented and shall include both routine surveillance of those activities and audits to verify compliance with all aspects of the quality assurance program and to determine its adequacy and effectiveness.

QAPD-4.2.1 Surveillances

1. A program of surveillance of the activities referenced above shall be planned, performed, documented, and reported to appropriate management personnel. The surveillance process consists of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements.

2. Surveillances shall accomplish the following:

   A. Monitor work in progress

   B. Document compliance or noncompliance with established requirements and procedures

   C. Identify actual and potential conditions adverse to quality

   D. Obtain timely corrective action commitment from cognizant managers for identified conditions adverse to quality

   E. Provide notification to responsible managers of the status and performance of work under surveillance

   F. Verify timely implementation of corrective actions

3. Audits or other independent assessments of the subject activities, conducted by the responsible organization, may be counted as satisfying the requirement to do surveillances of related activities in the corresponding surveillance schedule period.

QAPD-4.2.2 Audits

The following sections describe the audit process requirements.

QAPD-4.2.2.1 Scheduling Audits

1. Audits shall be scheduled to begin as early in the life of a project or activity as practicable and continue at intervals consistent with the schedule for accomplishing the work and commensurate with assigned control level. The audit schedule shall be reviewed periodically and revised as necessary to assure that coverage is maintained current.

2. Periodically scheduled QA program audits shall be supplemented by, or integrated with, either audits or surveillances of a technical nature (e.g., performance-based audits) which assess the quality of selected work products and work processes.

QAPD-4.2.2.2 Planning and Preparation for Audits

The organization performing the audit shall develop and document a plan for each audit.

1. The plan shall include the scope, requirements, purpose, audit personnel, activities to be audited, organizations to be notified, applicable documents, schedule, and written procedures or checklists to be used.

2. Audit planning shall include a review of past assessment results to determine the nature of problems that have occurred. When recurring problems are found, the audit team shall review corrective actions that have been taken and attempt to determine whether the corrective actions were effective in preventing recurrence.

3. Audit preparation shall include review of pertinent background information, procedures, and technical documents so that audit team members are familiar with the work being audited.

4. Audits shall include technical evaluations of the applicable procedures, instructions, activities, and items, as appropriate.

5. The scope shall include related corrective actions taken since the previous assessment.

QAPD-4.2.2.3 Audit Team Selection

1. Audit team members shall be identified prior to the start of the audit activity. The team members shall be selected on the basis of technical qualifications and knowledge of the item or process being audited and shall be independent from the items or processes being audited. Audit team members shall have sufficient authority and organizational freedom to carry out their assigned responsibilities. In the case of internal audits, personnel having direct responsibility for performing the activities being audited shall not be involved in the selection of the audit team.

2. An audit team leader shall be appointed to provide indoctrination and supervision of the team, organize and direct the audit, and coordinate the preparation and issuance of the audit report.

3. Before starting the audit, the audit team leader shall ensure that the assigned personnel collectively have experience and training commensurate with the scope, complexity, or special nature of the work to be audited.

4. Technical specialists, with appropriate technical expertise or experience in the work being audited, shall be used when auditing the adequacy of technical processes.

QAPD-4.2.2.4 Auditor Qualification

Auditors shall be technically qualified in their assigned roles. In addition, they shall have appropriate training or orientation to develop their competence for performing audits. Competence of personnel performing various audit functions shall be developed by one or more of the following methods:

1. Orientation to provide a working knowledge and understanding of the QA program requirements and the auditing organization's implementing procedures used to perform audits and report audit results

2. Training programs that provide general and specialized training in audit performance, including fundamentals, objectives, characteristics, organization, performance, and results of quality auditing. Training shall include methods of examining, questioning, evaluating, and documenting specific audit items and methods of evaluating the effectiveness of corrective actions for conditions adverse to quality.

3. On-the-job training, guidance, and counseling under the direct supervision of a lead auditor. Such training shall include audit planning, performing, reporting, and follow-up actions.

QAPD-4.2.2.5 Technical Specialist Qualification

Technical specialists selected for audit assignments shall receive indoctrination commensurate with the scope, complexity, or special nature of the work being audited. In addition, they shall be trained to the requirements of the audit process associated with their duties.

QAPD-4.2.2.6 Lead Auditor Qualification

A lead auditor shall be capable of organizing and directing audits, reporting audit results, and evaluating planned and implemented corrective action. A lead auditor also shall be certified as meeting the requirements provided in this section for education and experience, communication skills, training, audit participation, and the successful completion of a lead auditor examination.

1. Lead Auditor Education and Experience:

The prospective lead auditor shall have verifiable evidence that a minimum of 10 credits have been accumulated under the following scoring system:

A. Education (four credits maximum)

i. An associate's degree from an accredited institution scores one credit. If the degree is in engineering, physical sciences, mathematics, or QA, it scores two credits.

ii. A bachelor's degree from an accredited institution scores two credits. If the degree is in engineering, physical sciences, mathematics, or QA, it scores three credits. In addition, score one more credit for a master's degree (or higher) in engineering, physical sciences, business management, or QA from an accredited institution.

B. Experience (nine credits maximum)

i. The prospective lead auditor shall have participated in a minimum of five QA audits or equivalent verifications (such as management assessments, pre-award surveys, or comprehensive surveillance, as long as the parameters of the audit process are met) within three years prior to the date of certification, one of which shall be a nuclear QA audit within the year prior to qualification. In addition, for technical experience in such areas as scientific investigation, site characterization, nuclear waste management, production, transportation, engineering, manufacturing, construction, operation, or maintenance, or experience applicable to the auditing organization's area of responsibility, score one credit for each full year, with a maximum of five credits.

ii. If two years of this experience have been in a nuclear field, score one additional credit; or

iii. If two years of this experience have been in QA, score two additional credits; or

iv. If two years of this experience have been in auditing or assessment, score three additional credits; or

v. If two years of this experience have been in nuclear-related QA, score three additional credits; or

vi. If two years of this experience have been in nuclear-related QA auditing or assessment, score four additional credits.

C. Professional Competence (two credits maximum)

For certification of competency in engineering, science, or QA specialties, issued and approved by a state agency or national professional or technical society, score two credits.

D. Rights of Management (two credits maximum)

When determined appropriate, the organization performing the qualification may grant up to two credits for other performance factors applicable to auditing that are not explicitly called out in this section (such as leadership, sound judgment, maturity, analytical ability, tenacity, past performance, and completed QA training courses).

2. Lead Auditor Communication Skills

The prospective lead auditor shall have the capability to communicate effectively both in writing and orally. These skills shall be attested to in writing by the candidate's supervisor.

3. Lead Auditor Training

Prospective lead auditors shall be trained to the extent necessary to ensure their competence in skills as established by the organization responsible for performing audits. Training in the

following areas shall be accomplished and its completion verified based upon a management evaluation of the particular needs of each prospective lead auditor:

A. Knowledge and understanding of the participant organization's QA program and other program-related procedures, codes, standards, regulations, DOE orders, and regulatory guides, as applicable

B. General structure of QA plans and implementation procedures as a whole

C. Auditing techniques of examining, questioning, evaluating, reporting, and methods of identifying, following up, and closing corrective actions

D. Audit planning in functional areas of nuclear QA

4. Lead Auditor Examination

The prospective lead auditor shall pass an examination that evaluates his or her comprehension of, and ability to apply, the audit knowledge described in this section. The examination may be oral, written, practical, or any combination thereof.

The development and administration of the examination for a lead auditor is the responsibility of the organization responsible for the auditing program. This organization shall:

A. Maintain the integrity of the examination through confidentiality of files and, where applicable, proctor examinations

B. Develop and maintain objective evidence regarding the type and content of the examination

5. Lead Auditor Certification

Lead auditors shall be certified by the organization responsible for the auditing program as being qualified to lead audits. This certification will document the:

A. Name of the organization performing the certification

B. Name of the lead auditor

C. Date of certification or recertification

D. Basis of certification (such as education, experience, communication skills, and training)

E. Signature of the designated representative of the organization responsible for the certification

6. Lead Auditor Proficiency Maintenance

A. Lead auditors shall maintain their proficiency through one or a combination of the following:

i. Regular and active participation in the audit process

ii. Review and study of codes, standards, QA implementation procedures, instructions, and other documents related to QA program auditing

iii. Participation in training programs

iv. Management of the auditing organization shall evaluate the proficiency of lead auditors annually. Based on the evaluation, management shall choose to extend the qualification, require retraining, or require requalification. Management evaluations shall be documented.

B. Lead auditors who fail to maintain their proficiency for a two-year period shall require requalification to the requirements of this section of the QAPD. However, participation in only one nuclear audit is required.

QAPD-4.2.2.7 Performing Audits

1. Audits shall be performed using the written procedures or checklists related to the activity being audited.

2. Elements that have been selected for audit shall be evaluated against specified requirements. Objective evidence shall be examined to the depth necessary to determine if those elements are being implemented effectively.

3. Audit results shall be documented by audit personnel and reported to and reviewed by management having responsibility for the area audited. Conditions requiring prompt corrective action shall be reported immediately to management of the audited organization.

4. Conditions adverse to quality shall be documented and corrected according to the requirements of Section QAPD-2.3.3.

QAPD-4.2.2.8 Reporting Audit Results

1. The audit report shall be prepared and signed by the audit team leader and issued to the management of the audited organization and any affected organizations. The audit report shall include the following, as appropriate:

A. A description of the audit scope

B. Identification of the auditors

C. Identification of persons contacted during the audit

D. A summary of the documents reviewed, persons interviewed, and the specific results of the reviews and interviews (i.e., a summary of the checklist contents)

E. A summary of audit results, including a statement of the QA program adequacy, implementation, and effectiveness, as appropriate to the scope

F. A description of each reported condition adverse to quality in sufficient detail to enable corrective action to be taken by the audited organization

G. A description of commendable quality practices

2. Additionally, common audit findings shall be grouped in the report whenever possible so that related or systematic breakdowns in the QA program are identified. Findings or deficiencies shall be categorized based on their relative importance to indicate their degree of impact on compliance application, waste characterization, repository performance assessment, waste isolation, waste transportation, nuclear safety, environmental protection, or management and operation of the WIPP facility.

QAPD-4.2.2.9 Audit Response and Follow Up

Management of the audited organization will investigate conditions adverse to quality; determine and schedule corrective actions, including measures to preclude recurrence; and notify the auditing organization in writing of the actions planned or taken. The adequacy of audit responses shall be evaluated by or for the auditing organization. Follow-up action shall be taken to verify that corrective action is accomplished as scheduled.

QAPD-4.2.2.10 Audit Records

The following documents, when developed in fulfillment of the audit requirements of this QAPD, shall be controlled as QA records in accordance with Section QAPD-2.5 of this QAPD: audit plans, audit reports, audit responses, and documentation of corrective action completion and follow-up.

QAPD-5.0 Sample Control Requirements

This section identifies the requirements for controlling samples of waste and environmental media. The control measures shall include provisions for the identification, handling, storage, shipping, archiving, and disposition of the samples, including those identified as nonconforming.

QAPD-5.1 Sample Control

1. Samples shall be controlled and identified in a manner consistent with their intended use.

2. Implementing procedures shall define responsibilities, including organizational interfaces, related to documenting and tracking sample possession from sample collection and identification through handling, preservation, shipment, transfer, analysis, storage, and final disposition.

3. Sample control measures shall include provisions for the identification of the in situ orientation of samples, where appropriate.

4. A chain-of-custody record form shall be maintained. The chain-of-custody record shall provide a document trail of all persons who have custody of a given sample, including the date and time of its transfer.

5. Sample control measures, including identification and documentation, shall ensure that samples can be traced at all times, from collection through final disposition.

6. Where samples have a maximum life expectancy or expiration date, methods shall be employed that preclude the use of the sample beyond its specified life.

7. Representative archival samples from difficult-to-repeat sample collection activities, such as principal bore holes, shall be maintained.

8. Implementing procedures shall specify the representative samples to be archived if the need to archive samples is identified.

QAPD-5.2 Sample Identification

1. Each sample shall be uniquely identified from its initial collection through the final disposition of the sample.

2. Sample identification shall be verified and documented before each transfer or release for testing, analysis, or disposition.

3. Identification shall be maintained by placing the identification directly on the samples wherever possible or in a manner that ensures identification is maintained. If direct physical markings are either impractical or insufficient, other appropriate means shall be employed (e.g., physical separation, labels or tags attached to containers, or procedural control). When used, physical markings shall:

A. Be applied using materials and methods that provide clear and legible identification

B. Not effect the sample content or form

C. Be transferable to each identified sample part when the sample is subdivided

D. Not be obliterated or hidden by surface treatments or sample preparation unless other means of identification are substituted

4. If sample storage is required, methods shall be established for the control of sample identification that are commensurate with the planned duration and storage conditions. As applicable, these methods shall provide for:

A. The maintenance or replacement of markings and identification tags that have been damaged because of age or during handling

B. The protection of identification markings from excessive deterioration due to environmental exposure

QAPD-5.3 Handling, Storing, and Shipping Samples

1. Handling, storing, cleaning, packaging, shipping, and preserving samples shall be conducted in accordance with established work and inspection implementing procedures. Controls shall provide for the maintenance of sample characteristics, sample integrity, and sample identification during storage.

2. The controls shall be consistent with planned duration and storage conditions and shall describe actions to be taken where maximum sample life expectancy limits are identified.

3. Storage methodology shall be developed and implemented to ensure that samples are maintained in predetermined environmental conditions commensurate with their intended use and purpose.

4. Samples shall be controlled to preclude the mixing of like samples.

5. Samples on which analysis or tests have been performed shall be identified and maintained in a separate part of the storage area.

6. If required for critical, sensitive, perishable, or high-value samples, specific measures for the handling, storage, cleaning, packaging, shipping, and sample preservation shall be identified and used.

7. Measures shall be established for sample marking and labeling for packaging, shipping, handling, and storage as necessary to adequately identify, maintain, and preserve the sample. Markings and labels shall indicate the need for and the presence of special environments or the need for other special controls, if necessary.

8. Samples requiring special protective equipment (such as containers) and special protective environments (such as inert gas or limits on moisture and temperature) shall be specified, employed, verified, and documented.

QAPD-5.4 Disposition of Nonconforming Samples

1. Samples that do not conform to requirements specified in work controlling documents (such as job packages, travelers, or work requests) shall be identified, documented, evaluated, and segregated in accordance with Section QAPD-2.3.

2. The disposition for nonconforming samples shall be identified and documented and shall be limited to "use-as-is," "limited use," or "discard."

3. Samples that have lost their identity shall be documented as nonconforming and shall not be used.

QAPD-6.0 Scientific Investigation Requirements

Scientific investigations shall be defined, controlled, verified, and documented. Process variables affecting scientific investigations shall be measured and controlled. Test processes conducted in support of such investigations shall be controlled in accordance with the requirements of Sections QAPD-3.4, *Inspection and Testing*, QAPD-3.4.4, *Test Requirements*, and QAPD-3.4.5, *Monitoring, Measuring, Testing, and Data Collection Equipment*, as applicable, and as supplemented by the requirements of this section.

QAPD-6.1 Planning Scientific Investigations

1. Variables that affect interrelated scientific investigations shall be identified and controlled appropriately in each related investigation.

2. The intended use of the data shall be documented before collection as part of the planning for data processing. Any alternate use of the data shall be evaluated for appropriateness and the justification for use shall be documented.

3. Planning shall consider the compatibility of data processing with any conceptual or mathematical models used at each applicable stage.

4. The technical adequacy of procedures for conducting scientific investigations and their implementation shall be reviewed and approved by qualified persons other than those who prepared the procedures. Changes to procedures for conducting scientific investigations shall be reviewed and approved in a manner commensurate with the original procedure.

5. Development activities used to establish new methods or procedures for conducting scientific investigations shall be documented. The results of developmental testing shall be reviewed for adequacy and approved by qualified persons prior to implementation of the procedures for data collection.

6. Planning shall be coordinated with organizations providing input to or using the results of the investigation.

7. Planning shall include the establishment of acceptance criteria for data quality evaluation to ensure that the data generated are valid and satisfy documented requirements for the following characteristics, as appropriate: data precision, data accuracy, data representativeness, data comparability, and data completeness.

8. Planning shall include the identification of known sources of error and uncertainty, as well as any input data that are suspect or whose quality is beyond the control of the performing organizations.

QAPD-6.2 Performing Scientific Investigations

1. Scientific investigations shall be performed in accordance with requirements documented in test plans, procedures, and scientific notebooks.

2. If deviation from test standards or the establishment of specially prepared test procedures is deemed appropriate (e.g., no nationally recognized test standards exist), the modified or new test procedures shall be documented in sufficient detail to be repeatable and shall be justified, evaluated, and approved by the cognizant technical organization.

3. Scientific notebooks shall contain, at a minimum:

   A. A statement of the objectives and description of work to be performed or reference to an approved plan that describes the work

   B. The methods used

   C. Identification of the samples

   D. The M&TE used

   E. A description of the work performed and the results obtained, the names of individuals performing the work, and dated initials or signature, as appropriate, of individuals making the entries

   F. A description of changes made to methods used, as appropriate

   G. The potential sources of uncertainty and error in test plans, procedures, and parameters that must be controlled and measured to ensure that tests are valid

4. Scientific results shall be periodically reviewed by an independent qualified individual to verify that there is sufficient detail to retrace the investigation and confirm the results, if feasible, or repeat the investigation and achieve comparable results without recourse to the original investigator.

5. Practices, techniques, equipment, and manual or computerized methods used to obtain and analyze data shall be verified to ensure that they are technically sound and have been properly selected. Controls shall be established for these processes to ensure that they are properly implemented, including controls to prevent tampering.

6. Data collection and analysis shall be controlled by procedures of sufficient detail to allow the processes to be repeated. Where appropriate, quality control checks shall be performed using recognized methods such as replicate, spike, and split samples;

7. control charts; blanks; reagent checks; replication of the methods used to obtain the results; or alternate analysis methods.

8. Test media (e.g., fluids), when used, shall be characterized and controlled in accordance with test procedures.

9. Scientific notebooks and technical implementation documents shall be maintained as QA records.

QAPD-6.3 Data Documentation, Control, and Validation

QAPD-6.3.1 Data Identification and Usage

A. All data shall be recorded so that they are clearly identifiable and traceable to the test, experiment, study, or other source from which they were generated. Identification and traceability of the data shall be maintained for the lifetime of the WIPP.

B. The method of data recording (e.g., scientific notebooks, log books, data sheets, or computerized instrumentation systems) shall be controlled to avoid data loss and permit data retrievability. Controls shall be established to ensure that data integrity and security are maintained wherever data are stored. Controls shall prescribe how specific types of data will be stored with respect to media, conditions, location, retention time, security, and access. Data shall be suitably protected from damage and destruction during their prescribed lifetime and shall be readily retrievable.

C. Data transfer and reduction controls shall be established to ensure that data transfer is error free (or within a prescribed permissible error rate), that no information is lost in transfer, and that the input is completely recoverable. Data transfer and reduction will be controlled to permit independent reproducibility by another qualified individual. Examples of data transfer include copying raw data from a notebook into computerized data form, or copying from computer tape to disk.

D. Data that are determined to be erroneous, rejected, superseded, or otherwise unsuited for their intended use shall be controlled to prevent their inadvertent use.

Controls shall include the identification, segregation, and disposition of inadequate data. The basis for the disposition of erroneous data shall be justified and documented.

E. All processes which change either the form of expression or quantity of data, values, or number of data items (data reduction) shall be controlled by prescribed methods that allow for the validation of the conversion process.

F. Data collection and analysis shall be critically reviewed and questions resolved before the results are either used or reported. Uncertainty limits shall be assigned to the data prior to their use.

QAPD-6.3.2 Data Validation

Data validation is a systematic process used to review data to ensure that the required data quality characteristics have been obtained. Results of the review may require that qualifiers be placed on the use of the data.

1. Validation methods shall be planned and documented. The documentation shall include the acceptance criteria used to determine if the data are valid.

2. All applicable data collected shall be validated. Validation shall include the following:

A. The relevant documentation is reviewed to evaluate the technical adequacy, the suitability for the intended use, and the adequacy of the QA record.

B. The results of the data review shall be documented.

C. The reviewer shall be independent of the collection activities.

3. Data validation shall be controlled to permit independent reproducibility by another qualified individual.

4. Data considered as established fact by the scientific and engineering community, such as engineering handbook data or critical tables, do not require validation.

QAPD-6.4 Qualification of Existing Data

1. This section contains requirements unique to the post-qualification of data and information that are relied upon to support the WIPP compliance application and were collected prior to the implementation of this QAPD. While the qualification process shall be conducted in accordance with the program control requirements of the CBFO QAPD, it is not intended that the QAPD identify the data that are subject to this process or the technical requirements of the qualification process. The qualification process shall be conducted in accordance with approved procedures that provide for documentation of the decision process, the factors used in arriving at the choice of the qualification method, and the decision that the data are qualified for their intended use.

2. Existing data shall be qualified using one or a combination of the following methods:

A. Determination that the data were collected under a QA program that is equivalent in effect to ASME NQA-1-1989 edition; ASME NQA-2a-1990 addenda, Part 2.7, to ASME NQA-2-1989 edition; and NQA-3-1989. Factors to be considered include:

i. Qualifications of personnel or organizations generating the data

ii. Technical adequacy of the equipment and procedures used to collect and analyze the data

iii. Environmental conditions under which the data were obtained (if germane)

iv. Quality and reliability of the measurement control program under which the data were generated

v. Extent to which data demonstrate properties of interest (e.g., physical, chemical, geologic, or mechanical)

vi. Extent to which conditions generating the data may partially meet requirements of this QAPD

vii. Prior uses of the data and the associated verification processes

viii. Prior peer or other professional reviews of data and their results

ix. Extent and reliability of the documentation associated with the data

x. Extent and quality of corroborating data or confirmatory testing results

xi. Degree to which data generating processes were independently audited

xii. The importance of the data in showing that the repository design meets the performance objectives

B. The use of corroborating data, with the data relationships and inferences clearly identified and justified

C. Confirmatory testing that is performed and documented

D. Peer review conducted in a manner that is compatible with NUREG-1297, *Peer Review for High-Level Nuclear Waste Repositories*

i. Peer reviews shall be performed when the adequacy of information or the suitability of procedures and methods essential to showing that a repository system meets its performance requirements with respect to safety and calculations, or reference to previously established standards and practices.

ii. Peer reviews performed in support of WIPP compliance activities shall be documented, as shall all peer review processes.

E. Peer reviews are used for the following activities:

i. Conceptual models selected and developed by DOE

ii. Waste characterization analysis as required in 40 CFR 194.24(b)

iii. Engineered barrier evaluation as required in 40 CFR 194.44

QAPD-7.0 Software Requirements

This section of the QAPD establishes software quality assurance (SQA) requirements for CBFO participants who develop, acquire, maintain, or use computer software that is important to compliance application and waste characterization.

QAPD-7.1 Applicability

1. The requirements in this section apply to computer software used in the manipulation or production of data that are, in turn, used in the processing, gathering, or generation of information whose output is relied upon to make design, analytical, operational, or compliance-related decisions with respect to the performance of the waste confinement, waste characterization, waste transportation, or waste acceptance processes. The requirements also apply to safety software used by CBFO and its contractors. The application of these requirements shall be prescribed in written plan(s), policies, procedures, or instructions.

2. The **basic requirements** defined in this section apply to those activities involved in the processing, control, or measurement of the hazardous, radioactive, and waste matrix materials of the TRU or TRU mixed waste. Waste matrix materials include but are not limited to metals, cellulosics, chelating agents, water, and other liquids, plastics, and rubber. The requirements also apply to safety software used by CBFO and its contractors.

3. The **NQA-2 Part 2.7 requirements** defined in this section apply to software used in the processing, control, or measurement of the radioactive and waste matrix materials of the TRU waste. These requirements also apply to software used to model the performance of the WIPP for purposes of compliance application and/or reapplication. The requirements also apply to safety software used by CBFO and its contractors.

4. Exempt from the requirements of this section of the QAPD is software that is considered to be "systems software" (e.g., operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, query languages, word processing programs, spreadsheets, database managers, and graphing programs) or other software that does not generate data that are used in the formulation of conclusions. Specific applications supporting Section QAPD-7.1, written for use within these types of software (e.g., detailed formulas or macros) that can be verified by hand calculations or other means, shall meet the following requirements of this section:

    A. A listing of the software code (i.e., details of formulas, file/table/cell references, and/or macros) shall be developed and maintained.

    B. Documentation shall be prepared to demonstrate by hand or other independent calculations that the specific application provides the correct results for the specified range of input parameters.

QAPD-7.2 Basic Requirements for Inventory and Classification of Software

1. An inventory of all applicable software shall be maintained that identifies the software name, version, classification, exemption status, operating environment, and the person and organization responsible for the software.

2. Software governed by this section of the QAPD shall be categorized. The criteria for classification shall be documented in the inventory and shall address the purpose of the software relative to its use in engineering, scientific, testing, data collection, design, analysis, and operations activities, as well as its importance to safety or its significance in managing information or augmenting mission-essential decisions.

QAPD-7.3 Software Quality Assurance

QAPD-7.3.1 Basic Requirements for Software Quality Assurance

Controls governing applicable software development projects shall be identified in controlled and documented plans. The plans shall be formally reviewed and approved. Controls governing the configuration and use of the software shall be identified in plans or procedures appropriate to the organizations using the software. The following activities shall be addressed in plans or procedures:

1. Software development

2. Software verification and validation

3. Software configuration control

4. Software operation and maintenance

Plans may be issued separately or as a single, composite plan, depending on the nature and complexity of the project. The software control plans may be a section of the overall project plan, provided that each software item is addressed and the software control portion of the plan prescribes the documentation, reviews, and controls required by this section.

QAPD-7.3.2 NQA-2 Part 2.7 Requirements for Software Quality Assurance

Plans for ensuring software quality shall be prepared for each new software project at the start of the software life cycle. For acquired software, the software quality plan shall be prepared before the software enters the purchaser organization. Plans may be prepared individually for each software project, may exist as a generic document to be applied to software prepared within or procured by an organization, or may be incorporated into the overall QA program. The plan shall identify:

1. The software products governed by the plan

2. The types of documentation to be prepared, reviewed, and maintained during the software design, development, implementation, test, and use

3. The organizations responsible for performing the work and achieving software quality, and their tasks and responsibilities

4. The process for reporting and documenting software discrepancies, evaluating the impact of discrepancies on previous calculations, and determining the appropriate corrective action(s)

5. The standards, conventions, techniques, or methodologies that guide the software development, as well as the methods used to ensure implementation of requirements

6. The procedure(s) used for establishing and maintaining the integrity of data, embodied mathematical models, and output files

QAPD-7.4 Software Procurement

QAPD-7.4.1 Basic Requirements for Software Procurement

This section of the QAPD identifies responsibilities of the sponsoring organization for acquired software upon receipt of the software.

All procured software governed by this section shall be tested in accordance with documented and approved test procedures using approved test-case specifications to ensure that the acquired software will perform satisfactorily in its operating environment. The installation tests (including the test procedures), the test case specifications, and the results of the installation tests shall be identified, documented, and maintained as records according to established procedures.

QAPD-7.4.2 NQA-2 Part 2.7 Requirements for Software Procurement

1. The procurement of software and related services shall be performed in accordance with Section QAPD-3.3 of this QAPD.

2. Once the software has been installed, but before its use, the sponsoring organization shall perform user acceptance to verify the functional capability of the software and the acceptability of the supplier's supporting documentation (e.g., the user manual, technical specifications, and the results of supplier testing).

3. For procured software, the supplier shall report software errors and failures to the sponsoring organization. The sponsoring organization shall also report software errors to the supplier.

QAPD-7.5 Software Developed Under Other QA Programs

QAPD-7.5.1 Basic Requirements

Software that has not been developed or approved in accordance with this QAPD shall be evaluated to determine its adequacy to perform intended functions. The evaluation shall be documented. The software shall be uniquely identified and controlled prior to the evaluation, clearly traceable to the software requirements, accepted by the sponsoring organization, and placed under configuration control prior to use.

QAPD-7.5.2 NQA-2 Part 2.7 Requirements

The evaluation of existing software developed in accordance with other QA programs shall serve as the basis to:

1. Determine the adequacy of existing verification and validation activities and software documentation to support operations and maintenance.

2. Identify the activities to be performed and the documentation necessary to accept the software for its intended use and place it under configuration control. The evaluation shall be documented and shall contain, at a minimum:

    A. User application requirements

    B. Test plans and test cases required to validate software acceptability

    C. User documentation as described in Section QAPD-7.9.2.6

QAPD-7.6 Software Development and Life Cycle

QAPD-7.6.1 Basic Requirements

The developmental activities of software projects subject to this QAPD shall be identified in documented and approved plans to ensure that the project proceeds in an orderly and traceable manner. Sufficient information shall be provided to clearly indicate the necessary tasks, the deliverables and baselines for each phase, the required reviews, appropriate milestones, and the responsibilities associated with each task.

Software project development plans shall identify the items that need to be baselined and the methods to be used for controlling the configuration of those baselines throughout the development process. Configuration control planning for software are addressed in Section QAPD-7.8 of this QAPD.

QAPD-7.6.2 NQA-2 Part 2.7 Requirements

1. The activities associated with the evolution of the software shall be accomplished using an iterative or sequential approach. The approach shall include the analysis of the problem under study, the transformation of the analysis into the design, the implementation of the design into validated computer software, and the development of sufficient documentation to demonstrate that the specified requirements have been successfully included in the computer software.

2. The iterative or sequential approach to software development consists of phases, with each phase leading to the development of a specific work product representing components of the software baseline. The software phases are:

    A. Definition of requirements

B. Design

C. Implementation

D. Testing

E. Installation and checkout

F. Operations and maintenance

G. Retirement

3. Following the development of the software quality plan, no strict sequence of performing activities is required (i.e., activities may be performed serially or recursively) provided that all the specified requirements for each software development phase have been met and the intent of the requirements has not been subverted.

QAPD-7.6.2.1 Requirements Phase

Software requirements shall be specified, documented, and reviewed. These requirements shall pertain to functionality, performance, design constraints, data attributes, and external interfaces (e.g., hardware limitations) as outlined in Section QAPD-7.9.2.2. Each requirement shall be specified in sufficient detail to permit the accomplishment of design and validation activities. Software requirements shall be traceable throughout the software development cycle, and a verification and validation plan shall be prepared after the software requirements have been documented and approved.

QAPD-7.6.2.2 Design Phase

The software design shall be based on the software requirements and shall be documented and reviewed. The design shall specify the overall structure (control and data flow) and the reduction of the overall structure into physical solutions (algorithms, equations, control logic, and data structures). The design may necessitate the modification of the requirements documentation and the verification and validation plans.

QAPD-7.6.2.3 Implementation Phase

The software design shall be translated into a form (programming language) suitable for processing by a computer. The executable software shall be analyzed to identify and correct errors.

QAPD-7.6.2.4 Testing Phase

1. Test requirements and acceptance criteria shall be specified, documented, and reviewed and shall be based upon applicable design or other pertinent technical bases. Appropriate tests, such as verification tests, requirements-driven tests, hardware integration tests, and in-use tests, shall be controlled. Software testing, using documented test plans, test cases, and test results are the primary methods of software validation.

2. Testing of software shall be performed to the extent that unintended functions are identified and reviewed and their impact determined and corrected. If appropriate, determine if modifications are needed to the requirements, design, implementation, or test plans and test cases.

3. Design-driven tests shall be used to demonstrate the capability of the software to produce valid results for test problems encompassing the range of intended use as defined by the software documentation. Testing of software used for operational control shall demonstrate the required performance over the entire range of the controlled function or process. Acceptable test methods consist of:

   A. Hand calculations

   B. Calculations using comparable proven problems

   C. Empirical data and information from confirmed published data and correlations or technical literature

   D. Comparison with other validated software of similar purpose

   E. Manual inspections or qualitative checks not involving numerical manipulation (examples include visual inspection of database reformatting or data plotting)

4. Requirements-driven tests shall be used to validate software by comparing test results of software execution with objective evidence obtained by the above methods. The results of this evaluation shall be of sufficient scope and depth to prove the capabilities and limitations delineated in the software documentation.

5. Test records shall identify each of the following:

   A. Computer program tested

   B. Computer hardware used

   C. Test equipment and calibrations, where applicable

   D. Date of test

   E. Tester or data recorder

   F. Simulation models used, where applicable

   G. Test problems

   H. Results and acceptability

   I. Action taken in connection with any deviations noted

   J. Persons evaluating test results

QAPD-7.6.2.5 Installation and Checkout Phase

1. During installation and checkout, the software becomes part of a system consisting of applicable software components, hardware, and data. The process of integrating the software with other applicable components may consist of installing both the hardware and software, converting or creating databases, and verifying that all components of the system have been included in the installation. Test problems shall be developed and documented to permit confirmation of the acceptable performance of the software in its operating environment. Installation and checkout of software shall consist of:

   A. Execution of tests for installation and integration

   B. Documented acceptance of the software for operational use

   C. Placement of the software under configuration control prior to use

2. Completion of the installation and checkout activities establishes the software baseline.

QAPD-7.6.2.6 Operations and Maintenance Phase

1. Operation of the software is conducted by the user in accordance with the operation and usage instructions described in the software user documentation. Once the software has been made available for use, the software requirements and the design integrity shall be maintained. Maintenance activities shall be performed and documented in a traceable, planned, and orderly manner.

2. In all cases, verification and validation of software shall be completed and approved and corrective actions performed, as necessary, prior to relying upon the software to perform its intended function.

   A. Post Installation Maintenance

   Software shall be maintained to remove latent errors (corrective maintenance), to respond to new or revised requirements (perfective maintenance), or to adapt the software to changes in the operating environment (adaptive maintenance). Software modifications shall be approved by authorized personnel, documented, verified, validated, and controlled.

   B. In-Use Tests

   Test problems shall be run whenever the software is installed on a different computer or when significant hardware or system software configuration changes are made. These tests shall be documented, performed by an individual technically competent in the subject area(s), and serve as the basis for determining if the software still meets specified requirements.

   Periodic in-use manual or automatic self-check routines shall be prescribed and performed for that software where computer failure or electronic drift can affect required outcomes.

QAPD-7.6.2.7 Retirement Phase

Criteria shall be developed to determine when software can be retired from use. Methods shall be developed to prevent the use of software that is no longer controlled. Upon retirement, user support for a software product is terminated.

QAPD-7.7 Software Verification and Validation

QAPD-7.7.1 Basic Requirements

1. Verification and validation of software shall include the review of software activities, documentation, and tests to ensure that the software:

   A. Adequately and correctly performs all intended functions

   B. Does not perform any unintended function that either by itself, or in combination with other functions, can degrade the intended outcomes of the software

2. Verification and validation shall be performed by any competent individual(s) or group(s) other than those who performed the software design. The individuals may be from the same organization and may include the designer's supervisor, provided the supervisor:

   A. Did not specify a singular design approach

   B. Did not rule out certain design considerations

   C. Did not establish the design inputs used

   D. Is the only individual in the organization competent to perform the verification or validation

QAPD-7.7.2 NQA-2 Part 2.7 Requirements

QAPD-7.7.2.1 Verification

Verification is a formal checking activity performed throughout the evolution of the software life cycle. Verification activities shall be clearly documented, including the identification of those performing and approving the verification. The reviewed documents shall be updated and placed under configuration control. Documentation of review comments and their disposition shall be retained. Unincorporated comments and their disposition shall also be retained in accordance with established procedures.

QAPD-7.7.2.2 Requirements

Verification review(s) of software requirements shall ensure that the requirements are complete, verifiable through testing, consistent, and technically feasible as described in Section QAPD-7.6.2.1.

QAPD-7.7.2.3 Design

Verification review of software design shall evaluate the technical adequacy of the design approach and ensure that all the requirements have been addressed and that the design is complete, verifiable (through testing, using approved test plans and test cases), consistent, technically feasible, and traceable to the software requirements as described in Section QAPD-7.6.2.2.

QAPD-7.7.2.4 Implementation

Verification of the implementation of software design shall consist of the examination of software logic and source code to ensure adherence to standards and conventions and to ensure that the design has been implemented as described in Section QAPD-7.6.2.3.

QAPD-7.7.2.5 Testing

Verification of software testing shall consist of reviews to ensure that the specified test criteria, the expected results, and the software development documentation have been met as described in Section QAPD-7.6.2.4.

QAPD-7.7.2.6 Installation and Checkout

Verification of installation and checkout activities consists of reviews to ensure that the software baseline has been established.

QAPD-7.7.3 Validation

1. Software validation is primarily a formal testing activity that shall be performed prior to installation and checkout. It shall be used to demonstrate that the computational model embodied in the software is an acceptable representation of the process or system for which it is intended and that the software produces correct solutions within defined limits for each parameter employed.

2. Validation methods, test data, software-generated results, and conclusions shall be documented in a form that can be understood by an independent individual technically competent to use the software for the particular problem under study. The documentation shall be reviewed to assure the test requirements have been satisfied .

3. When the adequacy of the conceptual, mathematical, or computational models or the suitability of procedures and methods cannot be established through testing, alternate calculations, or reference to previously established standards and practices, a documented peer review shall be performed to meet the software validation requirements.

4. The validation of software modifications shall be subject to selective regression testing to

    A. Detect errors introduced during the modification of the systems or system components

    B. Verify that the modifications have not caused unintended adverse effects

C. Verify that the modified systems or system components still meet specified requirements

QAPD-7.8 Software Configuration Management

QAPD-7.8.1 Basic Requirements

1. A. Implementation of baseline and change control processes are fundamental to configuration management. A baseline is a collection of all approved components of the software development cycle. As each component is approved, it is added to the overall software baseline. A software baseline serves as the basis for further development and maintenance that can be changed only through the use of formal change control procedures. Change control is the process by which a change to a baseline is proposed, evaluated, and approved or rejected.

2. B. Software configuration controls shall be planned, including the identification of organizational positions that are authorized to make changes, and the methods, procedures, and instructions to be used to control the identification of, access to, changes to, and the status of computer software. Configuration control documents shall indicate how changes will be validated, including regression testing, and how the tests will be documented. These control documents shall be formally reviewed, approved, and in place before the software is released for use.

QAPD-7.8.2 NQA-2 Part 2.7 Requirements

QAPD-7.8.2.1 Configuration Identification

Software shall be placed under configuration control as each configuration item is approved. A software baseline shall define the most recent approved software configuration. The configuration items and their associated documentation shall be traceable to one another. A labeling system for configuration items shall be implemented that:

1. Uniquely identifies each configuration item

2. Identifies changes to configuration items by revision or version identifier

3. Provides the ability to uniquely identify each approved configuration of the revised software that is available for use

QAPD-7.8.2.2 Configuration Change Control

1. Changes to software shall be systematically proposed, evaluated, documented, and approved to ensure that the impact and rationale for making the change is carefully assessed prior to updating the software baseline. Changes to previously accepted software shall be subject to the same level of control as the original software.

2. Information concerning approved changes shall be transmitted to all affected organizations. All changes shall be formally evaluated and approved by the organization responsible for the

original design, unless an alternate organization has been given the authority to approve the changes. Only authorized changes shall be made to software baselines. Software verification activities shall be performed for the change as necessary to ensure that the change is appropriately reflected in the software documentation and to ensure that traceability is maintained. The degree of software validation shall be commensurate with the nature and scope of the change.

QAPD-7.8.2.3 Configuration Status Accounting

Information shall be maintained that reflects the current status of the software baseline. This includes the identity and version of the approved configuration and the status of any proposed and approved changes to the baseline components. This information shall be available to all designated users of the software upon request.

QAPD-7.9 Documentation

QAPD-7.9.1 Basic Requirements

Software shall be described in one or more documents that detail user instructions, technical bases, functional requirements, and maintenance-related information sufficient to allow independent verification and maintenance and to provide traceability of the documentation to the software. The documentation shall be reviewed by an individual competent in the technical subject area for which the use of the software is intended. The review shall verify that the documentation adequately and accurately reflects the software that constitutes the system, and is sufficient to objectively demonstrate that the software requirements have been successfully implemented. Appropriate documentation shall be made available to all designated users of the software.

QAPD-7.9.2 NQA-2 Part 2.7 Requirements

QAPD-7.9.2.1 Procurement Documentation

The applicable quality assurance requirements shall be specified and the required vendor-supplied software documentation, plans, and procedures shall be identified in the software procurement documentation.

QAPD-7.9.2.2 Requirements Documentation

1. Software requirements documentation shall outline the requirements that the proposed software must satisfy. The software requirements shall, as applicable, address the following:

    A. Functionality – the functions the software performs

    B. Performance – the time-related issues of software operation such as speed, recovery time, and response time

C. Constraints – limits imposed on implementation activities; any elements that will restrict design options

D. Attributes – non-time-related issues of software operation such as portability, acceptance criteria, access control, and maintainability

E. External interfaces – interactions with people, hardware, and other software

2. Software requirements shall be traceable throughout the software development cycle.

QAPD-7.9.2.3 Design and Implementation Documentation

Software design and implementation documentation consists of a document or series of documents that:

1. Describe the major components of the software design as they relate to the software requirements

2. Describe the theoretical basis, embodied mathematical model, control flow, control logic, and data structure(s) of the software

3. Describe the allowable or prescribed ranges for inputs and outputs

4. Describe the design in a manner that can be translated into executable code

QAPD-7.9.2.4 Verification and Validation Documentation

1. Software verification and validation documentation shall consist of associated plans and shall describe the activities (including the results of reviews and tests) and the criteria for accomplishing the verification of the software throughout the software evolution process. The documentation shall also specify the hardware and software configurations pertinent to the software verification and validation.

2. Software verification and validation documentation shall be organized in a manner that allows traceability from the software requirements to both the software design and to the validated capabilities of the software.

QAPD-7.9.2.5 Change Documentation

Changes to software shall be formally documented. This documentation shall contain a description of the change, the rationale for the change, and the identification of affected configuration items of the software baseline.

QAPD-7.9.2.6 User Documentation

User documentation should be sufficient to allow any qualified user (i.e., one having adequate technical background) to install and run the software and properly respond to errors. User documentation, at a minimum, shall include:

1. The software name and version identifier

2. Statements of functional requirements and system limitations, including hardware

3. An explanation of the mathematical models and derivation of the numerical methods used in the software design (physical and mathematical assumptions on which the software is based shall be included, along with an explanation of the capabilities and limitations inherent in the software)

4. Instructions that describe user interaction with the software, user messages initiated as a result of improper input and how the user can respond, the identification and description of input and output specifications and formats, and input parameters

5. A description of any required training necessary to use the software

6. Information for obtaining operation and maintenance support

QAPD-7.9.2.7 Error Documentation

Documentation of errors detected during the use of the software following installation and checkout shall be maintained. This documentation can be used for process improvement and to prevent recurrence of errors during the development and maintenance of other software. This documentation shall contain the identity of the software, the classification of the error in terms of its significance to the integrity of the software output, and the corrective action(s).

QAPD-7.10 Problem Reporting and Corrective Action

QAPD-7.10.1 Basic Requirements

Problems (e.g., errors, faults, failures) detected in released software shall be promptly reported in accordance with documented procedures. When problems are detected in a software item, work previously performed using versions of the software that contain that problem shall be evaluated to determine the impact on the completed work. The evaluations shall be documented and retained in accordance with records requirements.

QAPD-7.10.2 NQA-2 Part 2.7 Requirements

1. A system shall be established and maintained to record, classify, analyze, track, and report software problems (in released versions) and the associated corrective actions. Problems shall be promptly reported to any affected organizations and the resolution shall be formally processed.

2. When problems are discovered in software or software results, the sponsoring organization shall determine the affect on previous uses and the need for corrective action based on sufficient information obtained from the affected users. Corrective action shall ensure that

   A. Problems are identified, evaluated, documented and, if required, corrected

B. Problems are assessed for their impact on past and present uses of the software

C. Changes to software are in accordance with the software configuration management requirements of this section of the QAPD

D. Results are provided to the affected users, along with any revised software documentation

3. Problems that could significantly affect decisions based upon prior use or that require significant modification to the software shall be identifiable to all users. Errors that have been determined to represent a condition adverse to quality shall be controlled in accordance with Section QAPD-2.3 of this QAPD.

QAPD-7.11 Access Control

To the extent appropriate, controls shall be established to permit authorized and prevent unauthorized access to software that has been accepted in accordance with this section.

QAPD-8.0 Glossary

Acceptance: The documented determination by the receiving organization that a work project is suitable for the intended purpose.

Acquired Software: Computer software obtained that was not developed by the user organization.

Alternative Calculations: Calculations that are made with alternative methods to verify correctness of the original calculation.

Approval: The documented determination by a responsible individual that a work product is suitable for the intended purpose and shall be used as required.

Assessment/Evaluation: The act of reviewing, inspecting, testing, checking, conducting surveillances, auditing, or otherwise determining and documenting whether items, processes, or services meet specified requirements. Assessments are performed by or for management. Evaluations are performed by the line organization.

Assessment, External: An assessment of those portions of an organization's quality assurance program not under the direct control or within the organizational structure of the auditing organization.

Assessment, Internal: An assessment of those portions of an organization's quality assurance program retained under its direct control and within its organizational structure.

Assessor: An individual who is qualified to perform assigned portions of an assessment.

Audit: A planned and documented independent assessment to determine by investigation, examination, or evaluation of objective evidence the adequacy of and compliance with established procedures, instructions, drawings, and other applicable documents, and the effectiveness of implementation. An audit should not be confused with surveillance or inspection activities performed for the sole purpose of process control or product acceptance.

Auditor: An individual who is qualified to perform assigned portions of an audit.

Audit (or Assessment) Team Leader: A lead auditor (or assessor) who is assigned to direct the efforts of an audit (or assessment) team.

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, and the corresponding standard or known values derived from the standard.

Certificate of Conformance: A document signed or otherwise authenticated by an authorized individual certifying the degree to which items or services meet specified requirements.

Certification: The act of determining, verifying, and attesting to, in writing the qualifications of personnel, processes, procedures, or items in accordance with specified requirements.

Characteristic: A property or attribute of an item, process, or service that is distinct, describable, and measurable.

Commercial Grade Item: An item that is (1) not subject to design or specification criteria unique to a CBFO program or facility, (2) used in applications other than the nuclear industry, and (3) ordered from the manufacturer or supplier on the basis of specifications set forth in the manufacturer's published product description.

Compliance Certification Application: The compliance certification application submitted to the EPA pursuant to section 8 (d) (1) of the WIPP Land Withdrawal Act of 1992 (Pub. L. 102-579, 106 Statue 4777) or any compliance re-certification applications submitted to the EPA pursuant to section 8(f) of the WIPP Land Withdrawal Act.

Condition Adverse to Quality: An all-inclusive term used in reference to any of the following: failures, malfunctions, deficiencies, defective items, nonconformances, and technical inadequacies. A condition adverse to quality is considered significant when

- if uncorrected, the condition adverse to quality could have a serious effect on safety, operability, waste isolation, TRU waste site certification, regulatory compliance demonstration, or effective implementation of the QA program
- the condition adverse to quality requires immediate notification of regulatory entities (e.g., 10 CFR Part 21, HWFP Module I.E.13)
- the condition adverse to quality indicates a significant failure or breakdown in the implementation of QA Program requirements
- repeated attempts to resolve a condition adverse to quality have been unsuccessful
- the condition adverse to quality is identified in items or activities important to safety or waste isolation and compromises the ability to prevent or mitigate the consequences of an accident, thereby presenting a significant hazard to safety and health of workers and/or the public

Configuration Control: The process of identifying and defining the configuration items in a system, controlling the release and change of these items throughout the system life cycle, and the recording and reporting of the status of configuration items and change requests.

Configuration Item: A collection of hardware or software elements treated as a unit for the purpose of configuration control.

Controlled Document: A document that is prepared, reviewed, approved, and distributed in accordance with established implementation procedures. Controlled documents are subject to controlled distribution and to a defined and controlled change process.

Corrective Action: Measures that are taken to rectify conditions adverse to quality and, where necessary, to preclude recurrence.

Corrective Action Report (CAR): A document used to identify and rectify conditions adverse to quality (CAQ), and track the associated corrective actions. CARs address CAQs that are primarily programmatic in nature, as opposed to nonconformance reports (NCRs) which address CAQs relating to a specific item(s) such as a piece of hardware or data. The category of CARs includes: corrective action reports or corrective action requests, nonconformance corrective action reports (NCARs), management corrective action reports (MCARs), deficiency reports (DRs), process deficiency reports (PDRs), audit findings, condition adverse to quality reports(CAQR), etc.

Data Accuracy: The degree to which data agree with an accepted reference or true value. Accuracy is a measure of the bias in a system.

Data Comparability: A measure of the confidence with which one data set can be compared to another.

Data Completeness: A measure of the amount of valid data obtained compared to the amount that was planned.

Data Precision: A measure of the mutual agreement between comparable data gathered or developed under similar conditions, usually expressed in terms of a standard deviation.

Data Representativeness: The degree to which data accurately and precisely represent a characteristic of a population, a parameter, variations at a sampling point, or environmental conditions.

Data Quality Objectives (DQOs): Qualitative and quantitative statements derived from outputs of the first six steps of the DQO Process (see below). DQOs 1) clarify the study objective, 2) define the most appropriate type of data to collect, 3) determine the most appropriate conditions from which to collect the data, and 4) specify tolerable limits on decision errors which will be used as the basis for establishing the quantity and quality of data needed to support compliance decisions. DQOs are used to develop a scientific and resource-effective data collection design.

DQO Process: A strategic planning approach based on the Scientific Method that is used to prepare for a data collection activity. The DQO process provides a systematic procedure for defining the criteria that a data collection design should satisfy, including when to collect samples, where to collect samples, the tolerable level of decision errors for the study, and how many samples to collect. By using the DQO process, DOE will assure that the type, quantity, and quality of environmental data used in decision making will be appropriate for the intended application. In addition, DOE will guard against committing resources to data collection efforts that do not support a defensible decision. The DQO process consists of seven steps and is more fully described in EPA 1994b.

Design Basis: Information that identifies the specific functions to be performed by items and the specific values or ranges of values chosen for controlling parameters as reference bounds for design.

Design Input: Those criteria, parameters, bases, or other design requirements upon which the detailed final design is based.

Design Output: Drawings, specifications, and other documents resulting from the translation of design input requirements.

Design Process: The technical process that begins with the identification of design input and ends with the issuance of design output documents.

Design Review: A documented evaluation of design output during the design process to determine the design adequacy and the conformance to specified acceptance criteria.

Disposal System: Any combination of engineered and natural barriers that isolate transuranic waste after disposal. For the purposes of the WIPP, this will include the combination of the repository/shaft system and the controlled area.

Document: Written or pictorial information that describes, specifies, reports, or certifies activities, requirements, procedures, or results.

Document Control: The process that provides for document adequacy review, approval for release by authorized personnel, and distribution for use at the prescribed work locations.

Error: A discrepancy between a computed, observed, or measured value or condition and the true, specified, or theoretically correct value or condition.

Graded Approach: The process by which the level of analysis, documentation, verification, and other controls necessary to comply with QA program requirements are developed commensurate with specified factors.

Independent Assessment: An assessment, conducted by a group or organization having authority and freedom from the line organization, to evaluate the scope, status, adequacy, programmatic implementation, or effectiveness of a program or process.

Item: An all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, unit, support system, or data.

Lead Auditor: An individual trained, qualified, and certified to organize and direct an audit, report audit findings, and evaluate corrective actions.

Lifetime Records: Records required to be maintained for the useful life of the items to which they pertain while the items are installed in the plant or facility (life of the item), or for the lifetime of the equipment, facilities, or programs to which the records apply.

Line Management: Those management positions that are directly responsible for task products and services. Includes CBFO supervisors and team leaders and contractor management within the context of the definition.

Line Organization: The organization directly responsible for task products and services. Includes CBFO offices and teams and contractor organizations within the context of the definition.

Macro: Single computer instructions invoked by a symbol, name, or key that represents commands, actions, or keystrokes.

Management Assessment: Assessment performed by management that focuses on how well the integrated quality assurance program is working. The management assessment should identify management problems that hinder the organization from achieving its objectives in accordance with quality, safety, and environmental requirements.

Measuring and Test Equipment: All devices used to calibrate, measure, gage, test, inspect, or otherwise determine compliance with prescribed technical requirements.

Monitoring and Data Collection (M&DC) Equipment: A subcategory of M&TE that is used in the collection of measurement data for the establishment of test conditions and general information and the collection of general measurement data not utilized to verify the conformance of an item or equipment to specified criteria.

Nonconformance: A deficiency in a characteristic or record that renders the quality of an item or sample unacceptable or indeterminate.

Nonpermanent Records: Records having value for a specific, limited time and authorized by the National Archives and Records Administration to be destroyed after that time.

Nonreactor Nuclear Facility: Those activities or operations that involve radioactive or fissionable materials in such form and quantity that a nuclear hazard potential exists to the employees or the general public. Incidental use and the generation of radioactive materials in a facility operation (e.g., check and calibration sources, radioactive isotopes used in research and experimental and analytical laboratory activities, electron microscopes, and x-ray machines) would not ordinarily require the facility to be included in this definition. The transportation of radioactive materials, accelerators, and reactors and their operations are not included.

Participant: A DOE contractor organization that furnishes items or services in support of CBFO-sponsored programs, including those TRU waste generator and storage sites characterizing waste for shipment to WIPP.

Peer: A person having technical expertise in the subject matter to be reviewed to a degree at least equivalent to that needed for the original work.

Peer Review: A documented, critical review performed by peers who are independent of the work being reviewed. 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. Peer reviews confirm the adequacy of work.

Periodic: Occurring or recurring at regular intervals. For the purposes of this QAPD, these intervals are determined by the responsible management unless otherwise specified.

Post-Closure QA Records: QA records required to be maintained beyond the operating life of the WIPP repository, for periods of several hundreds of years, and in a manner that would permit

future generations to maintain them longer, if desired, using present reasonably available technology.

Procedure: A document that specifies or describes how an activity is to be performed. The term "procedure" also includes instructions and drawings.

Process: A series of actions that achieve an end or result.

Procurement Document: Purchase orders, contracts, specifications, or other documents used to define technical and quality assurance requirements for the procurement of items or services.

Qualification (Personnel): The characteristics or abilities gained through education, training, or experience, as measured against established requirements such as standards or tests, that qualify an individual to perform a required function.

Qualification Testing: A test that is intended to provide a desired level of confidence that an item meets specified criteria.

Quality: The condition achieved when an item, service, or process meets or exceeds the user's requirements and expectations.

Quality Assurance: All those planned and systematic actions necessary to provide adequate confidence that an item will perform satisfactorily in service.

Quality Assurance Objectives: Objectives that represent the required quality of data necessary to draw valid conclusions regarding program objectives.

Quality Assurance Program: The program established to assign responsibilities and authorities, define policies and requirements, and provide for the performance and assessment of work.

Quality Assurance Record: A completed record or any authenticated portion of a record that provides objective evidence of the quality of items or activities.

Quality System: See *Quality Assurance Program*.

RCRA Related Deficiency: A deficiency that is a violation of the requirements of the WIPP Hazardous Waste Facility Permit.

Readiness Review: A systematic documented review of the readiness for startup or continued extended use of a facility, process, or activity. Readiness reviews are typically conducted before proceeding beyond project milestones and prior to commencement of a major phase of work activities.

Receipt Inspection: A method of accepting an item or related service from a supplier by examination or testing of the item or related service to verify conformance to specified requirements.

Records: Books, papers, maps, photographs, machine readable materials or other documentary materials, regardless of physical form or characteristics, made or received by an agency of the United States Government under Federal law or in connection with the transaction of public business and preserved or appropriate for preservation by that agency or its legitimate successor as evidence of the organization, functions, policies, decisions, procedures, operations or other activities of the government or because of the informational value of the data they contain.

Records Holding Facility: A CBFO records storage facility meeting regulatory requirements for the storage of inactive records pending their final disposition.

Repair: The process of restoring an item to a condition such that the capability of an item to function reliably and safely is unimpaired even though that item still does not conform to the original requirement.

Rework: The process by which an item is restored to original specifications by completion or correction.

Safety: An all-inclusive term used synonymously with environment, safety, and health to encompass protection of the public, the workers, and the environment.

Safety Software: Includes the following:

1. Safety System Software. Software for a nuclear facility that performs a safety function as part of a structure, system, or component and is cited in either (a) a DOE approved documented safety analysis or (b) an approved hazard analysis.

2. Safety and Hazard Analysis Software and Design Software. Software that is used to classify, design, or analyze nuclear facilities. This software is not part of a structure, system, or component (SSC) but helps to ensure the proper accident or hazards analysis of nuclear facilities or an SSC that performs a safety function.

3. Safety Management and Administrative Controls Software. Software that performs a hazard control function in support of nuclear facility or radiological safety management programs or technical safety requirements or other software that performs a control function necessary to provide adequate protection from nuclear facility or radiological hazards. This software supports eliminating, limiting, or mitigating nuclear hazards to workers, the public, or the environment.

Sample: A subset of a population (e.g., wastes, environmental media, materials, cores) whose properties are used to gain information about the population.

Scientific and Engineering Software: Software that uses numerical methods to complete scientific, engineering, and mathematical calculations.

Scientific Investigation: Any research, experiment, test, study, or activity that is performed for the purpose of investigating a natural system or the man-made aspects of a geologic repository, including the investigations that support design of the facilities and the waste package.

Scientific Notebook: A record of the methods and results of scientific investigations that is used when the work involves a high degree of professional judgment or trial and error methods, or both.

Service: The performance of work, such as design, construction, fabrication, inspection, nondestructive examination, testing, environmental qualification, equipment qualification, repair, installation, or similar activities.

Significant Condition Adverse to Quality: See *Condition Adverse to Quality*.

Site Characterization: The program of exploration and research both in the laboratory and the field that is undertaken to establish the natural conditions and the ranges of parameters of a particular site.

Software: Computer programs, procedures, rules, and associated documentation and data pertaining to the operation of a computer system.

Software Baseline: An item or product that has been formally reviewed and agreed upon, that serves as the basis for further development, and that can be changed only through formal change control procedures.

Software Quality Assurance Plan: A plan for the development of software products necessary to provide adequate confidence that the software conforms to established requirements.

Software Routine: A collection of computer macros or script files, a spreadsheet application, or other stand-alone software application (either acquired or developed) that generally operates within another program, such as a spreadsheet, and must be independently verified by visual inspection and/or hand calculation.

Software Validation: The process of test and evaluation of the completed software to ensure compliance with software requirements.

Software Verification: The process of determining whether or not the product of a given phase of the software development cycle fulfills the requirements imposed by the previous phase.

Software Verification and Validation: The process of determining whether the requirements for a system or component are complete and correct, the products of each development phase fulfill the requirements or conditions imposed by the previous phase, and the final system or component complies with specified requirements.

Source Verification: A purchaser method of accepting an item or related service from a supplier by monitoring, auditing, surveillance, witnessing, or observing activities performed by the supplier.

Special Process: A process, the results of which are highly dependent on the control of the process or the skill of the operators, or both, and in which the specified quality cannot be readily determined by inspection or test of the product.

Supplier: Any individual or organization who furnishes items or services in accordance with a contract. An all-inclusive term used in place of any of the following: vendor, seller, source, participant, contractor, or subcontractor.

Surveillance: The act of monitoring or observing to verify whether an item, activity, system, or process conforms to specified requirements. Surveillance of a technical work activity is normally done in real time (i.e., the surveillance is accomplished as the work is being performed).

Suspect/Counterfeit Items (S/CIs): An item is suspect when inspection or testing indicates that it may not conform to established Government or industry-accepted specifications or national consensus standards or whose documentation, appearance, performance, material, or other characteristics may have been misrepresented by the supplier or manufacturer. A counterfeit item is one that has been copied or substituted without legal right or authority or whose material, performance, or characteristics have been misrepresented by the supplier or manufacturer. Items that do not conform to established requirements are not normally considered S/CIs if nonconformity results from one or more of the following conditions (which must be controlled by site procedures as nonconforming items):

1. defects resulting from inadequate design or production quality control;
2. damage during shipping, handling, or storage;
3. improper installation;
4. deterioration during service;
5. degradation during removal;
6. failure resulting from aging or misapplication; or
7. other controllable causes.

System Software: Software which is used exclusively in the preparation, installation, or operation of executable software applications. Examples of such software include operating systems, administrative and management systems, system utilities, compilers, assemblers, translators, interpreters, automated protocols, utilities and tools, teleprocessing managers, and query languages.

Technical Review: A documented critical review of work that has been performed within the state of the art. The review is accomplished by one or more qualified reviewers who are independent of the work but collectively have equivalent technical expertise to those who performed the original work. The review is an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification or validation for applicability, correctness, adequacy, completeness, and assurance that established requirements are satisfied.

Technical Specialist: An individual assigned to an assessment team when the scope, complexity, or special nature of the work to be examined warrants assessment of the technical adequacy of the work or the effectiveness of the technical process.

Testing: An element of verification to determine the capability of an item to meet specified requirements or processes that facilitate the collection of data in conducting scientific investigations by subjecting the item or environment to a set of physical, chemical, environmental, or operating conditions.

Traceability: The ability to trace the history, application, and location of an item, data, or sample using recorded documentation. As related to metrology, traceability means the ability to relate individual measurement results through an unbroken chain of calibrations to one or more of the following:

- U.S. national standards maintained by National Institute of Standards and Technology or the U.S. Naval Observatory
- Fundamental or natural physical constants with values assigned or accepted by the National Institute of Standards and Technology
- National standards of other countries which are correlated with NIST

Transuranic Waste: Waste containing more than 100 nCi of alpha-emitting TRU isotopes per gram of waste, with half-lives greater than 20 years, except for (1) high-level radioactive waste, (2) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations, or (3) waste that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR § 61.

TRU Mixed Waste: TRU waste that is also a hazardous waste as defined by the Hazardous Waste Act and 20 NMAC 4.1.200 (incorporating 40 CFR § 261.3).

Use As Is: A disposition permitted for a nonconforming item when it can be established that the item is satisfactory for its intended use.

Validation: An activity that demonstrates or confirms that a process, item, data set, or service satisfies the requirements defined by the user.

Waiver: Documented authorization to depart from specified requirements.

WIPP: The Waste Isolation Pilot Plant, as authorized pursuant to Section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164; 93 Stat. 1259, 1265) to provide a research and development facility for demonstrating the safe disposal of radioactive wastes produced by national defense activities.

Work: The process of performing a defined task or activity, for example, research and development, operations, maintenance and repair, administration, software development and use, inspection, safeguards and security, data collection, and analysis.

Work Suspension: A formal directive issued by management that work must be stopped until the related significant condition adverse to quality or nonconformance has been resolved.

QAPD-9.0 References

10 CFR Part 71, Subpart H, Packaging and Transportation of Radioactive Material, Quality Assurance

10 CFR Part 830, Nuclear Safety Management

40 CFR Part 194, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations

ASME NQA-1-1989, Quality Assurance Program Requirements for Nuclear Facilities

ASME NQA-2a-1990 addenda, Part 2.7, Quality Assurance Requirements of Computer Software for Nuclear Facility Applications

ASME NQA-3-1989, Quality Assurance Program Requirements for the Collection of Scientific and Technical information for Site Characterization of High-Level Nuclear Waste Repositories

DOE/WIPP- 02-3122, Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant

DOE, Division of Nuclear Safety, G-830.120, Implementation Guide for use with 10 CFR Part 830.120 Quality Assurance

DOE O 414.1C, Quality Assurance

National Fire Protection Association (NFPA) Standard 232-1986, Standards for the Protection of Records

NUREG-1297 (1988), Peer Review for High-Level Nuclear Waste Repositories

NUREG/BR-0167 (1993), Software Quality Assurance Program and Guidelines

SNT-TC-1A, Current Revision, The American Society of Nondestructive Testing (ASNT) Recommended Practice

Waste Isolation Pilot Plant Hazardous Waste Facility Final Permit, EPA No. NM4890139088

TRUPACT II Certificate of Compliance, Certificate Number 9218

HalfPACT Certificate of Compliance, Certificate Number 9279

RH 72-B Certificate of Compliance, Certificate Number 9212

10-160B Certificate of Compliance, Certificate Number 9204

ATTACHMENT A: CBFO Organization, Responsibilities, and Interfaces

Effective implementation of the CBFO QA program is dependent on efforts at all CBFO levels. The CBFO organization is structured such that those assigned responsibility for performing the work are responsible for achieving and maintaining quality. Management is responsible for defining quality, developing appropriate plans to attain quality, and providing support of the workers in pursuit of quality. Persons or organizations not directly responsible for performing the work verify quality achievement. Management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.

The CBFO Manager is responsible for overall implementation of DOE programs, policies, orders, and guidance pertaining to TRU waste disposal at WIPP. As such, the Manager provides policy direction and oversight of activities that affect TRU waste characterization and grants DOE waste certification authority to the TRU waste sites. This responsibility includes policy direction and oversight for waste characterization, certification, packaging, and transportation activities at participating sites. Overall responsibility for the development and implementation of the CBFO QA program belongs to the CBFO Manager. Authority for execution of the QA function, which ensures effective implementation, is delegated to the CBFO QA Manager in accordance with the allowable delegations as defined by EM-1.

The Office Director of the National TRU Program (NTP) is responsible to ensure that program requirements are met with regard to TRU waste testing, sampling, analysis, sample handling and custody, associated data management, and waste transportation.

CBFO Deputy Manager, Assistant Manager for Operations, and Office Directors are responsible for planning, organizing, directing, controlling, and evaluating those activities in their area of responsibility that support the CBFO mission and implement the QAPD. Their responsibilities include, but are not limited, to:

- Ensuring that adequate technical and QA training is provided for personnel performing activities important to the satisfaction of CBFO organizational and quality objectives
- Ensuring compliance with all applicable regulations, DOE orders, applicable state, and local laws, and other requirements applicable to CBFO programs
- Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records
- Exercising the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, health, or quality considerations
- Developing, implementing, and maintaining plans, policies, and procedures that implement the QAPD
- Identifying, investigating, reporting, and correcting quality problems

Each CBFO employee, including contractor personnel working to CBFO procedures, is responsible for the quality of his or her work and for promptly reporting all existing, developing, or potential conditions adverse to quality to the responsible management for evaluation and action.

Organizations at all management levels shall establish communication channels that provide timely, routine, and wide dissemination of information pertinent to quality performance.

Where more than one CBFO organization is involved in the execution of activities covered by the QAPD, the responsibility and authority of each organization shall be clearly established and documented. The internal interfaces between organizational units are depicted in CBFO organizational charts. CBFO external interfaces include other DOE elements, CBFO program participants, suppliers, the Environmental Protection Agency, the independent oversight contractor, and the New Mexico Environment Department.

ATTACHMENT B: CBFO Quality Assurance Manager Responsibilities

The CBFO Manager has overall responsibility for the CBFO QA program. Authority for execution of the CBFO QA function, including the independent verification of effective implementation, is delegated to the CBFO QA Manager in accordance with the allowable delegations as defined by EM-1. It is the policy of CBFO to grant the CBFO QA organization sufficient authority, freedom, and access to all work areas to:

- Identify quality problems
- Recommend solutions
- Verify implementation of solutions
- Ensure that unsatisfactory conditions are controlled until proper disposition has occurred

The CBFO QA Manager shall:

- Have direct access to responsible management at a level where appropriate action can be effected
- Be sufficiently independent from cost and schedule considerations
- Have the organizational freedom to communicate with management
- Have the authority and responsibility to stop unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations
- Have no other assigned responsibilities related to the quality assurance program that would prevent adequate attention to quality assurance matters

The CBFO QA Manager has the authority and overall responsibility to independently assess the effective implementation of the CBFO QAPD, both within the CBFO organization and in those participant organizations supporting CBFO.

The CBFO QA Manager has the following additional authorities and responsibilities:

- The organizational freedom to communicate with management
- Scheduling and conducting independent QA assessments, including WIPP core participant organizations
- Scheduling and conducting audits of activities related to waste generating site certification when notified by the Office Director of the Office of the National TRU Program, that the waste generating site is ready

- Scheduling and conducting recertification audits and surveillances of waste generating sites
- Preparing, as appropriate, and reviewing internal procedures that implement the provision of the QAPD
- Tracking, performing trend analysis, and reporting quality problem areas
- Developing, establishing, and interpreting CBFO QA policy and ensuring effective implementation
- Preparing, issuing, and maintaining the CBFO QAPD
- Interfacing with the CBFO staff, participants, and other stakeholders on quality assurance matters
- Reviewing and approving subordinate QA plans, including participant Quality Assurance Project Plans
- Performing adequacy reviews of QA program documents
- Certifying all CBFO lead auditors and qualifying auditors and technical specialists
- Assuring the independence of lead auditors, auditors, and technical specialists

ATTACHMENT C: TRU Waste Characterization and Certification Organizational and Individual Responsibilities

1. CBFO Office Director, Office of the National TRU Program

The Office Director (OD), Office of the National TRU Program (NTP) executes program functions related to characterization of waste for disposal at the WIPP. The OD of the NTP also manages activities that prepare waste sites for certification and notifies the CBFO QA Manager when new sites are ready for independent audit.

2. CBFO Assistant Manager for Operations

The Assistant Manager for Operations is responsible for regulatory compliance of the WIPP. The Assistant Manager for Operations manages the Compliance team, which is responsible for environmental activities at the WIPP. The Assistant Manager for Operations is responsible for the preparation of compliance documentation and the implementation of programs to meet the requirements specified in final operating permits for the WIPP facility.

3. CBFO Office Director, Office of Site Operations

The Office Director, Office of Disposal, is responsible for operations, safety and health oversight at the WIPP.

4. DOE Site Offices

The DOE site offices are responsible for ensuring that the requirements of the QAPjPs are in compliance with all DOE orders and that the resources and funding are available to accomplish Program activities. The DOE site offices are responsible for providing a liaison between the site contractors and the CBFO.

5. TRU Waste Sites

Each participating site shall develop and implement a QAPjP that demonstrates compliance with and implementation of WIPP TRU waste characterization requirements and the applicable requirements of the WIPP Hazardous Waste Facility Permit and its associated Waste Analysis Plan. These QAPjPs shall include or reference the appropriate management and technical criteria of the Program, as well as qualitative or quantitative criteria for determining that Program activities are being satisfactorily performed. QAPjPs shall identify the organizations and positions responsible for their implementation. The QAPjPs shall also reference site-specific documentation that details how each of the required elements of the Program will be performed. QAPjPs and subsequent revisions must be reviewed for concurrence by the site project manager, site project QA manager, the cognizant DOE site office, the CBFO OD NTP and the CBFO QA Manager.

Prior to the implementation of Program activities at participating sites, standard operating procedures (SOPs) will be developed for all activities affecting Program quality that require written instructions or procedures. For the purposes of the Program, the term SOP refers to any site-specific implementing document. Compliance with SOPs will ensure that tasks are performed in a consistent manner that results in achieving the quality required for the Program. The organization, format, content, and designation of SOPs must be described in the QAPjPs.

6. Site Project Manager

Each participating site's contractor designates a site project manager to oversee characterization program activities at the site. A description of the site project manager's role in relation to the other organizational functions at the site must be included in the site's QAPjP. The site project manager (or designee) reviews and recommends approval of the site QAPjP and subsequent revisions before it is submitted to CBFO for review. Specific Program responsibilities assigned to the site project manager include the following:

- Waste selection and tracking
- Data validation/verification
- Data reconciliation with DQOs
- Assignment of EPA Hazardous Waste Numbers
- QA/QC reports to DOE site office
- Data transmission to CBFO

7. Site Project Quality Assurance Management.

Each participating site's contractor designates a site project QA manager. The site project QA manager shall have the responsibilities and authorities described in section QAPD-2.1.1.3 of this QAPD. This individual will have the authority to stop Program activities at a participating site if quality is not assured or controlled.

The site project QA manager shall summarize all relevant information on the QA/QC activities during the period in a semiannual report. This semiannual report shall be distributed to the DOE site office and the site project manager at the same time. The site project manager shall review the report, comment if appropriate, and then forward a copy of the report with comments to the DOE site office.

8. Site Waste Certification Official. Each participating site's contractor designates a waste certification official who must document and certify that all TRU waste payload containers prepared for shipment to WIPP meet all the requirements specified in the *Contact Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot*

Plant (CH-WAC; DOE 2002) and transmit the waste certification data to the WIPP M&O contractor.

9. Site Transportation Certification Official. Each participating site's contractor designates a transportation certification official who documents and certifies that payload assemblies for shipment to WIPP meet all the requirements of the *TRUPACT-II Authorized Methods for Payload Control* (TRAMPAC; NRC 1997).

Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix SCR-2009
Feature, Event, and Process Screening for PA

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix SCR-2009
Feature, Event, and Process Screening for PA

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Acronyms and Abbreviations

μm	micrometer
AIC	active institutional controls
BNL	Brookhaven National Laboratory
Bq	becquerels
CAG	Compliance Application Guidance
CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic
Ci	curie
cm	centimeter
CPD	Carlsbad Potash District
CRA	Compliance Recertification Application
DBDSP	Delaware Basin Drilling Surveillance Program
DFR	driving force ratio
DOE	U.S. Department of Energy
DP	disturbed performance
DRZ	disturbed rock zone
EP	event and process
EPA	U.S. Environmental Protection Agency
ERMS	Electronic Record Management System
FEP	feature, event, and process
FLAC	Fast Lagrangian Analysis Continua
FMT	Fracture-Matrix Transport
FSU	Florida State University
ft	foot
ft^2	square foot
ft^3	cubic foot
g	gram
gal	gallon

gpm	gallons per minute
H	human-initiated
HCN	historic, current, and near-future
hr	hour
IB	inside boundary
in	inch
K_d	retardation distribution coefficient
kg	kilogram
kg/m^3	kilograms per cubic meter
km	kilometer
km^2	square kilometer
kW	kilowatt
L	liter
lb/gal	pounds per gallon
LWA	Land Withdrawal Act
m	meter
m^2	square meter
m^3	cubic meter
Ma BP	million years before present
MB	marker bed
MeV	megaelectron volt
mi	mile
mL	milliliter
MPa	megapascal
MPI	Mississippi Potash Inc.
mV	millivolt
N	natural
NMBMMR	New Mexico Bureau of Mines and Mineral Resources
OB	outside boundary
oz	ounce
PA	performance assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test

PIC	passive institutional control
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
RH-TRU	remote-handled transuranic
s	second
SKI	Statens Kärnkraftinspektion
SNL	Sandia National Laboratories
SO-C	screened-out consequence
SO-P	screened-out probability
SO-R	screened-out regulatory
T field	transmissitivity field
TRU	transuranic
TSD	Technical Support Document
TWBIR	Transuranic Waste Baseline Inventory Report
UP	undisturbed performance
V	volt
W	waste and repository-induced
W	watt
W/Ci	watts per curie
W/g	watts per gram
WIPP	Waste Isolation Pilot Plant
WPO	WIPP Project Office
yd^3	cubic yard
yr	year

Elements and Chemical Compounds

Al	aluminum
Am	americium
An	actinide
C	carbon
CH_4	methane
CO_2	carbon dioxide

Cs	cesium
EDTA	ethylenediaminetetraacetate
Fe	iron
MgO	magnesium oxide
Np	neptunium
Pm	promethium
Pu	plutonium
Rn	radon
Sr	strontium
Th	thorium
U	uranium

SCR-1.0 Introduction

The U.S. Department of Energy (DOE) has developed the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the disposal of transuranic (TRU) wastes generated by defense programs. In May of 1998, the U.S. Environmental Protection Agency (EPA) certified that the WIPP would meet the disposal standards (U.S. Environmental Protection Agency 1998a, p. 27405) established in 40 CFR Part 191 Subparts B and C (U.S. Environmental Protection Agency 1993), thereby allowing the WIPP to begin waste disposal operations. This certification was based, in part, on performance assessment (PA) calculations that were included in the DOE's Compliance Certification Application (CCA) (U.S. Department of Energy 1996). These calculations demonstrate that the cumulative releases of radionuclides to the accessible environment will not exceed those allowed by the EPA standard.

The WIPP Land Withdrawal Act (LWA) (U.S. Congress 1992) requires the WIPP to be recertified (demonstrating continued compliance with the disposal standards) every five years. As such, the DOE prepared the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), which demonstrated that the WIPP complied with the EPA's requirements for radioactive waste disposal. The CRA-2004 included changes to the WIPP long-term compliance baseline since the CCA. Similarly, and in compliance with the recertification rules, the DOE has prepared the 2009 Compliance Recertification Application (CRA-2009) that documents changes since the CRA-2004, and demonstrates compliance with the long-term disposal requirements of 40 CFR Part 191 and the compliance criteria of 40 CFR Part 194.

To assure that PA calculations account for important aspects of the disposal system, features, events, and processes (FEPs) considered to be potentially important to the disposal system are identified. These FEPs are used as a tool for determining what phenomena and components of the disposal system can and should be dealt with in PA calculations. For the WIPP CCA, a systematic process was used to compile, analyze, screen, and document FEPs for use in PA. The FEP screening process used in the CCA, the CRA-2004, and the CRA-2009 is described in detail in the CCA, Chapter 6.0, Section 6.2. For recertification applications, this process evaluates any new information that may have impacts on or present inconsistencies to those screening arguments and decisions presented since the last certification or recertification. The FEPs baseline is managed according to Sandia Activity/Project Specific Procedure 9-4, *Performing FEPs Baseline Impact Assessment for Planned or Unplanned Changes* (Revision 1) (Kirkes 2006). For the CRA-2009, a reassessment of FEPs concluded that of the 235 FEPs considered for the CRA-2004, 188 have not been changed, 35 have been updated with new information, 10 have been split into 20 similar, but more descriptive FEPs, 1 screening argument has been changed to correct errors discovered during review, and 1 has had its screening decision changed. Therefore, there are 245 WIPP FEPs for the CRA-2009. Note that none of these new or updated FEPs require changes to PA models or codes; existing models represent these FEPs in their current configurations.

Table SCR-1 lists the FEPs that have been added, separated, or had screening decision changes since the CRA-2004.

Table SCR-1. FEPs Change Summary Since CRA-2004

EPA FEP I.D.[a,b]	FEP Name	Summary of Change
FEPs Combined or Separated		
H27	Liquid Waste Disposal – Outside Boundary (OB)	Name changed to "Liquid Waste Disposal Boundary – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
H28	Enhanced Oil and Gas Production – OB	Name changed to "Enhanced Oil and Gas Production – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
H29	Hydrocarbon Storage – OB	Name changed to "Hydrocarbon Storage – OB" to specify that this FEP pertains to those activities outside the WIPP land withdrawal boundary.
W6	Shaft Seal Geometry	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W7	Shaft Seal Physical Properties	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W8	Shaft Seal Chemical Composition	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W17	Radiological Effects on Shaft Seals	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W36	Consolidation of Shaft Seals	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W37	Mechanical Degradation of Shaft Seals	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
W74	Chemical Degradation of Shaft Seals	Name changed to be specific to shaft seals, rather than generic "seals," which also included panel closures (seals).
FEPs With Changed Screening Decisions		
H41	Surface Disruptions	Screening changed from screened-out regulatory (SO-R) to screened-out consequence (SO-C) because of inconsistency with screening rationale.
New FEPs for CRA-2009		
H60	Liquid Waste Disposal – Inside Boundary (IB)	New FEP; separated from H27. The creation of this new FEP allows for more appropriate screening based on regulatory provisions pertaining to activities within the WIPP land withdrawal boundary.
H61	Enhanced Oil and Gas Production – IB	New FEP; separated from H28. The creation of this new FEP allows for more appropriate screening based on regulatory provisions that pertain to activities within the WIPP land withdrawal boundary.
H62	Hydrocarbon Storage – IB	New FEP; separated from H29. The creation of this new FEP allows for more appropriate screening based on regulatory provisions that pertain to activities within the WIPP land withdrawal boundary.

[a] H = Human-induced FEP.
[b] W = Waste and Repository-Induced FEP.

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Table SCR-1. FEPs Change Summary Since CRA-2004 (Continued)

EPA FEP I.D.[a,b]	FEP Name	Summary of Change
W109	Panel Closure Geometry	New FEP; separated from W6. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W110	Panel Closure Physical Properties	New FEP; separated from W7. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W111	Panel Closure Chemical Composition	New FEP; separated from W8. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W112	Radiological Effects on Panel Closures	New FEP; separated from W17. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W113	Consolidation of Panel Closures	New FEP; separated from W36. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W114	Mechanical Degradation of Panel Closures	New FEP; separated from W37. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.
W115	Chemical Degradation of Panel Closures	New FEP; separated from W74. The creation of this new FEP allows for more appropriate screening based on potential differences in design and composition of shaft seals versus panel closures.

[a] H = Human-induced FEP.
[b] W = Waste and Repository-Induced FEP.

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SCR-2.0 Basis for FEPs Screening Process

SCR-2.1 Requirement for FEPs

The origin of FEPs is related to the EPA's radioactive waste disposal standard's requirement to use PA methodology. The DOE was required to demonstrate that the WIPP complied with the containment requirements of 40 CFR § 191.13 (U.S. Environmental Protection Agency 1993). These requirements state that the DOE must use PA to demonstrate that the probabilities of cumulative radionuclide releases from the disposal system during the 10,000 years following closure will fall below specified limits. The PA analyses supporting this determination must be quantitative and must consider uncertainties caused by all significant processes and events that may affect the disposal system, including inadvertent human intrusion into the repository during the future. The scope of PA is further defined by the EPA at 40 CFR § 194.32 (U.S. Environmental Protection Agency 1996a), which states,

> Any compliance application(s) shall include information which:
>
> (1) Identifies all potential processes, events or sequences and combinations of processes and events that may occur during the regulatory time frame and may affect the disposal system;
>
> (2) Identifies the processes, events or sequences and combinations of processes and events included in performance assessments; and
>
> (3) Documents why any processes, events or sequences and combinations of processes and events identified pursuant to paragraph (e)(1) of this section were not included in performance assessment results provided in any compliance application.

Therefore, the PA methodology includes a process that compiles a comprehensive list of the FEPs that are potentially relevant to disposal system performance. Those FEPs shown by screening analysis to have the potential to affect performance are represented in scenarios and quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. For the CCA, the DOE first compiled a comprehensive list of FEPs, which was then subjected to a screening process that eventually lead to the set of FEPs used in PA to demonstrate the WIPP's compliance with the long-term disposal standards.

SCR-2.2 FEPs List Development for the CCA

As a starting point, the DOE assembled a list of potentially relevant FEPs from the compilation developed by Stenhouse, Chapman, and Sumerling (1993) for the Swedish Nuclear Power Inspectorate (Statens Kärnkraftinspektion, or SKI). The SKI list was based on a series of FEP lists developed for other disposal programs and is considered the best-documented and most comprehensive starting point for the WIPP. For the SKI study, an initial raw FEP list was compiled based on nine different FEP identification studies.

The compilers of the SKI list eliminated a number of FEPs as irrelevant to the particular disposal concept under consideration in Sweden. These FEPs were reinstated for the WIPP effort, and

several FEPs on the SKI list were subdivided to facilitate screening for the WIPP. Finally, to ensure comprehensiveness, other FEPs specific to the WIPP were added based on review of key project documents and broad examination of the preliminary WIPP list by both project participants and stakeholders. The initial unedited list is contained in the CCA, Appendix SCR, Attachment 1. The initial unedited FEP list was restructured and revised to derive the comprehensive WIPP FEP list used in the CCA. The number of FEPs was reduced to 237 in the CCA to eliminate the ambiguities presented in a generic list. Restructuring the list did not remove any substantive issues from the discussion. As discussed in more detail in the CCA, Appendix SCR, Attachment 1, the following steps were used to reduce the initial unedited list to the appropriate WIPP FEP list used in the CCA.

- References to subsystems were eliminated because the SKI subsystem classification was not appropriate for the WIPP disposal concept. For example, in contrast to the Swedish disposal concept, canister integrity does not have a role in post-operational performance of the WIPP, and the terms near-field, far-field, and biosphere are not unequivocally defined for the WIPP site.

- Duplicate FEPs were eliminated. Duplicate FEPs arose in the SKI list because individual FEPs could act in different subsystems. FEPs had a single entry in the CCA list whether they were applicable to several parts of the disposal system or to a single part only (for example, the FEP Gas Effects). Disruption appears in the seals, backfill, waste, canister, and near-field subsystems in the initial FEP list. These FEPs are represented by a single FEP, Disruption Due to Gas Effects.

- FEPs that are not relevant to the WIPP design or inventory were eliminated. Examples include FEPs related to high-level waste, copper canisters, and bentonite backfill.

- FEPs relating to engineering design changes were eliminated because they were not relevant to a compliance application based on the DOE's design for the WIPP.

- FEPs relating to constructional, operational, and decommissioning errors were eliminated. The DOE has administrative and quality control procedures to ensure that the facility will be constructed, operated, and decommissioned properly.

- Detailed FEPs relating to processes in the surface environment were aggregated into a small number of generalized FEPs. For example, the SKI list includes the biosphere FEPs Inhalation of Salt Particles, Smoking, Showers and Humidifiers, Inhalation and Biotic Material, Household Dust and Fumes, Deposition (Wet and Dry), Inhalation and Soils and Sediments, Inhalation and Gases and Vapors (Indoor and Outdoor), and Suspension in Air, which are represented by the FEP Inhalation.

- FEPs relating to the containment of hazardous metals, volatile organic compounds, and other chemicals that are not regulated by Part 191 were not included.

- A few FEPs have been renamed to be consistent with terms used to describe specific WIPP processes (for example, Wicking, Brine Inflow).

These steps resulted in a list of WIPP-relevant FEPs retained for further consideration in the first certification PA. These FEPs were screened to determine which would be included in the PA models and scenarios for the CCA PA.

SCR-2.3 Criteria for Screening of FEPs and Categorization of Retained FEPs

The purpose of FEP screening is to identify those FEPs that should be accounted for in PA calculations, and those FEPs that need not be considered further. The DOE's process of removing FEPs from consideration in PA calculations involved the structured application of explicit screening criteria. The criteria used to screen out FEPs are explicit regulatory exclusion (SO-R), probability (SO-P), or consequence (SO-C). All three criteria are derived from regulatory requirements. FEPs not screened out as SO-R, SO-P, or SO-C were retained for inclusion in PA calculations and are classified as either undisturbed performance (UP) or disturbed performance (DP) FEPs.

SCR-2.3.1 Regulation (SO-R)

Specific FEP screening criteria are stated in Part 191 and Part 194. Such screening criteria relating to the applicability of particular FEPs represent screening decisions made by the EPA. That is, in the process of developing and demonstrating the feasibility of the Part 191 standard and the Part 194 criteria, the EPA considered and made conclusions on the relevance, consequence, and probability of particular FEPs occurring. In so doing, it allowed some FEPs to be eliminated from consideration.

SCR-2.3.2 Probability of Occurrence of a FEP Leading to Significant Release of Radionuclides (SO-P)

Low-probability events can be excluded on the basis of the criterion provided in 40 CFR § 194.32(d), which states, "performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years." In practice, for most FEPs screened out on the basis of low probability of occurrence, it has not been possible to estimate a meaningful quantitative probability. In the absence of quantitative probability estimates, a qualitative argument was used.

SCR-2.3.3 Potential Consequences Associated with the Occurrence of the FEPs (SO-C)

The DOE recognizes two uses for this criterion:

1. FEPs can be eliminated from PA calculations on the basis of insignificant consequence. Consequence can refer to effects on the repository or site or to radiological consequence. In particular, 40 CFR § 194.34(a) (U.S. Environmental Protection Agency 1996a) states, "The results of performance assessments shall be assembled into 'complementary, cumulative distribution functions' (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events." The DOE has omitted events and processes (EPs) from PA calculations where there is a reasonable expectation that

the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

2. FEPs that are potentially beneficial to subsystem performance may be eliminated from PA calculations if necessary to simplify the analysis. This argument may be used when there is uncertainty as to exactly how the FEP should be incorporated into assessment calculations or when incorporation would incur unreasonable difficulties.

In some cases, the effects of the particular event or process occurring, although not necessarily insignificant, can be shown to lie within the range of uncertainty of another FEP already accounted for in the PA calculations. In such cases, the event or process may be included in PA calculations implicitly, within the range of uncertainty associated with the included FEP.

Although some FEPs could be eliminated from PA calculations on the basis of more than one criterion, the most practical screening criterion was used for classification. In particular, a regulatory screening classification was used in preference to a probability or consequence screening classification. FEPs that have not been screened out based on any of the three criteria were included in the PA.

SCR-2.3.4 UP FEPs

FEPs classified as UP are accounted for in calculations of UP of the disposal system. UP is defined in 40 CFR § 191.12 (U.S. Environmental Protection Agency 1993) as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." The UP FEPs are accounted for in the PA calculations to evaluate compliance with the containment requirements in section 191.13. Undisturbed PA calculations are also used to demonstrate compliance with the individual and groundwater protection requirements of 40 CFR § 191.15 (U.S. Environmental Protection Agency 1993) and Part 191 Subpart C, respectively.

SCR-2.3.5 DP FEPs

The FEPs classified as DP are accounted for only in assessment calculations for DP. The DP FEPs that remain following the screening process relate to the potential disruptive effects of future drilling and mining events in the controlled area. Consideration of both DP and UP FEPs is required to evaluate compliance with section 191.13.

SCR-2.4 FEPs Categories and Timeframes

In the following sections, FEPs are discussed under the categories Natural FEPs, Human-Induced EPs, and Waste- and Repository-Induced FEPs. (IDs of Natural FEPs begin with "N," and IDs of Waste- and Repository-Induced FEPs begin with "W.") The FEPs are also considered within time frames during which they may occur. Because of the regulatory requirements concerning human activities, two time periods were used when evaluating human-induced EPs. These time frames were defined as Historical, Current, and Near-Future Human Activities (HCN) and Future Human Activities (Future). These time frames are also discussed in the following section.

SCR-2.4.1 Description of Natural FEPs

Natural FEPs are those that relate to hydrologic, geologic, and climate conditions that have the potential to affect long-term performance of the WIPP disposal system over the regulatory time frame. These FEPs do not include the impacts of other human-related activities such as the effect of boreholes on FEPs related to natural changes in groundwater chemistry. Only natural FEPs are included in the screening process.

Consistent with section 194.32(d), the DOE has screened out several natural FEPs from PA calculations on the basis of a low probability of occurrence at or near the WIPP site. In particular, natural events for which there is no evidence indicating that they have occurred within the Delaware Basin have been screened on this basis. For FEPs analysis, the probabilities of occurrence of these events are assumed to be zero. Quantitative, nonzero probabilities for such events, based on numbers of occurrences, cannot be ascribed without considering regions much larger than the Delaware Basin, thus neglecting established geological understanding of the FEPs that occur within particular geographical provinces.

In considering the overall geological setting of the Delaware Basin, the DOE has eliminated many FEPs from PA calculations on the basis of low consequence. FEPs that have had little effect on the characteristics of the region in the past are expected to be of low consequence for the regulatory time period.

SCR-2.4.2 Description of Human-Induced EPs

Human-induced EPs (Human EPs) are those associated with human activities in the past, present, and future. The EPA provided guidance in their regulations concerning which human activities are to be considered, their severity, and the manner in which to include them in the future predictions.

The scope of PAs is clarified with respect to human-induced EPs in section 194.32. At 40 CFR § 194.32(a), the EPA states,

> Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.

Thus PAs must include consideration of human-induced EPs relating to mining and drilling activities that might take place during the regulatory time frame. In particular, PAs must consider the potential effects of such activities that might take place within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of human intrusion.

Further criteria concerning the scope of PAs are provided at 40 CFR § 194.32(c):

> Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

In order to implement the criteria in section 194.32 relating to the scope of PAs, the DOE has divided human activities into three categories: (1) human activities currently taking place and those that took place prior to the time of the compliance application, (2) human activities that might be initiated in the near future after submission of the compliance application, and (3) human activities that might be initiated after repository closure. The first two categories of EPs, corresponding to the HCN time frame, are considered under UP, and EPs in the third category, which belong to the Future time frame, may lead to DP conditions. A description of these three categories follows.

1. Historical and current human activities include resource-extraction activities that have historically taken place and are currently taking place outside the controlled area. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. Current human activities taking place within the controlled area are essentially those associated with development of the WIPP repository. Historic human activities include existing boreholes.

2. Near-future human activities include resource-extraction activities that may be expected to occur outside the controlled area based on existing plans and leases. Thus the near future includes the expected lives of existing mines and oil and gas fields, and the expected lives of new mines and oil and gas fields that the DOE expects will be developed based on existing plans and leases. These activities are of potential significance insofar as they could affect the geological, hydrological, or geochemical characteristics of the disposal system or groundwater flow pathways outside the disposal system. The only human activities expected to occur within the controlled area in the near future are those associated with development of the WIPP repository. The DOE expects that any activity initiated in the near future, based on existing plans and leases, will be initiated prior to repository closure. Activities initiated prior to repository closure are assumed to continue until their completion.

3. Future human activities include activities that might be initiated within or outside the controlled area after repository closure. This includes drilling and mining for resources within the disposal system at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. Future human activities could influence the transport of contaminants within and outside the disposal system by directly removing waste from the disposal system or altering the geological, hydrological, or geochemical characteristics of the disposal system.

SCR-2.4.2.1 Scope of Future Human Activities in PA

PAs must consider the effects of future human activities on the performance of the disposal system. The EPA has provided criteria relating to future human activities in section 194.32(a), which limits the scope of consideration of future human activities in PAs to mining and drilling.

SCR-2.4.2.1.1 Criteria Concerning Future Mining

The EPA provides the following additional criteria concerning the type of future mining that should be considered by the DOE in 40 CFR § 194.32(b):

> Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.

Thus consideration of future mining may be limited to mining within the controlled area at the locations of resources that are similar in quality and type to those currently extracted from the Delaware Basin. Potash is the only resource that has been identified within the controlled area in quality similar to that currently mined from underground deposits elsewhere in the Delaware Basin. The hydrogeological impacts of future potash mining within the controlled area are accounted for in calculations of the DP of the disposal system. Consistent with section 194.32(b), all economically recoverable resources in the vicinity of the disposal system (outside the controlled area) are assumed to be extracted in the near future.

SCR-2.4.2.1.2 Criteria Concerning Future Drilling

With respect to consideration of future drilling, in the preamble to Part 194, the EPA

> …reasoned that while the resources drilled for today may not be the same as those drilled for in the future, the present rates at which these boreholes are drilled can nonetheless provide an estimate of the future rate at which boreholes will be drilled.

Criteria concerning the consideration of future deep and shallow drilling in PAs are provided in 40 CFR § 194.33 (U.S. Environmental Protection Agency 1996a). The EPA also provides a criterion in 40 CFR § 194.33(d) concerning the use of future boreholes subsequent to drilling:

> With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

Thus PAs need not consider the effects of techniques used for resource extraction and recovery that would occur subsequent to the drilling of a borehole in the future. Theses activities are screened SO-R.

The EPA provides an additional criterion that limits the severity of human intrusion scenarios that must be considered in PAs. In 40 CFR § 194.33(b)(1) the EPA states,

> Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.

SCR-2.4.2.1.3 Screening of Future Human EPs

Future Human EPs accounted for in PA calculations for the WIPP are those associated with mining and deep drilling within the controlled area at a time when institutional controls cannot be assumed to completely eliminate the possibility of such activities. All other future Human EPs, if not eliminated from PA calculations based on regulation, have been eliminated based on low consequence or low probability. For example, the effects of future shallow drilling within

the controlled area were eliminated from CCA PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-2.4.3 Description of Waste- and Repository-Induced FEPs

The waste- and repository-induced FEPs are those that relate specifically to the waste material, waste containers, shaft seals, magnesium oxide (MgO) backfill, panel closures, repository structures, and investigation boreholes. All FEPs related to radionuclide chemistry and radionuclide migration are included in this category. The FEPs related to radionuclide transport resulting from future borehole intersections of the WIPP excavation are defined as waste- and repository-induced FEPs.

SCR-3.0 FEPs

The reassessment of FEPs (Kirkes 2008) results in a new FEPs baseline for CRA-2009. As discussed in Section SCR-1.0, 189 of the 235 WIPP FEPs have not changed since the CRA-2004. However, 35 FEPs required updates to their FEP descriptions and/or screening arguments, 10 FEPs have been split into 20 similar but more descriptive FEPs, and 1 FEP has had its screening decision changed. The single screening decision change does not result in a new FEP incorporated into PA calculations; the FEP continues to be screened out of PA. Thus the CRA-2009 evaluates 245 WIPP FEPs.

Table SCR-2 outlines the results of the assessment, and subsequent sections of this document present the actual screening decisions and supporting arguments. Those FEPs not separated by gridlines in the first column of Table SCR-2 have been addressed by group because of close similarity with other FEPs within that group. This grouping process was formerly used in the CCA and also by the EPA in their Technical Support Document (TSD) for section 194.32 (U.S. Environmental Protection Agency 1998b).

Table SCR-2. FEPs Reassessment Results

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N1	Stratigraphy	No	No change.	UP
N2	Brine Reservoirs	No	No change.	DP
N3	Changes in Regional Stress	No	No change.	SO-C
N4	Regional Tectonics	No	No change.	SO-C
N5	Regional Uplift and Subsidence	No	No change.	SO-C
N6	Salt Deformation	No	No change.	SO-P
N7	Diapirism	No	No change.	SO-P
N8	Formation of Fractures	No	No change.	SO-P UP (Repository)
N9	Changes in Fracture Properties	No	No change.	SO-C UP (Near Repository)
N10	Formation of New Faults	No	No change.	SO-P
N11	Fault Movement	No	No change.	SO-P
N12	Seismic Activity	No	Updated with new seismic data.	UP
N13	Volcanic Activity	No	No change.	SO-P
N14	Magmatic Activity	No	No change.	SO-C
N15	Metamorphic Activity	No	No change.	SO-P
N16	Shallow Dissolution	No	No change.	UP

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N18	Deep Dissolution	No	No change.	SO-P
N20	Breccia Pipes	No	No change.	SO-P
N21	Collapse Breccias	No	No change.	SO-P
N22	Fracture Infills	No	No change.	SO-C - Beneficial
N23	Saturated Groundwater Flow	No	No change.	UP
N24	Unsaturated Groundwater Flow	No	No change.	UP
N25	Fracture Flow	No	No change.	UP
N27	Effects of Preferential Pathways	No	No change.	UP
N26	Density effects on Groundwater Flow	No	No change.	SO-C
N28	Thermal effects on Groundwater Flow	No	No change.	SO-C
N29	Saline Intrusion [Hydrogeological Effects]	No	No change.	SO-P
N30	Freshwater Intrusion [Hydrogeological effects]	No	No change.	SO-P
N31	Hydrological Response to Earthquakes	No	No change.	SO-C
N32	Natural Gas Intrusion	No	No change.	SO-P
N33	Groundwater Geochemistry	No	No change.	UP
N34	Saline Intrusion (Geochemical Effects)	No	No change.	SO-C
N38	Effects of Dissolution	No	No change.	SO-C
N35	Freshwater Intrusion (Geochemical Effects)	No	No change.	SO-C
N36	Changes in Groundwater Eh	No	No change.	SO-C
N37	Changes in Groundwater pH	No	No change.	SO-C
N39	Physiography	No	No change.	UP
N40	Impact of a Large Meteorite	No	Errors identified in screening argument corrected; no change in screening decision.	SO-P
N41	Mechanical Weathering	No	No change.	SO-C
N42	Chemical Weathering	No	No change.	SO-C
N43	Aeolian Erosion	No	No change.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
N44	Fluvial Erosion	No	No change.	SO-C
N45	Mass Wasting [Erosion]	No	No change.	SO-C
N46	Aeolian Deposition	No	No change.	SO-C
N47	Fluvial Deposition	No	No change.	SO-C
N48	Lacustrine Deposition	No	No change.	SO-C
N49	Mass Wasting [Deposition]	No	No change.	SO-C
N50	Soil Development	No	No change.	SO-C
N51	Stream and River Flow	No	No change.	SO-C
N52	Surface Water Bodies	No	No change.	SO-C
N53	Groundwater Discharge	No	No change.	UP
N54	Groundwater Recharge	No	No change.	UP
N55	Infiltration	No	No change.	UP
N56	Changes in Groundwater Recharge and Discharge	No	No change.	UP
N57	Lake Formation	No	No change.	SO-C
N58	River Flooding	No	No change.	SO-C
N59	Precipitation (e.g. Rainfall)	No	No change.	UP
N60	Temperature	No	No change.	UP
N61	Climate Change	No	No change.	UP
N62	Glaciation	No	No change.	SO-P
N63	Permafrost	No	No change.	SO-P
N64	Seas and Oceans	No	No change.	SO-C
N65	Estuaries	No	No change.	SO-C
N66	Coastal Erosion	No	No change.	SO-C
N67	Marine Sediment Transport and Deposition	No	No change.	SO-C
N68	Sea Level Changes	No	No change.	SO-C
N69	Plants	No	No change.	SO-C
N70	Animals	No	No change.	SO-C
N71	Microbes	No	No change.	SO-C (UP - for colloidal effects and gas generation)
N72	Natural Ecological Development	No	No change.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H1	Oil and Gas Exploration	No	No change.	SO-C (HCN) DP (Future)
H2	Potash Exploration	No	No change.	SO-C (HCN) DP (Future)
H4	Oil and Gas Exploitation	No	No change.	SO-C (HCN) DP (Future)
H8	Other Resources	No	No change.	SO-C (HCN) DP (Future)
H9	Enhanced Oil and Gas Recovery	No	No change.	SO-C (HCN) DP (Future)
H3	Water Resources Exploration	No	Updated with most recent monitoring information.	SO-C (HCN) SO-C (Future)
H5	Groundwater Exploitation	No	Updated with most recent monitoring information.	SO-C (HCN) SO-C (Future)
H6	Archaeological Investigations	No	No change.	SO-R (HCN) SO-R (Future)
H7	Geothermal	No	No change.	SO-R (HCN) SO-R (Future)
H10	Liquid Waste Disposal	No	No change.	SO-R (HCN) SO-R (Future)
H11	Hydrocarbon Storage	No	No change.	SO-R (HCN) SO-R (Future)
H12	Deliberate Drilling Intrusion	No	No change.	SO-R (HCN) SO-R (Future)
H13	Conventional Underground Potash Mining	No	No change.	UP (HCN) DP (Future)
H14	Other Resources (mining for)	No	No change.	SO-C (HCN) SO-R (Future)
H15	Tunneling	No	No change.	SO-R (HCN) SO-R (Future)
H16	Construction of Underground Facilities (for Example Storage, Disposal, Accommodation)	No	No change.	SO-R (HCN) SO-R (Future)
H17	Archaeological Excavations	No	No change.	SO-C (HCN) SO-R (Future)
H18	Deliberate Mining Intrusion	No	No change.	SO-R (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-Induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H19	Explosions for Resource Recovery	No	No change.	SO-C (HCN) SO-R (Future)
H20	Underground Nuclear Device Testing	No	No change.	SO-C (HCN) SO-R (Future)
H21	Drilling Fluid Flow	No	Screening argument revised.	SO-C (HCN) DP (Future)
H22	Drilling Fluid Loss	No	Screening argument revised.	SO-C (HCN) DP (Future)
H23	Blowouts	No	No change.	SO-C (HCN) DP (Future)
H24	Drilling-Induced Geochemical Changes	No	No change.	UP (HCN) DP (Future)
H25	Oil and Gas Extraction	No	Screening argument updated.	SO-C (HCN) SO-R (Future)
H26	Groundwater Extraction	No	Screening argument updated.	SO-C (HCN) SO-R (Future)
H27	Liquid Waste Disposal–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)
H28	Enhanced Oil and Gas Production–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)
H29	Hydrocarbon Storage–OB	No	FEP title has been modified to show that this event or process specifically applies to activities outside the WIPP boundary. Screening argument has also been updated with new information.	SO-C (HCN) SO-C (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H60	Liquid Waste Disposal–IB	N/A – new FEP	This is a new FEP that is similar to H27, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H61	Enhanced Oil and Gas Production–IB	N/A – new FEP	This is a new FEP that is similar to H28, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H62	Hydrocarbon Storage–IB	N/A – new FEP	This is a new FEP that is similar to H29, except that it specifically applies to activities inside the WIPP boundary.	SO-R (HCN) SO-R (Future)
H30	Fluid-injection Induced Geochemical Changes	No	No change.	UP (HCN) SO-R (Future)
H31	Natural Borehole Fluid Flow	No	No change.	SO-C (HCN) SO-C (Future, holes not penetrating waste panels) DP (Future, holes penetrating panels)
H32	Waste-Induced Borehole Flow	No	No change.	SO-R (HCN) DP (Future)
H34	Borehole-Induced Solution and Subsidence	No	No change.	SO-C (HCN) SO-C (Future)
H35	Borehole-Induced Mineralization	No	No change.	SO-C (HCN) SO-C (Future)
H36	Borehole-Induced Geochemical Changes	No	No change.	UP (HCN) DP (Future) SO-C (for units other than the Culebra)
H37	Changes in Groundwater Flow Due to Mining	No	No change.	UP (HCN) DP (Future)
H38	Changes in Geochemistry Due to Mining	No	No change.	SO-C (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H39	Changes in Groundwater Flow Due to Explosions	No	No change.	SO-C (HCN) SO-R (Future)
H40	Land Use Changes	No	No change.	SO-R (HCN) SO-R (Future)
H41	Surface Disruptions	Yes	Screening decision changed from SO-R to SO-C to remove inconsistency with rationale.	UP (HCN) SO-C (Future)
H42	Damming of Streams or Rivers	No	No change.	SO-C (HCN) SO-R (Future)
H43	Reservoirs	No	No change.	SO-C (HCN) SO-R (Future)
H44	Irrigation	No	No change.	SO-C (HCN) SO-R (Future)
H45	Lake Usage	No	No change.	SO-R (HCN) SO-R (Future)
H46	Altered Soil or Surface Water Chemistry by Human Activities	No	No change.	SO-C (HCN) SO-R (Future)
H47	Greenhouse Gas Effects	No	No change.	SO-R (HCN) SO-R (Future)
H48	Acid Rain	No	No change.	SO-R (HCN) SO-R (Future)
H49	Damage to the Ozone Layer	No	No change.	SO-R (HCN) SO-R (Future)
H50	Coastal Water Use	No	No change.	SO-R (HCN) SO-R (Future)
H51	Sea water Use	No	No change.	SO-R (HCN) SO-R (Future)
H52	Estuarine Water Use	No	No change.	SO-R (HCN) SO-R (Future)
H53	Arable Farming	No	No change.	SO-C (HCN) SO-R (Future)
H54	Ranching	No	No change.	SO-C (HCN) SO-R (Future)
H55	Fish Farming	No	No change.	SO-R (HCN) SO-R (Future)
H56	Demographic Change and Urban Development	No	No change.	SO-R (HCN) SO-R (Future)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
H57	Loss of Records	No	No change.	NA (HCN) DP (Future)
H58	Solution Mining for Potash	No	Updated with information regarding solution activities and plans in the region.	SO-R (HCN) SO-R (Future)
H59	Solution Mining for Other Resources	No	Updated with new information regarding brine wells in the region.	SO-C (HCN) SO-C (Future)
W1	Disposal Geometry	No	No change.	UP
W2	Waste Inventory	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	UP
W3	Heterogeneity of Waste Forms	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	DP
W4	Container Form	No	Updated to reflect the inventory data sources used for the CRA-2009 PA.	SO-C – Beneficial
W5	Container Material Inventory	No	No change.	UP
W6	Shaft Seal Geometry	No	Title changed to be specific to shaft seals.	UP
W7	Shaft Seal Physical Properties	No	Title changed to be specific to shaft seals.	UP
W109	Panel Closure Geometry	N/A – new FEP.	Split from W6 to be specific to panel closures.	UP
W110	Panel Closure Physical Properties	N/A – new FEP	Split from W7 to be specific to panel closures.	UP
W8	Shaft Seal Chemical Composition	No	Title changed to be specific to shaft seals.	SO-C Beneficial
W111	Panel Closure Chemical Composition	N/A – new FEP	Split from W8 to be specific to panel closures.	SO-C Beneficial

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W9	Backfill Physical Properties	No	No change.	SO–C
W10	Backfill Chemical Composition	No	No change.	UP
W11	Post-Closure Monitoring	No	No change.	SO-C
W12	Radionuclide Decay and In-Growth	No	No change.	UP
W13	Heat from Radioactive Decay	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-C
W14	Nuclear Criticality: Heat	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-P
W15	Radiological Effects on Waste	No	Updated to reflect the inventory used for the CRA.	SO-C
W16	Radiological Effects on Containers	No	Updated to reflect the inventory used for the CRA.	SO-C
W17	Radiological Effects on Shaft Seals	No	FEP title changed to be specific to shaft seals; screening argument updated to reflect the inventory used for the CRA.	SO-C
W112	Radionuclide Effects on Panel Closures	N/A – new FEP	Split from W17 to be specific to panel closures.	SO-C
W18	Disturbed Rock Zone (DRZ)	No	No change.	UP
W19	Excavation-Induced Changes in Stress	No	No change.	UP
W20	Salt Creep	No	No change.	UP
W21	Changes in the Stress Field	No	No change.	UP
W22	Roof Falls	No	No change.	UP
W23	Subsidence	No	Source of subsidence monitoring data added.	SO-C
W24	Large Scale Rock Fracturing	No	Source of subsidence monitoring data added.	SO-P
W25	Disruption Due to Gas Effects	No	No change.	UP
W26	Pressurization	No	No change.	UP

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W27	Gas Explosions	No	No change.	UP
W28	Nuclear Explosions	No	Updated to reflect the inventory used for the CRA-2009 PA.	SO-P
W29	Thermal Effects on Material Properties	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W30	Thermally-Induced Stress Changes	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W31	Differing Thermal Expansion of Repository Components	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W72	Exothermic Reactions	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W73	Concrete Hydration	No	Updated to reflect the inventory used for the CRA. New thermal calculations added.	SO-C
W32	Consolidation of Waste	No	No change.	UP
W36	Consolidation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W37	Mechanical Degradation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W39	Underground Boreholes	No	No change.	UP
W113	Consolidation of Panel Closures	N/A – new FEP	Split from W36 to be specific to panel closures.	UP
W114	Mechanical Degradation of Panel Closures	N/A – new FEP	Split from W37 to be specific to panel closures.	UP
W33	Movement of Containers	No	Updated to reference new inventory data.	SO-C
W34	Container Integrity	No	No change.	SO–C Beneficial

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W35	Mechanical Effects of Backfill	No	Screening argument updated to reflect reduction in MgO.	SO–C
W40	Brine Inflow	No	No change.	UP
W41	Wicking	No	No change.	UP
W42	Fluid Flow Due to Gas Production	No	No change.	UP
W43	Convection	No	No change.	SO-C
W44	Degradation of Organic Material	No	New thermal rise calculations referenced.	UP
W45	Effects of Temperature on Microbial Gas Generation	No	New thermal rise calculations referenced.	UP
W48	Effects of Biofilms on Microbial Gas Generation	No	New thermal rise calculations referenced.	UP
W46	Effects of Pressure on Microbial Gas Generation	No	No change.	SO-C
W47	Effects of Radiation on Microbial Gas Generation	No	Screening argument updated with new radionuclide inventory.	SO-C
W49	Gases from Metal Corrosion	No	No change.	UP
W51	Chemical Effects of Corrosion	No	No change.	UP
W50	Galvanic Coupling (Within the Repository)	No	No change.	SO-C
W52	Radiolysis of Brine	No	No change.	SO-C
W53	Radiolysis of Cellulose	No	Screening argument updated with new radionuclide inventory.	SO-C
W54	Helium Gas Production	No	Screening argument updated with new radionuclide inventory.	SO-C
W55	Radioactive Gases	No	Reference made to CRA-2009 inventory data.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

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Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W56	Speciation	No	No change.	UP in disposal rooms and Culebra. SO-C elsewhere, and SO-C Beneficial in cementitious seals
W57	Kinetics of Speciation	No	No change.	SO-C
W58	Dissolution of Waste	No	No change.	UP
W59	Precipitation of Secondary Minerals	No	No change.	SO-C Beneficial
W60	Kinetics of Precipitation and Dissolution	No	No change.	SO-C
W61	Actinide Sorption	No	No change.	UP in the Culebra and Dewey Lake; SO-C—Beneficial in the disposal room, shaft seals, panel closures, and other geologic units.
W62	Kinetics of Sorption	No	No change.	UP in the Culebra and Dewey Lake; SO-C—Beneficial in the disposal room, shaft seals, panel closures, and other geologic units.
W63	Changes in Sorptive Surfaces	No	No change.	UP
W64	Effects of Metal Corrosion	No	No change.	UP
W66	Reduction-Oxidation Kinetics	No	No change.	UP
W65	Reduction-Oxidation Fronts	No	No change.	SO-P
W67	Localized Reducing Zones	No	No change.	SO-C
W68	Organic Complexation	No	No change.	UP
W69	Organic Ligands	No	No change.	UP
W71	Kinetics of Organic Complexation	No	No change.	SO-C
W70	Humic and Fulvic Acids	No	No change.	UP

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W74	Chemical Degradation of Shaft Seals	No	Title changed to be specific to shaft seals.	UP
W76	Microbial Growth on Concrete	No	No change.	UP
W115	Chemical Degradation of Panel Closures	N/A – new FEP	Split from W74 to be specific to panel closures.	UP
W75	Chemical Degradation of Backfill	No	No change.	SO-C
W77	Solute Transport	No	No change.	UP
W78	Colloid Transport	No	No change.	UP
W79	Colloid Formation and Stability	No	No change.	UP
W80	Colloid Filtration	No	No change.	UP
W81	Colloid Sorption	No	No change.	UP
W82	Suspensions of Particles	No	No change.	DP
W83	Rinse	No	No change.	SO-C
W84	Cuttings	No	No change.	DP
W85	Cavings	No	No change.	DP
W86	Spallings	No	No change.	DP
W87	Microbial Transport	No	No change.	UP
W88	Biofilms	No	No change.	SO-C Beneficial
W89	Transport of Radioactive Gases	No	Screening argument updated with CRA-2009 inventory data.	SO-C
W90	Advection	No	No change.	UP
W91	Diffusion	No	No change.	UP
W92	Matrix Diffusion	No	No change.	UP
W93	Soret Effect	No	New thermal values added for aluminum corrosion.	SO-C
W94	Electrochemical Effects	No	No change.	SO-C
W95	Galvanic Coupling (Outside the Repository)	No	No change.	SO-P
W96	Electrophoresis	No	No change.	SO-C

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

Table SCR-2. FEPs Reassessment Results (Continued)

EPA FEP I.D.[a,b,c]	FEP Name	Screening Decision Changed	Change Summary	Screening Classification
W97	Chemical Gradients	No	No change.	SO-C
W98	Osmotic Processes	No	No change.	SO-C
W99	Alpha Recoil	No	No change.	SO-C
W100	Enhanced Diffusion	No	No change.	SO-C
W101	Plant Uptake	No	No change.	SO-R (for section 191.13) SO-C (for section 191.15)
W102	Animal Uptake	No	No change.	SO-R (for section 191.13) SO-C (for section 191.15)
W103	Accumulation in Soils	No	No change.	SO-C Beneficial (for section 191.13) SO-C (for section 191.15)
W104	Ingestion	No	No change.	SO-R SO-C (for section 191.15)
W105	Inhalation	No	No change.	SO-R SO-C (for section 191.15)
W106	Irradiation	No	No change.	SO-R SO-C (for section 191.15)
W107	Dermal Sorption	No	No change.	SO-R SO-C (for section 191.15)
W108	Injection	No	No change.	SO-R SO-C (for section 191.15)

[a] N = Natural FEP
[b] H = Human-induced EP
[c] W = Waste- and Repository-induced FEP

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SCR-4.0 Screening of Natural FEPs

This section presents the screening arguments and decisions for natural FEPs. Natural FEPs may be important to the performance of the disposal system. Screening of natural FEPs is done in the absence of human influences on the FEPs. Of the 70 natural FEPs, 68 remain completely unchanged, one has had errors corrected in the screening argument, and one has been updated to include additional information. No screening decisions (classifications) for natural FEPs were changed, and no additional natural FEPs have been identified.

SCR-4.1 Geological FEPs

SCR-4.1.1 Stratigraphy

SCR-4.1.1.1 FEP Numbers: N1 and N2
FEP Titles: *Stratigraphy* (N1)
Brine Reservoir (N2)

SCR-4.1.1.2 Screening Decision: UP (N1)
DP (N2)

The *Stratigraphy* of the geological formations in the region of the WIPP is accounted for in PA calculations. The presence of *Brine Reservoirs* in the Castile Formation (hereafter referred to as the Castile) is accounted for in PA calculations.

SCR-4.1.1.2.1 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.1.2.2 Screening Argument

The stratigraphy and geology of the region around the WIPP, including the distribution and characteristics of pressurized brine reservoirs in the Castile, are discussed in detail in the CCA, Chapter 2.0, Section 2.1.3. The stratigraphy of the geological formations in the region of the WIPP is accounted for in PA calculations through the setup of the model geometries (Appendix PA-2009, Section PA-4.2.1). The presence of brine reservoirs is accounted for in the treatment of inadvertent drilling (Appendix PA-2009, Section PA-4.2.10).

SCR-4.1.2 Tectonics

SCR-4.1.2.1 FEP Numbers: N3, N4, and N5
FEP Titles: *Changes in Regional Stress* (N3)
Regional Tectonics (N4)
Regional Uplift and Subsidence (N5)

SCR-4.1.2.1.1 Screening Decision: SO-C

The effects of *Regional Tectonics*, *Regional Uplift* and *Subsidence*, and *Change in Regional Stress* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.2.1.3 Screening Argument

Regional tectonics encompasses two related issues of concern: the overall level of regional stress and whether any significant changes in regional stress might occur.

The tectonic setting and structural features of the area around the WIPP are described in the CCA, Chapter 2.0, Section 2.1.5. In summary, there is no geological evidence for Quaternary regional tectonics in the Delaware Basin. The eastward tilting of the region has been dated as mid-Miocene to Pliocene by King (1948, pp. 120–21) and is associated with the uplift of the Guadalupe Mountains to the west. Fault zones along the eastern margin of the basin, where it flanks the Central Basin Platform, were active during the Late Permian. Evidence for this includes the displacement of the Rustler Formation (hereafter referred to as the Rustler) observed by Holt and Powers (1988, pp. 4–14) and the thinning of the Dewey Lake Redbeds Formation (hereafter referred to as the Dewey Lake) reported by Schiel (1994). There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Other faults identified within the evaporite sequence of the Delaware Basin are inferred by Barrows' figures in Borns et al. (1983, pp. 58–60) to be the result of salt deformation rather than regional tectonic processes. According to Muehlberger, Belcher, and Goetz (1978, p. 338), the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains and are of minor regional significance. The effects of regional tectonics and changes in regional stress have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

There are no reported stress measurements from the Delaware Basin, but a low–level, regional stress regime with low deviatoric stress has been inferred from the geological setting of the area (see the CCA, Chapter 2.0, Section 2.1.5). The inferred low level of regional stress and the lack of Quaternary tectonic activity indicate that regional tectonics and any changes in regional stress will be minor and therefore of low consequence to the performance of the disposal system. Even if rates of regional tectonic movement experienced over the past 10 million years continue, the extent of regional uplift and subsidence over the next 10,000 years would only be about several

feet (ft) (approximately 1 meter [m]). This amount of uplift or subsidence would not lead to a breach of the Salado because the salt would deform plastically to accommodate this slow rate of movement. Uniform regional uplift or a small increase in regional dip consistent with this past rate could give rise to downcutting by rivers and streams in the region. The extent of this downcutting would be little more than the extent of uplift, and reducing the overburden by 1 or 2 m would have no significant effect on groundwater flow or contaminant transport in units above or below the Salado. Thus the effects of regional uplift and subsidence have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.2.1.4 Tectonic Setting and Site Structural Features

The DOE has screened out, on the basis of either probability or consequence or both, all tectonic, magmatic, and structural processes. The screening discussions can be found in the CCA, Appendix SCR. The information needed for this screening is included here and covers (1) regional tectonic processes such as subsidence, uplift, and basin tilting; (2) magmatic processes such as igneous intrusion and events such as volcanism; and (3) structural processes such as faulting and loading and unloading of the rocks because of long-term sedimentation or erosion. Discussions of structural events, such as earthquakes, are considered to the extent that they may create new faults or activate old faults. The seismicity of the area is considered in the CCA, Chapter 2.0, Section 2.6 for the purposes of determining seismic design parameters for the facility.

SCR-4.1.2.1.5 Tectonics

The processes and features included in this section are those more traditionally considered part of tectonics–processes that develop the broad-scale features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Most broad-scale structural elements of the area around the WIPP developed during the Late Paleozoic (see the CCA, Appendix GCR, pp. 3-58 through 3-77). There is little historical or geological evidence of significant tectonic activity in the vicinity, and the level of stress in the region is low. The entire region tilted slightly during the Tertiary, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in a separate section.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tobosa Basin. By Late Pennsylvanian to Early Permian time, the Central Basin Platform developed (see the CCA, Chapter 2.0, Figure 2-19), separating the Tobosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian Period. Southwest of the Delaware Basin, the Diablo Platform began developing either in the Late Pennsylvanian or Early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin.

According to Brokaw et al. (1972, p. 30), pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do

not. A relatively uniform eastward tilt, generally from about 14 to 19 meters per kilometer (m/km) (75 to 100 feet per mile [ft/mi]), has been superimposed on the sedimentary sequence. King (1948, pp. 108 and 121) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to the later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

King (1948, p. 144) also infers the uplift from the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it varies in age from Miocene (about 12 million years before present) to Pliocene (Hawley 1993). This is the most likely range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

Analysis of the present regional stress field indicates that the Delaware Basin lies within the Southern Great Plains stress province. This province is a transition zone between the extensional stress regime to the west and the region of compressive stress to the east. An interpretation by Zoback and Zoback (1991, p. 350) of the available data indicates that the level of stress in the Southern Great Plains stress province is low. Changes to the tectonic setting, such as the development of subduction zones and a consequent change in the driving forces, would take much longer than 10,000 years to occur.

To the west of the Southern Great Plains province is the Basin and Range province, or Cordilleran Extension province, where according to Zoback and Zoback (1991, pp. 348–51) normal faulting is the characteristic style of deformation. The eastern boundary of the Basin and Range province is marked by the Rio Grande Rift. Sanford, Jakasha, and Cash (1991, p. 230) note that, as a geological structure, the Rift extends beyond the relatively narrow geomorphological feature seen at the surface, with a magnetic anomaly at least 500 km (300 mi) wide. On this basis, the Rio Grande Rift can be regarded as a system of axial grabens along a major north-south trending structural uplift (a continuation of the Southern Rocky Mountains). The magnetic anomaly extends beneath the Southern Great Plains stress province, and regional-scale uplift of about 1,000 m (3,300 ft) over the past 10 million years also extends into eastern New Mexico.

To the east of the Southern Great Plains province is the large Mid-Plate province that encompasses central and eastern regions of the conterminous United States and the Atlantic basin west of the Mid-Atlantic Ridge. The Mid-Plate province is characterized by low levels of paleo- and historic seismicity. Where Quaternary faulting has occurred, it is generally strike-slip and appears to be associated with the reactivation of older structural elements.

Zoback et al. (1991) report no stress measurements from the Delaware Basin. The stress field in the Southern Great Plains stress province has been defined from borehole measurements in west Texas and from volcanic lineaments in northern New Mexico. These measurements were interpreted by Zoback and Zoback (1991, p. 353) to indicate that the least principal horizontal stress is oriented north-northeast and south-southwest and that most of the province is characterized by an extensional stress regime.

There is an abrupt change between the orientation of the least principal horizontal stress in the Southern Great Plains and the west-northwest orientation of the least principal horizontal stress characteristic of the Rio Grande Rift. In addition to the geological indications of a transition zone as described above, Zoback and Zoback (1980, p. 6134) point out that there is also evidence for a sharp boundary between these two provinces. This is reinforced by the change in crustal thickness from about 40 km (24 mi) beneath the Colorado Plateau to about 50 km (30 mi) or more beneath the Southern Great Plains east of the Rio Grande Rift. The base of the crust within the Rio Grande Rift is poorly defined but is shallower than that of the Colorado Plateau (Thompson and Zoback 1979, p. 152). There is also markedly lower heat flow in the Southern Great Plains (typically < 60 m W m^{-2}) reported by Blackwell, Steele, and Carter (1991, p. 428) compared with that in the Rio Grande Rift (typically > 80 m W m^{-2}) reported by Reiter, Barroll, and Minier (1991, p. 463).

On the eastern boundary of the Southern Great Plains province, there is only a small rotation in the direction of the least principal horizontal stress. There is, however, a change from an extensional, normal faulting regime to a compressive, strike-slip faulting regime in the Mid-Plate province. According to Zoback and Zoback (1980, p. 6134), the available data indicate that this change is not abrupt and that the Southern Great Plains province can be viewed as a marginal part of the Mid-Plate province.

SCR-4.1.3 Structural FEPs

SCR-4.1.3.1 Deformation

SCR-4.1.3.1.1 FEP Numbers: N6 and N7
FEP Titles: *Salt Deformation* (N6)
Diapirism (N7)

SCR-4.1.3.1.1.1 Screening Decision: SO-P

Natural *Salt Deformation* and *Diapirism* at the WIPP site over the next 10,000 yrs on a scale severe enough to significantly affect performance of the disposal system have been eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.1.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.3.1.1.3 Screening Argument

SCR-4.1.3.1.1.3.1 Deformation

Some of the evaporites in the northern Delaware Basin have been deformed and it has been proposed that the likely mechanism for deformation is gravity foundering of the more dense anhydrites in less dense halite (e.g., Anderson and Powers 1978, Jones 1981, Borns et al. 1983, and Borns 1987). Diapirism occurs when the deformation is penetrative, i.e., halite beds disrupt overlying anhydrites. As Anderson and Powers (1978) suggested, this may have happened northeast of the WIPP at the location of drillhole ERDA-6. This is the only location where diapirism has been suggested for the evaporites of the northern Delaware Basin. The geologic situation suggests that deformation occurred before the Miocene-Pliocene Ogallala Formation was deposited (Jones 1981). Mechanical modeling is consistent with salt deformation occurring

over about 700,000 yrs to form the deformed features known in the northern part of the WIPP site (Borns et al. 1983). The DOE drew the conclusion that evaporites at the WIPP site deform too slowly to affect performance of the disposal system.

Because brine reservoirs appear to be associated with deformation, Powers et al. (1996) prepared detailed structure elevation maps of various units from the base of the Castile upward through the evaporites in the northern Delaware Basin. Drillholes are far more numerous for this study than at the time of the study by Anderson and Powers (1978). Subdivisions of the Castile appear to be continuous in the vicinity of ERDA-6 and at ERDA-6. There is little justification for interpreting diapiric piercement at that site. The location and distribution of evaporite deformation in the area of the WIPP site is similar to that proposed by earlier studies (e.g., Anderson and Powers 1978, Borns et al. 1983, Borns and Shaffer 1985).

Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

A more recent study of structure for the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra) (Powers 2003) shows that the larger deformation associated with deeper units is reflected by the Culebra, although the structural relief is muted. In addition, evaporite deformation in the northern part of the WIPP site, associated with the area earlier termed the "disturbed zone" (Powers et al. 1978), is hardly observable on a map of Culebra structure (Powers 2003). There is no evidence of more recent deformation at the WIPP site based on such maps.

Deformed salt in the lower Salado and upper strata of the Castile has been encountered in a number of boreholes around the WIPP site; the extent of existing salt deformation is summarized in the CCA, Chapter 2.0, Section 2.1.6.1, and further detail is provided in the CCA, Appendix DEF.

A number of mechanisms may result in salt deformation: in massive salt deposits, buoyancy effects or diapirism may cause salt to rise through denser, overlying units; and in bedded salt with anhydrite or other interbeds, gravity foundering of the interbeds into the halite may take place. Results from rock mechanics modeling studies (see the CCA, Appendix DEF) indicate that the time scale for the deformation process is such that significant natural deformation is unlikely to occur at the WIPP site over any time frame significant to waste isolation. Thus natural salt deformation and diapirism severe enough to alter existing patterns of groundwater flow or the behavior of the disposal system over the regulatory period has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 yrs.

SCR-4.1.3.2 Fracture Development

SCR-4.1.3.2.1 FEP Number: N8
FEP Title: *Formation of Fractures*

SCR-4.1.3.2.1.1 Screening Decision: SO-P, UP (Repository)
Formation of Fractures has been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 yrs. The *Formation of Fractures* near the repository is accounted for in PA through treatment of the DRZ.

SCR-4.1.3.2.1.2 Summary of New Information
No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.3.2.1.3 Screening Argument
The formation of fractures requires larger changes in stress than are required for changes to the properties of existing fractures to overcome the shear and tensile strength of the rock. It has been concluded from the regional tectonic setting of the Delaware Basin that no significant changes in regional stress are expected over the regulatory period. The EPA agrees that fracture formation in the Rustler is likely a result of halite dissolution and subsequent overlying unit fracturing loading/unloading, as well as the syn- and postdepositional processes. Intraformational postdepositional dissolution of the Rustler has been ruled out as a major contributor to Rustler salt distribution and thus to new fracture formation based on work by Holt and Powers in the CCA (Appendix DEF, Section DEF3.2) and Powers and Holt (1999 and 2000), who believe that depositional facies and syndepositional dissolution account for most of the patterns on halite distribution in the Rustler. The argument against developing new fractures in the Rustler during the regulatory period appears reasonable. The formation of new fracture sets in the Culebra has therefore been eliminated from PA calculations on the basis of a low probability of occurrence over 10,000 yrs.

Repository-induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations.

A mechanism such as salt diapirism could develop fracturing in the Salado, but there is little evidence of diapirism in the Delaware Basin. Salt deformation has occurred in the vicinity of the WIPP, and fractures have developed in deeper Castile anhydrites as a consequence. Deformation rates are slow, and it is highly unlikely that this process will induce significant new fractures in the Salado during the regulatory time period. Surface domal features at the northwestern end of Nash Draw were of undetermined origin prior to WIPP investigations (e.g., Vine 1963), but extensive geophysical studies were conducted of these features as part of early WIPP studies (see Powers 1996). Two of the domal features were drilled, demonstrating that they had a solution-collapse origin (breccia pipes) and were not related in any way to salt diapirism (Snyder and Gard 1982).

SCR-4.1.3.2.2 FEP Number: N9
FEP Title: *Changes in Fracture Properties*

SCR-4.1.3.2.2.1 Screening Decision: SO-C, UP (near repository)
Naturally induced *Changes in Fracture Properties* that may affect groundwater flow or radionuclide transport in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. *Changes in Fracture Properties* near the repository are accounted for in PA calculations through treatment of the DRZ.

SCR-4.1.3.2.2.2 Summary of New Information
No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.3.2.2.3 Screening Argument
Groundwater flow in the region of the WIPP and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport will be influenced by fracture characteristics. Changes in fracture properties could arise through natural changes in the local stress field; for example, through tectonic processes, erosion or sedimentation changing the amount of overburden, dissolution of soluble minerals along beds in the Rustler or upper Salado, or dissolution or precipitation of minerals in fractures.

Tectonic processes and features (changes in regional stress [N3]; tectonics [N4]; regional uplift and subsidence [N5]; salt deformation [N6]; diapirism [N7]) have been screened out of PA. These processes are not expected to significantly change the character of fractures during the regulatory period.

Surface erosion or deposition (e.g., N41–N49) are not expected to significantly change the overburden on the Culebra during the regulatory period. The relationship between Culebra transmissivity and depth is significant (Holt and Yarbrough 2002, Holt and Powers 2002), but the potential change to Culebra transmissivity based on deposition or erosion from these processes over the regulatory period is insignificant.

Shallow dissolution (N16), where soluble beds from the upper Salado or Rustler are removed by groundwater, has been extensively considered. There are no direct effects on the Salado at depths of the repository. Extensive study of the upper Salado and Rustler halite units (Holt and Powers 1988, the CCA, Appendix FAC, Powers and Holt 1999 and 2000, Powers 2003) indicates little potential for dissolution at the WIPP site during the regulatory period. Existing fracture properties are expressed through the relationship between Culebra transmissivity values and geologic factors at and near the WIPP site (Holt and Yarbrough 2002; Holt and Powers 2002, p. 215). These will be incorporated in PA (see N16, Shallow Dissolution).

Mineral precipitation within fractures (N22) is expected to be beneficial to performance, and it has been screened out on the basis of low consequence. Natural dissolution of fracture fillings within the Culebra is incorporated within FEP N16 (Shallow Dissolution). There is no new information on the distribution of fracture fillings within the Culebra. The effects of fracture fillings are also expected to be represented in the distribution of Culebra transmissivity values around the WIPP site and are thus incorporated into PA.

Repository-induced fracturing of the DRZ and Salado interbeds is accounted for in PA calculations (UP), and is discussed further in FEPs W18 and W19.

SCR-4.1.3.2.3 FEP Numbers: N10 and N11
FEP Titles: *Formation of New Faults* (N10)
Fault Movement (N11)

SCR-4.1.3.2.3.1 Screening Decision: SO-P

Naturally induced *Fault Movement* and *Formation of New Faults* of sufficient magnitude to significantly affect the performance of the disposal system have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 yrs.

SCR-4.1.3.2.3.2 Summary of New Information

No changes have been made to this FEP.

SCR-4.1.3.2.3.3 Screening Argument

Faults are present in the Delaware Basin in both the units underlying the Salado and in the Permian evaporite sequence (see the CCA, Section 2.1.5.3). According to Powers et al. (1978 included in the CCA, Appendix GCR), there is evidence that movement along faults within the pre-Permian units affected the thickness of Early Permian strata, but these faults did not exert a structural control on the deposition of the Castile, the Salado, or the Rustler. Fault zones along the margins of the Delaware Basin were active during the Late Permian Period. Along the eastern margin, where the Delaware Basin flanks the Central Basin Platform, Holt and Powers (1988, also included in the CCA, Appendix FAC) note that there is displacement of the Rustler, and Schiel (1994) notes that there is thinning of the Dewey Lake. There is, however, no surface displacement along the trend of these fault zones, indicating that there has been no significant Quaternary movement. Muehlberger et al. (1978, p. 338) note that the nearest faults on which Quaternary movement has been identified lie to the west of the Guadalupe Mountains.

The WIPP is located in an area of tectonic quiescence. Seismic monitoring conducted for the WIPP since the CCA continues to record small events at distance from the WIPP, and these events are mainly in areas associated with hydrocarbon production. Two nearby events (magnitude 3.5, October 1997, and magnitude 2.8, December 1998) are related to rockfalls in the Nash Draw mine and are not tectonic in origin (U.S. Department of Energy 1999). These events did not cause any damage at the WIPP. The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically induced fault movement within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 yrs. The stable tectonic setting also allows the formation of new faults within the basin over the next 10,000 yrs to be eliminated from PA calculations on the basis of low probability of occurrence.

Evaporite dissolution at or near the WIPP site has the potential for developing fractures in the overlying beds. Three zones with halite (top of Salado, M1/H1 of the Los Medaños Member, and M2/H2 of the Los Medaños Member) underlie the Culebra at the site (Powers 2003). The upper Salado is present across the site, and there is no indication that dissolution of this area will occur in the regulatory period or cause faulting at the site. The Los Medaños units show both mudflat facies and halite-bearing facies within or adjacent to the WIPP site (Powers 2003). Although the

distribution of halite in the Rustler is mainly the result of depositional facies and syndepositional dissolution (Holt and Powers 1988, Powers and Holt 1999 and 2000), the possibility of past or future halite dissolution along the margins cannot be ruled out (Holt and Powers 1988, Beauheim and Holt 1999). If halite in the lower Rustler has been dissolved along the depositional margin, it has not occurred recently or has been of no consequence, as there is no indication on the surface or in Rustler structure of new (or old) faults in this area (e.g., Powers et al. 1978, Powers 2003).

The absence of Quaternary fault scarps and the general tectonic setting and understanding of its evolution indicate that large-scale, tectonically induced fault movement within the Delaware Basin can be eliminated from PA calculations on the basis of low probability over 10,000 years. The stable tectonic setting also allows the formation of new faults within the basin over the next 10,000 years to be eliminated from PA calculations on the basis of low probability of occurrence.

SCR-4.1.3.2.4 FEP Number: N12
FEP Title: *Seismic Activity*

SCR-4.1.3.2.4.1 Screening Decision: UP
The postclosure effects of *Seismic Activity* on the repository and the DRZ are accounted for in PA calculations.

SCR-4.1.3.2.4.2 Summary of New Information
Seismic monitoring conducted for the WIPP since the CRA-2004 continues to record small events at a distance from the WIPP, mainly in areas associated with hydrocarbon production. Three seismic events (magnitude 2.4, January 27, 2006; magnitude 3.8, December 19, 2005; and magnitude 3.6, May 23, 2004) occurred within 300 km of the WIPP (see U.S. Department of Energy 2005, 2006, 2007a). These events did not cause any damage at the WIPP.

SCR-4.1.3.2.4.3 Screening Argument
The following subsections present the screening argument for seismic activity (groundshaking).

SCR-4.1.3.2.4.4 Causes of Seismic Activity
Seismic activity describes transient ground motion that may be generated by several energy sources. There are two possible causes of seismic activity that could potentially affect the WIPP site: natural and human-induced. Natural seismic activity is caused by fault movement (earthquakes) when the buildup of strain in rock is released through sudden rupture or movement. Human-induced seismic activity may result from a variety of surface and subsurface activities, such as explosions (H19 and H20), mining (H13, H14, H58, and H59), fluid injection (H28), and fluid withdrawal (H25).

SCR-4.1.3.2.4.5 Groundshaking
Ground vibration and the consequent shaking of buildings and other structures are the most obvious effects of seismic activity. Once the repository and shafts have been sealed, however, existing surface structures will be dismantled. Postclosure PAs are concerned with the effects of seismic activity on the closed repository.

In regions of low and moderate seismic activity, such as the Delaware Basin, rocks behave elastically in response to the passage of seismic waves, and there are no long-term changes in

rock properties. The effects of earthquakes beyond the DRZ have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. An inelastic response, such as cracking, is only possible where there are free surfaces, as in the roof and walls of the repository prior to closure by creep. Seismic activity could, therefore, have an effect on the properties of the DRZ.

An assessment of the extent of damage in underground excavations caused by groundshaking depends largely on observations from mines and tunnels. Because such excavations tend to take place in rock types more brittle than halite, these observations cannot be related directly to the behavior of the WIPP. According to Wallner (1981, p. 244), the DRZ in brittle rock types is likely to be more highly fractured and hence more prone to spalling and rockfalls than an equivalent zone in salt. Relationships between groundshaking and subsequent damage observed in mines will therefore be conservative with respect to the extent of damage induced at the WIPP by seismic activity.

Dowding and Rozen (1978) classified damage in underground structures following seismic activity and found that no damage (cracks, spalling, or rockfalls) occurred at accelerations below 0.2 gravities and that only minor damage occurred at accelerations up to 0.4 gravities. Lenhardt (1988, p. 392) showed that a magnitude 3 earthquake would have to be within 1 km (0.6 mi) of a mine to result in falls of loose rock. The risk of seismic activity in the region of the WIPP reaching these thresholds is discussed below.

SCR-4.1.3.2.4.6 Seismic Risk in the Region of the WIPP

Prior to the introduction of a seismic monitoring network in 1960, most recorded earthquakes in New Mexico were associated with the Rio Grande Rift, although small earthquakes were detected in other parts of the region. In addition to continued activity in the Rio Grande Rift, the instrumental record has shown a significant amount of seismic activity originating from the Central Basin Platform and a number of small earthquakes in the Los Medaños area. Seismic activity in the Rio Grande Rift is associated with extensional tectonics in that area. Seismic activity in the Central Basin Platform may be associated with natural earthquakes, but there are also indications that this activity occurs in association with oil-field activities such as fluid injection. Small earthquakes in the Los Medaños region have not been precisely located, but may be the result of mining activity in the region. The CCA, Chapter 2.0, Section 2.6.2 contains additional discussion of seismic activity and risk in the WIPP region.

The instrumental record was used as the basis of a seismic risk study primarily intended for design calculations of surface facilities rather than for postclosure PAs. The use of this study to define probable ground accelerations in the WIPP region over the next 10,000 yrs is based on the assumptions that hydrocarbon extraction and potash mining will continue in the region and that the regional tectonic setting precludes major changes over the next 10,000 yrs.

Three source regions were used in calculating seismic risk: the Rio Grande Rift, the Central Basin Platform, and part of the Delaware Basin province (including the Los Medaños). Using conservative assumptions about the maximum magnitude event in each zone, the study indicated a return period of about 10,000 years (annual probability of occurrence of 10^{-4}) for events producing ground accelerations of 0.1 gravities. Ground accelerations of 0.2 gravities would have an annual probability of occurrence of about 5×10^{-6}.

The results of the seismic risk study and the observations of damage in mines caused by groundshaking give an estimated annual probability of occurrence of between 10^{-8} and 10^{-6} for events that could increase the permeability of the DRZ. The DRZ is accounted for in PA calculations as a zone of permanently high permeability (see Appendix PA-2009, Section PA-4.2.4); this treatment is considered to account for the effects of any potential seismic activity.

SCR-4.1.4 Crustal Process

SCR-4.1.4.1 FEP Number: N13
FEP Title: *Volcanic Activity*

SCR-4.1.4.1.1 Screening Decision: SO-P

Volcanic Activity has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 yrs.

SCR-4.1.4.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.4.1.3 Screening Argument

The Paleozoic and younger stratigraphic sequences within the Delaware Basin are devoid of locally derived volcanic rocks. Volcanic ashes (dated at 13 million years and 0.6 million years) do occur in the Gatuña Formation (hereafter referred to as the Gatuña), but these are not locally derived. Within eastern New Mexico and northern, central, and western Texas, the closest Tertiary volcanic rocks with notable areal extent or tectonic significance to the WIPP are approximately 160 km (100 mi) to the south in the Davis Mountains volcanic area. The closest Quaternary volcanic rocks are 250 km (150 mi) to the northwest in the Sacramento Mountains. No volcanic rocks are exposed at the surface within the Delaware Basin.

Volcanic activity is associated with particular tectonic settings: constructive and destructive plate margins, regions of intraplate rifting, and isolated hot-spots in intraplate regions. The tectonic setting of the WIPP site and the Delaware Basin is remote from plate margins, and the absence of past volcanic activity indicates the absence of a major hot spot in the region. Intraplate rifting has taken place along the Rio Grande some 200 km (120 mi) west of the WIPP site during the Tertiary and Quaternary Periods. Igneous activity along this rift valley is comprised of sheet lavas intruded on by a host of small-to-large plugs, sills, and other intrusive bodies. However, the geological setting of the WIPP site within the large and stable Delaware Basin allows volcanic activity in the region of the WIPP repository to be eliminated from performance calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.4.2 FEP Number: N14
FEP Title: *Magmatic Activity*

SCR-4.1.4.2.1 Screening Decision: SO-C

The effects of *Magmatic Activity* have been eliminated from the PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.4.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-4.1.4.2.3 Screening Argument

Magmatic activity is defined as the subsurface intrusion of igneous rocks into country rock. Deep intrusive igneous rocks crystallize at depths of several kilometers (several miles) and have no surface or near-surface expression until considerable erosion has taken place. Alternatively, intrusive rocks may form from magma that has risen to near the surface or in the vents that give rise to volcanoes and lava flows. Magma near the surface may be intruded along subvertical and subhorizontal discontinuities (forming dikes and sills, respectively), and magma in volcanic vents may solidify as plugs. The formation of such features close to a repository or the existence of a recently intruded rock mass could impose thermal stresses, inducing new fractures or altering the hydraulic characteristics of existing fractures.

The principal area of magmatic activity in New Mexico is the Rio Grande Rift, where extensive intrusions occurred during the Tertiary and Quaternary Periods. The Rio Grande Rift, however, is in a different tectonic province than the Delaware Basin, and its magmatic activity is related to the extensional stress regime and high heat flow in that region.

Within the Delaware Basin, there is a single identified outcrop of a lamprophyre dike about 70 km (40 mi) southwest of the WIPP (see the CCA, Chapter 2.0, Section 2.1.5.4 and the CCA, Appendix GCR for more detail). Closer to the WIPP site, similar rocks have been exposed within potash mines some 15 km (10 mi) to the northwest, and igneous rocks have been reported from petroleum exploration boreholes. Material from the subsurface exposures has been dated at around 35 million years. Some recrystallization of the host rocks took place alongside the intrusion, and there is evidence that minor fracture development and fluid migration also occurred along the margins of the intrusion. However, the fractures have been sealed, and there is no evidence that the dike acted as a conduit for continued fluid flow.

Aeromagnetic surveys of the Delaware Basin have shown anomalies that lie on a linear southwest-northeast trend that coincides with the surface and subsurface exposures of magmatic rocks. There is a strong indication, therefore, of a dike or a closely related set of dikes extending for at least 120 km (70 mi) across the region (see the CCA, Chapter 2.0, Section 2.1.5.4). The aeromagnetic survey conducted to delineate the dike showed a magnetic anomaly that is several kilometers (several miles) wide at depth and narrows to a thin trace near the surface. This pattern is interpreted as the result of an extensive dike swarm at depths of less than

approximately 4.0 km (2.5 mi) near the Precambrian basement, from which a limited number of dikes have extended towards the surface.

Magmatic activity has taken place in the vicinity of the WIPP site in the past, but the igneous rocks have cooled over a long period. Any enhanced fracturing or conduits for fluid flow have been sealed by salt creep and mineralization. Continuing magmatic activity in the Rio Grande Rift is too remote from the WIPP location to be of consequence to the performance of the disposal system. Thus the effects of magmatic activity have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.1.4.2.4 FEP Number: N15
FEP Title: *Metamorphic Activity*

SCR-4.1.4.2.4.1 Screening Decision: SO-P

Metamorphic Activity has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.4.2.4.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.4.2.4.3 Screening Argument

Metamorphic activity, that is, solid-state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure, requires depths of burial much greater than the depth of the repository. Regional tectonics that would result in the burial of the repository to the depths at which the repository would be affected by metamorphic activity have been eliminated from PA calculations on the basis of low probability of occurrence; therefore, metamorphic activity has also been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5 Geochemical Processes

SCR-4.1.5.1 FEP Number: N16
FEP Title: *Shallow Dissolution* (including lateral dissolution)

SCR-4.1.5.1.1 Screening Decision: UP

Shallow Dissolution is accounted for in PA calculations.

SCR-4.1.5.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.5.1.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between shallow dissolution involving circulation of groundwater, mineral dissolution in the Rustler and at the top of the

Salado in the region of the WIPP, and deep dissolution taking place in the Castile and the base of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in the CCA, Chapter 2.0, Section 2.1.6.2.

SCR-4.1.5.1.4 Shallow Dissolution

In the region around the WIPP, shallow dissolution by groundwater flow has removed soluble minerals from the upper Salado as well as the Rustler to form Nash Draw; extensive solution within the closed draw has created karst features including caves and dolines in the sulfate beds of the Rustler (see Lee, 1925, Bachman, 1980, 1985, and 1987a). An alluvial doline drilled at WIPP 33, about 850 m (2800 ft) west of the WIPP site boundary, is the nearest karst feature known in the vicinity of the site. Upper Salado halite dissolution in Nash Draw resulted in fracture propagation upward through the overlying Rustler (Holt and Powers 1988). The margin of dissolution of halite from the upper Salado has commonly been placed west of the WIPP site, near, but east of, Livingston Ridge, the eastern boundary of Nash Draw. Halite occurs in the Rustler east of Livingston Ridge, with the margin generally progressively eastward in higher stratigraphic units (e.g., Snyder 1985; Powers and Holt 1995). The distribution of halite in the Rustler has commonly been attributed to shallow dissolution (e.g., Powers et al. 1978; Lambert, 1983; Bachman 1985; Lowenstein 1987). During early studies for the WIPP, the variability of Culebra transmissivity in the vicinity of the WIPP was commonly attributed to the effects of Rustler halite dissolution and changes in fracturing as a consequence.

After a detailed sedimentologic and stratigraphic investigation of WIPP cores, shafts, and geophysical logs from the region around WIPP, the distribution of halite in the Rustler was attributed to depositional and syndepositional processes rather than postdepositional dissolution (Holt and Powers 1988; Powers and Holt 2000). Rustler exposures in shafts for the WIPP revealed extensive sedimentary structures in clastic units (Holt and Powers 1984, 1986, 1990), and the suite of features in these beds led these investigators (Holt and Powers 1988; Powers and Holt 1990, 2000) to reinterpret the clastic units. They conclude that the clastic facies represent mainly mudflat facies tracts adjacent to a salt pan. Although some halite was likely deposited in mudflat areas proximal to the salt pan, it was largely removed by syndepositional dissolution, as indicated by soil structures, soft sediment deformation, bedding, and small-scale vertical relationships (Holt and Powers 1988; Powers and Holt 1990, 1999, 2000). The depositional margins of halite in the Rustler are the likely points for past or future dissolution (e.g., Holt and Powers 1988; Beauheim and Holt 1990). Cores from drillholes at the H-19 drillpad near the Tamarisk Member halite margin show evidence of some dissolution of halite in the Tamarisk (Mercer et al. 1998), consistent with these predictions. The distribution of Culebra transmissivity values is not considered related to dissolution of Rustler halite, and other geological factors (e.g., depth, upper Salado dissolution) correlate well with Culebra transmissivity (e.g., Powers and Holt 1995; Holt and Powers 2002).

Since the CCA was completed, the WIPP has conducted additional work on shallow dissolution, principally of the upper Salado, and its possible relationship to the distribution of transmissivity values for the Culebra as determined through testing of WIPP hydrology wells.

Analysis Plan 088 (AP-088) (Beauheim 2002) noted that potentiometric surface values for the Culebra in many monitoring wells were outside the uncertainty ranges used to calibrate models of steady-state heads for the unit. AP-088 directed the analysis of the relationship between geological factors and values of transmissivity at Culebra wells. The relationship between geological factors, including dissolution of the upper Salado as well as limited dissolution in the Rustler, and Culebra transmissivity is being used to evaluate differences between assuming steady-state Culebra heads and changing heads.

Task 1 for AP-088 (Powers 2003) evaluated geological factors, including shallow dissolution in the vicinity of the WIPP site related to Culebra transmissivity. A much more extensive drillhole geological database was developed than was previously available, utilizing sources of data from WIPP, potash exploration, and oil and gas exploration and development. The principal findings related to shallow dissolution are (1) a relatively narrow zone (~ 200 – 400 m [656 – 1,312 ft] wide) could be defined as the margin of dissolution of the upper Salado in much of the area around WIPP, (2) the upper Salado dissolution margin commonly underlies surface escarpments such as Livingston Ridge, and (3) there are possible extensions or reentrants of incipient upper Salado dissolution extending eastward from the general dissolution margin. The WIPP site proper is not affected by this process.

Culebra transmissivity correlates well with depth or overburden, which affects fracture apertures (Powers and Holt 1995, Holt and Powers 2002; Holt and Yarbrough 2002). Dissolution of the upper Salado appears to increase transmissivity by one or more orders of magnitude (Holt and Yarbrough 2002). Because there is no indication of upper Salado dissolution at the WIPP site, Holt and Yarbrough (2002) did not include this factor for the WIPP site in estimates of base transmissivity values for the WIPP site and surroundings.

The effects of shallow dissolution (including the impacts of lateral dissolution) have been included in PA calculations.

SCR-4.1.5.2 FEP Numbers: N18, N20, and N21
FEP Titles: *Deep Dissolution* (N18)
Breccia Pipes (N20)
Collapse Breccias (N21)

SCR-4.1.5.2.1 Screening Decision: SO-P

Deep Dissolution and the formation of associated features (for example, solution chimneys or *Breccia Pipes*, *Collapse Breccias*) at the WIPP site have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.1.5.2.3 Screening Argument

This section discusses a variety of styles of dissolution that have been active in the region of the WIPP or in the Delaware Basin. A distinction has been drawn between shallow dissolution, involving circulation of groundwater and mineral dissolution in the Rustler and at the top of the Salado in the region of the WIPP, and deep dissolution taking place in the Castile and the base of the Salado. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities (karst) and result in the total collapse of overlying units. This topic is discussed further in the CCA, Chapter 2.0, Section 2.1.6.2.

SCR-4.1.5.2.4 Deep Dissolution

Deep dissolution is limited to processes involving dissolution of the Castile or basal Salado and features such as breccia pipes (also known as solution chimneys) associated with this process (see the CCA, Chapter 2.0, Section 2.1.6.2). Deep dissolution is distinguished from shallow and lateral dissolution not only by depth, but also by the origin of the water. Dissolution by groundwater from deep water-bearing zones can lead to the formation of cavities. Collapse of overlying beds leads to the formation of collapse breccias if the overlying rocks are brittle, or to deformation if the overlying rocks are ductile. If dissolution is extensive, breccia pipes or solution chimneys may form above the cavity. These pipes may reach the surface or pass upwards into fractures and then into microcracks that do not extend to the surface. Breccia pipes may also form through the downward percolation of meteoric waters, as discussed earlier. Deep dissolution is of concern because it could accelerate contaminant transport through the creation of vertical flow paths that bypass low-permeability units in the Rustler. If dissolution occurred within or beneath the waste panels themselves, there could be increased circulation of groundwater through the waste, as well as a breach of the Salado host rock.

Features identified as being the result of deep dissolution are present along the northern and eastern margins of the Delaware Basin. In addition to features that have a surface expression or that appear within potash mine workings, deep dissolution has been cited by Anderson et al. (1972, p. 81) as the cause of lateral variability within evaporite sequences in the lower Salado.

Exposures of the McNutt Potash Member of the Salado within a mine near Nash Draw have shown a breccia pipe containing cemented brecciated fragments of formations higher in the stratigraphic sequence. At the surface, this feature is marked by a dome, and similar domes have been interpreted as dissolution features. The depth of dissolution has not been confirmed, but the collapse structures led Anderson (1978, p. 52) and Snyder et al. (1982, p. 65) to postulate dissolution of the Capitan Limestone at depth; collapse of the Salado, Rustler, and younger formations; and subsequent dissolution and hydration by downward percolating waters. San Simon Sink (see the CCA, Chapter 2.0, Section 2.1.6.2), some 35 km (20 mi) east-southeast of the WIPP site, has also been interpreted as a solution chimney. Subsidence has occurred there in historical times according to Nicholson and Clebsch (1961, p. 14), suggesting that dissolution at depth is still taking place. Whether this is the result of downward-percolating surface water or deep groundwater has not been confirmed. The association of these dissolution features with the

inner margin of the Capitan Reef suggest that they owe their origins, if not their continued development, to groundwaters derived from the Capitan Limestone.

SCR-4.1.5.2.5 Dissolution within the Castile and Lower Salado

The Castile contains sequences of varved anhydrite and carbonate (that is, laminae deposited on a cyclical basis) that can be correlated between several boreholes. On the basis of these deposits, a basin-wide uniformity in the depositional environment of the Castile evaporites was assumed. The absence of varves from all or part of a sequence and the presence of brecciated anhydrite beds have been interpreted by Anderson et al. (1972) as evidence of dissolution. Holt and Powers (the CCA, Appendix FAC) have questioned the assumption of a uniform depositional environment and contend that the anhydrite beds are lateral equivalents of halite sequences without significant postdepositional dissolution. Wedges of brecciated anhydrite along the margin of the Castile have been interpreted by Robinson and Powers (1987, p. 78) as gravity-driven clastic deposits, rather than the result of deep dissolution.

Localized depressions at the top of the Castile and inclined geophysical marker units at the base of the Salado have been interpreted by Davies (1983, p. 45) as the result of deep dissolution and subsequent collapse or deformation of overlying rocks. The postulated cause of this dissolution was circulation of undersaturated groundwaters from the Bell Canyon Formation (hereafter referred to as Bell Canyon). Additional boreholes (notably WIPP-13, WIPP-32, and DOE-2) and geophysical logging led Borns and Shaffer (1985) to conclude that the features interpreted by Davies as being dissolution features are the result of irregularities at the top of Bell Canyon. These irregularities led to localized depositional thickening of the Castile and lower Salado sediments.

SCR-4.1.5.2.6 Collapse Breccias at Basin Margins

Collapse breccias are present at several places around the margins of the Delaware Basin. Their formation is attributed to relatively fresh groundwater from the Capitan Limestone that forms the margin of the basin. Collapse breccias corresponding to features on geophysical records that have been ascribed to deep dissolution have not been found in boreholes away from the margins. These features have been reinterpreted as the result of early dissolution prior to the deposition of the Salado.

SCR-4.1.5.2.7 Summary of Deep Dissolution

Deep dissolution features have been identified within the Delaware Basin, but only in marginal areas underlain by Capitan Reef. There is a low probability that deep dissolution will occur sufficiently close to the waste panels over the regulatory period to affect groundwater flow in the immediate region of the WIPP. Deep dissolution at the WIPP site has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.1.5.3 FEP Number: N22
FEP Title: *Fracture Infill*

SCR-4.1.5.3.1 Screening Decision: SO-C – Beneficial

The effects of *Fracture Infill* have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-4.1.5.3.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004. No changes have been made.

SCR-4.1.5.3.3 Screening Argument

SCR-4.1.5.3.3.1 Mineralization
Precipitation of minerals as fracture infills can reduce hydraulic conductivities. The distribution of infilled fractures in the Culebra closely parallels the spatial variability of lateral transmissivity in the Culebra. The secondary gypsum veins in the Rustler have not been dated. Strontium isotope studies (Siegel et al. 1991, pp. 5-53 to 5-57) indicate that the infilling minerals are locally derived from the host rock rather than extrinsically derived, and it is inferred that they reflect an early phase of mineralization and are not associated with recent meteoric waters.

Stable isotope geochemistry in the Rustler has also provided information on mineral stabilities in these strata. Both Chapman (1986, p. 31) and Lambert and Harvey (1987, p. 207) imply that the mineralogical characteristics of units above the Salado have been stable or subject to only minor changes under the various recharge conditions that have existed during the past 0.6 million years—the period since the formation of the Mescalero caliche and the establishment of a pattern of climate change and associated changes in recharge that led to present-day hydrogeological conditions. No changes in climate are expected other than those experienced during this period, and for this reason, no changes are expected in the mineralogical characteristics other than those expressed by the existing variability of fracture infills and diagenetic textures. Formation of fracture infills will reduce transmissivities and will therefore be of beneficial consequence to the performance of the disposal system.

SCR-4.2 Subsurface Hydrological FEPs

SCR-4.2.1 Groundwater Characteristics

SCR-4.2.1.1 FEP Numbers: N23, N24, N25, and N27
FEP Titles: *Saturated Groundwater Flow* (N23)
Unsaturated Groundwater Flow (N24)
Fracture Flow (N25)
Effects of Preferential Pathways (N27)

SCR-4.2.1.1.1 Screening Decision: UP

Saturated Groundwater Flow, *Unsaturated Groundwater Flow*, *Fracture Flow*, and *Effects of Preferential Pathways* are accounted for in PA calculations.

SCR-4.2.1.1.2 Summary of New Information

No new information has been identified for these FEPs. They continue to be accounted for in PA.

SCR-4.2.1.1.3 Screening Argument

Saturated groundwater flow, unsaturated groundwater flow, and fracture flow are accounted for in PA calculations. Groundwater flow is discussed in the CCA, Chapter 2.0, Section 2.2.1; and Chapter 6.0, Section 6.4.5 and Section 6.4.6.

The hydrogeologic properties of the Culebra are also spatially variable. This variability, including the effects of preferential pathways, is accounted for in PA calculations in the estimates of transmissivity and aquifer thickness.

SCR-4.2.1.2 FEP Number: N26
FEP Title: *Density Effect on Groundwater Flow*

SCR-4.2.1.2.1 Screening Decision: SO-C

Density Effects on Groundwater Flow has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.1.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.1.2.3 Screening Argument

The most transmissive unit in the Rustler, and hence the most significant potential pathway for transport of radionuclides to the accessible environment, is the Culebra. The properties of Culebra groundwaters are not homogeneous, and spatial variations in groundwater density (the CCA, Chapter 2.0, Section 2.2.1.4.1.2) could influence the rate and direction of groundwater flow. A comparison of the gravity-driven flow component and the pressure-driven component in the Culebra, however, shows that only in the region to the south of the WIPP are head gradients low enough for density gradients to be significant (Davies 1989, p. 53). Accounting for this variability would rotate groundwater flow vectors towards the east (down-dip) and hence fluid in the high-transmissivity zone would move away from the zone. Excluding brine density variations within the Culebra from PA calculations is therefore a conservative assumption, and density effects on groundwater flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2 Changes in Groundwater Flow

SCR-4.2.2.1 FEP Number: N28
FEP Title: *Thermal Effects on Groundwater Flow*

SCR-4.2.2.1.1 Screening Decision: SO-C

Natural Thermal Effects on Groundwater Flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.2.1.3 Screening Argument

The geothermal gradient in the region of the WIPP has been measured at about 30 °C (54 °F) per kilometer (50 °C [90 °F] per mile). Given the generally low permeability in the region and the limited thickness of units in which groundwater flow occurs (for example, the Culebra), natural convection will be too weak to have a significant effect on groundwater flow. No natural FEPs have been identified that could significantly alter the temperature distribution of the disposal system or give rise to thermal effects on groundwater flow. Such effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.2 FEP Number: N29
FEP Title: *Saline Intrusion* (hydrogeological effects)

SCR-4.2.2.2.1 Screening Decision: SO-P

Changes in groundwater flow arising from *Saline Intrusion* have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.2.2.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.2.2.3 Screening Argument

No natural events or processes have been identified that could result in saline intrusion into units above the Salado or cause a significant increase in fluid density. Natural saline intrusion has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. Saline intrusion arising from human events such as drilling into a pressurized brine pocket is discussed in FEPs H21 through H24 (Section SCR-5.2.1.4).

SCR-4.2.2.3 FEP Number: N30
FEP Title: *Freshwater Intrusion* (hydrogeological effects)

SCR-4.2.2.3.1 Screening Decision: SO-P

Changes in groundwater flow arising from *Freshwater Intrusion* have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.2.2.3.2 Summary

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.2.3.2.1 Screening Argument

A number of FEPs, including climate change, can result in changes in infiltration and recharge (see discussions for FEPs N53 through N55, Section SCR-4.5.3.1). These changes will affect the height of the water table and, hence, could affect groundwater flow in the Rustler through changes in head gradients. The generally low transmissivity of the Dewey Lake and the Rustler, however, will prevent any significant changes in groundwater density from occurring within the Culebra over the timescales for which increased precipitation and recharge are anticipated. No other natural events or processes have been identified that could result in freshwater intrusion into units above the Salado or cause a significant decrease in fluid density. Freshwater intrusion has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.2.2.4 FEP Number: N31
FEP Title: Hydrological Response to Earthquakes

SCR-4.2.2.4.1 Screening Decision: SO-C

Hydrological Response to Earthquakes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.4.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.2.4.3 Screening Argument

SCR-4.2.2.4.3.1 Hydrological Effects of Seismic Activity

There are a variety of hydrological responses to earthquakes. Some of these responses, such as changes in surface-water flow directions, result directly from fault movement. Others, such as changes in subsurface water chemistry and temperature, probably result from changes in flow pathways along the fault or fault zone. According to Bredehoeft et al. (1987, p. 139), further away from the region of fault movement, two types of changes to groundwater levels may take place as a result of changes in fluid pressure.

- The passage of seismic waves through a rock mass causes a volume change, inducing a transient response in the fluid pressure, which may be observed as a short-lived fluctuation of the water level in wells.

- Changes in volume strain can cause long-term changes in water level. A buildup of strain occurs prior to rupture and is released during an earthquake. The consequent change in fluid pressure may be manifested by the drying up or reactivation of springs some distance from the region of the epicenter.

Fluid-pressure changes induced by the transmission of seismic waves can produce changes of up to several meters (several yards) in groundwater levels in wells, even at distances of thousands of kilometers from the epicenter. These changes are temporary, however, and levels typically return to pre-earthquake levels in a few hours or days. Changes in fluid pressure arising from changes in volume strain persist for much longer periods, but they are only potentially consequential in tectonic regimes where there is a significant buildup of strain. The regional tectonics of the Delaware Basin indicates that such a buildup has a low probability of occurring over the next 10,000 years (see FEPs N3 and N4, Section SCR-4.1.2.1).

The expected level of seismic activity in the region of the WIPP will be of low consequence to the performance of the disposal system in terms of groundwater flow or contaminant transport. Changes in groundwater levels resulting from more distant earthquakes will be too short in duration to be significant. Thus hydrological response to earthquakes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.2.2.5 FEP Number: N32
FEP Title: *Natural Gas Intrusion*

SCR-4.2.2.5.1 Screening decision: SO-P

Changes in groundwater flow arising from *Natural Gas Intrusion* have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.2.2.5.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.2.2.5.2.1 Screening Argument

Hydrocarbon resources are present in formations beneath the WIPP (the CCA, Chapter 2.0, Section 2.3.1.2), and natural gas is extracted from the Morrow Formation. These reserves are, however, some 4,200 m (14,000 ft) below the surface, and no natural events or processes have been identified that could result in natural gas intrusion into the Salado or the units above. Natural gas intrusion has therefore been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.3 Subsurface Geochemical FEPs

SCR-4.3.1 Groundwater Geochemistry

SCR-4.3.1.1 FEP Number: N33
FEP Title: *Groundwater Geochemistry*

SCR-4.3.1.1.1 Screening Decision: UP

Groundwater Geochemistry in the hydrological units of the disposal system is accounted for in PA calculations.

SCR-4.3.1.1.2 Summary of New Information

No new information for this FEP has been identified since the CRA-2004.

SCR-4.3.1.1.3 Screening Argument

The most important aspect of groundwater geochemistry in the region of the WIPP in terms of chemical retardation and colloid stability is salinity. Groundwater geochemistry is discussed in detail in the CCA, Chapter 2.0, Section 2.2 and Section 2.4 and summarized here. The Delaware Mountain Group, Castile, and Salado contain basinal brines. Waters in the Castile and Salado are at or near halite saturation. Above the Salado, groundwaters are also relatively saline, and groundwater quality is poor in all of the permeable units. Waters from the Culebra vary spatially in salinity and chemistry. They range from saline sodium chloride-rich waters to brackish calcium sulfate-rich waters. In addition, a range of magnesium-to-calcium ratios has been observed, and some waters reflect the influence of potash mining activities, having elevated potassium-to-sodium ratios. Waters from the Santa Rosa are generally of better quality than those from the Rustler. Salado and Castile brine geochemistry is accounted for in PA calculations of the actinide (An) source term (the CCA, Chapter 6.0, Section 6.4.3.4). Culebra brine geochemistry is accounted for in the retardation factors used in PA calculations of actinide transport (see the CCA, Chapter 6.0, Section 6.4.6.2).

SCR-4.3.1.2 FEP Numbers: N34 and N38
FEP Titles: *Saline Intrusion* (geochemical effects) (N34)
Effects of Dissolution (N38)

SCR-4.3.1.2.1 Screening Decision: SO-C

The effects of *Saline Intrusion* and *Dissolution* on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.3.1.2.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.3.1.2.3 Screening Argument

Saline intrusion and effects of dissolution are considered together in this discussion because dissolution of minerals such as halite (NaCl), anhydrite ($CaSO_4$), or gypsum ($CaSO_4 \cdot 2H_2O$) (N38) could – in the most extreme case – increase the salinity of groundwaters in the Culebra to levels characteristic of those expected after saline intrusion (N34).

No natural events or processes have been identified that could result in saline intrusion into units above the Salado. Injection of Castile or Salado brines into the Culebra as a result of human intrusion, an anthropogenically induced event, was included in past PA calculations. Laboratory studies carried out to evaluate radionuclide transport in the Culebra following human intrusion produced data that can also be used to evaluate the consequences of natural saline intrusion.

The possibility that dissolution of halite, anhydrite, or gypsum might result in an increase in the salinity of low- to moderate-ionic-strength groundwaters in the Culebra also appears unlikely, despite the presence of halite in the Los Medaños under most of the WIPP site (Siegel and Lambert 1991, Figure 1-13), including the expected Culebra off-site transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra, flow towards the south or south-southeast, and eventually to the boundary of the WIPP site). (The Los Medaños Member of the Rustler, formerly referred to as the unnamed lower member of the Rustler, underlies the Culebra.) A dissolution-induced increase in the salinity of Culebra groundwaters is unlikely because (1) the dissolution of halite is known to be rapid; (2) (moderate-ionic-strength) groundwaters along the off-site transport pathway (and at many other locations in the Culebra) have had sufficient time to dissolve significant quantities of halite, if this mineral is present in the subjacent Los Medaños and if Culebra fluids have been in contact with it; and (3) the lack of high-ionic-strength groundwaters along the off-site transport pathway (and elsewhere in the Culebra) implies that halite is present in the Los Medaños but Culebra fluids have not contacted it, or that halite is not present in the Los Medaños. Because halite dissolves so rapidly if contacted by undersaturated solutions, this conclusion does not depend on the nature and timing of Culebra recharge (i.e., whether the Rustler has been a closed hydrologic system for several thousand to a few tens of thousands of years, or is subject to significant modern recharge).

Nevertheless, saline intrusion would not affect the predicted transport of thorium (Th), uranium (U), plutonium (Pu), and americium (Am) in the Culebra. This is because (1) the laboratory studies that quantified the retardation of Th, U, Pu, and Am for the CCA PA were carried out with both moderate-ionic-strength solutions representative of Culebra groundwaters along the expected off-site transport pathway and high-ionic-strength solutions representative of brines from the Castile and the Salado (Brush 1996; Brush and Storz 1996); and (2) the results obtained with the Castile and Salado brines were – for the most part – used to predict the transport of Pu(III) and Am(III); Th(IV), U(IV), Np(IV), and Pu(IV); and U(VI). The results obtained with the saline solutions were used for these actinide oxidation states because the extent to which saline and Culebra brines will mix along the offsite transport pathway in the Culebra was unclear at the time of the CCA PA; therefore, Brush (1996) and Brush and Storz (1996) recommended that PA use the results that predict less retardation. In the case of Pu(III) and Am(III); Th(IV), U(IV), Np(IV), and Pu(IV); and U(VI), the retardation distribution coefficient (K_ds) obtained with the saline solutions were somewhat lower than those obtained with the Culebra fluids. The

K_ds recommended by Brush and Storz (1996) are being used for the CRA-2009 PA. These K_ds are also based mainly on results obtained with saline solutions.

Finally, it is important to reiterate that the use of results from laboratory studies with saline solutions to predict radionuclide transport in the Culebra for previous PAs and the CRA-2009 PA implement the effects of saline intrusion caused by human intrusion, not natural saline intrusion. The conclusions that natural saline intrusion is unlikely, that significant dissolution is unlikely, and that these events or processes would have no significant consequence – in the unlikely event that they occur – continue to be valid.

SCR-4.3.1.3 FEP Numbers: N35, N36, and N37
FEP Titles: *Freshwater Intrusion* (Geochemical Effects) (N35)
Change in Groundwater Eh (N36)
Changes in Groundwater pH (N37)

SCR-4.3.1.3.1 Screening Decision: SO-C

The effects of *Freshwater Intrusion* on groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. *Changes in Groundwater Eh* and *Changes in Groundwater pH* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.3.1.3.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.3.1.3.3 Screening Argument

Natural changes in the groundwater chemistry of the Culebra and other units that resulted from saline intrusion or freshwater intrusion could potentially affect chemical retardation and the stability of colloids. Changes in groundwater Eh and groundwater pH could also affect the migration of radionuclides (see FEPs W65 to W70, Section SCR-6.5.5.2, Section SCR-6.5.5.3, Section SCR-6.5.6.1, and Section SCR-6.5.6.2). No natural EPs have been identified that could result in saline intrusion into units above the Salado, and the magnitude of any natural temporal variation from the effects of dissolution on groundwater chemistry, or because of changes in recharge, is likely to be no greater than the present spatial variation. These FEPs related to the effects of future natural changes in groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The most likely mechanism for (natural) freshwater intrusion into the Culebra (N35), changes in groundwater Eh (N36), and changes in groundwater pH (N37) is (natural) recharge of the Culebra. (Other FEPs consider possible anthropogenically induced recharge). These three FEPs are closely related because an increase in the rate of recharge could reduce the ionic strength(s) of Culebra groundwaters, possibly enough to saturate the Culebra with (essentially) fresh water, at least temporarily. Such a change in ionic strength could, if enough atmospheric oxygen remained in solution, also increase the Eh of Culebra groundwaters enough to oxidize Pu from the relatively immobile III and IV oxidation states (Pu(III) and Pu(IV)) – the oxidation states

expected under current conditions (Brush 1996; Brush and Storz 1996) – to the relatively mobile V and VI oxidation states (Pu(V) and Pu(VI)). Similarly, recharge of the Culebra with freshwater could also change the pH of Culebra groundwaters from the currently observed range of about 6 to 7 to mildly acidic values, thus (possibly) decreasing the retardation of dissolved Pu and Am. (These changes in ionic strength, Eh, and pH could also affect mobilities of Th, U, and neptunium (Np), but the long-term performance of the WIPP is much less sensitive to the mobilities of these radioelements than to those of Pu and Am.)

There is still considerable uncertainty regarding the extent and timing of recharge to the Culebra. Lambert (1986), Lambert and Carter (1987), and Lambert and Harvey (1987)) used a variety of stable and radiogenic isotopic-dating techniques to conclude that the Rustler (and the Dewey Lake) have been closed hydrologic systems for several thousand to a few tens of thousands of years. In other words, the last significant recharge of the Rustler occurred during the late Pleistocene in response to higher levels of precipitation and infiltration associated with the most recent continental glaciation of North America, and the current flow field in the Culebra is the result of the slow discharge of groundwater from this unit. Other investigators have agreed that it is possible that Pleistocene recharge has contributed to present-day flow patterns in the Culebra, but that current patterns are also consistent with significant current recharge (Haug et al. 1987; Davies 1989). Still others (Chapman 1986, 1988) have rejected Lambert's interpretations in favor of exclusively modern recharge, at least in some areas. For example, the low salinity of Hydrochemical Zone B south of the WIPP site could represent dilution of Culebra groundwater with significant quantities of recently introduced meteoric water (see Siegel et al. 1991, pp. 2-57–2-62 and Figure 2-17 for definitions and locations of the four hydrochemical facies in the Culebra in and around the WIPP site).

The current program to explain the cause(s) of the rising water levels observed in Culebra monitoring wells may elucidate the nature and timing of recharge. However, the justification of this screening decision does not depend on how this issue is resolved. If recharge occurs mainly during periods of high precipitation (pluvials) associated with periods of continental glaciation, the consequences of such recharge are probably already reflected in the ranges of geochemical conditions currently observed in the Culebra as a whole, as well as along the likely offsite transport pathway (the direction of flow from the point(s) at which brines from the repository would enter the Culebra in the event of human intrusion to the south or south-southeast and eventually to the boundary of the WIPP site). Hence, the effects of recharge, (possible) freshwater intrusion, and (possible) concomitant changes in groundwater Eh and pH can be screened out on the basis of low consequence to the performance of the far-field barrier. The reasons for the conclusion that the effects of pluvial recharge are inconsequential (i.e., are already included among existing variations in geochemical conditions) are (1) as many as 50 continental glaciations and associated pluvials have occurred since the late Pliocene Epoch 2.5 million years ago (2.5 Ma BP); (2) the glaciations and pluvials that have occurred since about 0.5 to 1 Ma BP have been significantly more severe than those that occurred prior to 1 Ma BP (see, for example, Servant 2001); (3) the studies that quantified the retardation of Th, U, Pu, and Am for the CCA PA calculations and the CCA Performance Assessment Verification Test (PAVT) were carried out under conditions that encompass those observed along the likely Culebra off-site transport pathway (Brush 1996; Brush and Storz 1996); and (4) these studies demonstrated that conditions in the Culebra are favorable for retardation of actinides despite the effects of as many as 50 periods of recharge.

It is also worth noting that the choice of the most recent glacial maximum as an upper limit for possible climatic changes during the 10,000-year (yr) WIPP regulatory period (Swift 1991; the CCA, Appendix CLI) established conservative upper limits for precipitation and recharge of the Culebra at the WIPP site. The review by Swift (1991), later incorporated in the CCA, Appendix CLI, provides evidence that precipitation in New Mexico did not attain its maximum level (about 60-100% of current precipitation) until a few thousand years before the last glacial maximum. Swift (1991) pointed out,

> Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid- Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise that are now restricted to warmer climates, suggests warm summers and mild, relatively dry winters (Harris 1987, 1988). Lacustrine evidence confirms the interpretation that conditions prior to and during the glacial advance that were generally drier than those at the glacial maximum. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber 1989). Late-Pleistocene lake levels in the San Agustin Plains in western New Mexico remained low until approximately 26.4 ka BP, and the $\delta^{18}O$ record from ostracode shells suggests that mean annual temperatures at that location did not decrease significantly until approximately 22 ka BP (Phillips et al. 1992).

Therefore, it is likely that precipitation and recharge did not attain levels characteristic of the most recent glacial maximum until about 70,000 to 75,000 years after the last glaciations had begun. High-resolution, deep-sea $\delta^{18}O$ data (and other data) reviewed by Servant (2001, Figure 1 and Figure 2) support the conclusion that, although the volume of ice incorporated in continental ice sheets can expand rapidly at the start of a glaciation, attainment of maximum volume does not occur until a few thousand or a few tens of thousands of years prior to the termination of the approximately 100,000-yr glaciations that have occurred during the last 0.5 to 1 Ma BP. Therefore, it is unlikely that precipitation and recharge will reach their maximum levels during the 10,000-yr regulatory period.

If, on the other hand, significant recharge occurs throughout both phases of the glacial-interglacial cycles, the conclusion that the effects of pluvial and modern recharge are inconsequential (i.e., are already reflected by existing variations in geochemical conditions) is also still valid. The effects of future natural changes in groundwater chemistry have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4 Geomorphological FEPs

SCR-4.4.1 Physiography

SCR-4.4.1.1 FEP Number: N39
FEP Title: *Physiography*

SCR-4.4.1.1.1 Screening Decision: UP

Relevant aspects of the *Physiography*, geomorphology, and topography of the region around the WIPP are accounted for in PA calculations.

SCR-4.4.1.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.4.1.1.3 Screening Argument

Physiography and geomorphology are discussed in detail in the CCA, Chapter 2.0, Section 2.1.4, and are accounted for in the setup of the PA calculations (the CCA, Chapter 6.0, Section 6.4.2).

SCR-4.4.1.2 FEP Number: N40
FEP Title: *Impact of a Large Meteorite*

SCR-4.4.1.2.1 Screening Decision: SO-P

Disruption arising from the *Impact of a Large Meteorite* has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.4.1.3 Summary of New Information

This FEP has been modified to correct errors discovered in Equations (SCR.5) and (SCR.6). As a result of these error corrections, it is necessary to select an upper bound on the distribution of meteorite sizes; Ceres, the largest known asteroid, has been used to determine the upper bound.

SCR-4.4.1.4 Screening Argument

Meteors frequently enter the earth's atmosphere, but most of these are small and burn up before reaching the ground. Of those that reach the ground, most produce only small impact craters that would have no effect on the postclosure integrity of a repository 650 m (2,150 ft) below the ground surface. While the depth of a crater may be only one-eighth of its diameter, the depth of the disrupted and brecciated material is typically one-third of the overall crater diameter (Grieve 1987, p. 248). Direct disruption of waste at the WIPP would only occur with a crater larger than 1.8 km (1.1 mi) in diameter. Even if waste were not directly disrupted, the impact of a large meteorite could create a zone of fractured rocks beneath and around the crater. The extent of such a zone would depend on the rock type. For sedimentary rocks, the zone may extend to a depth of half the crater diameter or more (Dence et al. 1977, p. 263). The impact of a meteorite causing a crater larger than 1 km (0.6 mi) in diameter could thus fracture the Salado above the repository.

Geological evidence for meteorite impacts on earth is rare because many meteorites fall into the oceans and erosion and sedimentation serve to obscure craters that form on land. Dietz (1961) estimated that meteorites that cause craters larger than 1 km (0.6 mi) in diameter strike the earth at the rate of about one every 10,000 years (equivalent to about 2×10^{-13} impacts per square kilometer per year). Using observations from the Canadian Shield, Hartmann (1965, p. 161) estimated a frequency of between 0.8×10^{-13} and 17×10^{-13} impacts/km^2/yr for impacts causing craters larger than 1 km (0.6 mi). Frequencies estimated for larger impacts in studies reported by Grieve (1987, p. 263) can be extrapolated to give a rate of about 1.3×10^{-12} impacts/km^2/yr for craters larger than 1 km (0.6 mi). It is commonly assumed that meteorite impacts are randomly

distributed across the earth's surface, although Halliday (1964, pp. 267-277) calculated that the rate of impact in polar regions would be some 50 to 60 percent of that in equatorial regions. The frequencies reported by Grieve (1987) would correspond to an overall rate of about 1 per 1,000 years on the basis of a random distribution.

Assuming the higher estimated impact rate of 17×10^{-13} impacts per square kilometer per year for impacts leading to fracturing of sufficient extent to affect a deep repository, and assuming a repository footprint of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) for the WIPP, yields a frequency of about 4×10^{-12} impacts per year for a direct hit above the repository. This impact frequency is several orders of magnitude below the screening threshold of 10^{-4} per 10,000 years provided in 40 CFR § 194.32(d).

Meteorite hits directly above the repository footprint are not the only impacts of concern, however, because large craters may disrupt the waste panels even if the center of the crater is outside the repository area. It is possible to calculate the frequency of meteorite impacts that could disrupt a deep repository such as the WIPP by using the conservative model of a cylinder of rock fractured to a depth equal to one-half the crater diameter, as shown in the CCA, Appendix SCR, Figure SCR-1. The area within which a meteorite could impact the repository is calculated by

$$S_D = \left(L + 2 \times \frac{D}{2}\right) \times \left(W + 2 \times \frac{D}{2}\right), \qquad \text{(SCR.1)}$$

where

L = length of the repository footprint (km)
W = width of the repository footprint (km)
D = diameter of the impact crater (km)
S_D = area of the region where the crater would disrupt the repository (km^2)

There are insufficient data on meteorites that have struck the earth to derive a distribution function for the size of craters directly. Using meteorite impacts on the moon as an analogy, however, Grieve (1987, p. 257) derived the following distribution function:

$$F_D \propto D^{-1.8} \qquad \text{(SCR.2)}$$

where

F_D = frequency of impacts resulting in craters larger than D (impacts/km^2/yr).

If $f(D)$ denotes the frequency of impacts giving craters of diameter D, then the frequency of impacts giving craters larger than D is

$$F_D = \int_D^{\infty} f(D)\, d\, D \qquad \text{(SCR.3)}$$

and

$$f(D) = F_1 \times 1.8 \times D^{-2.8}, \quad \text{(SCR.4)}$$

where

F_1 = frequency of impacts resulting in craters larger than 1 km (impacts/km^2/yr)
$f(D)$ = frequency of impacts resulting in craters of diameter D ((impacts/km^2/yr)

The overall frequency of meteorite impacts, in the size range of interest, that could disrupt or fracture the repository is thus given by

$$N = \int_{2h}^{M} f(D) \times S_D dD, \quad \text{(SCR.5)}$$

where

h = depth to repository (kilometers),
M = maximum size of meteorite considered (kilometers)
N = frequency of impacts leading to disruption of the repository (impacts per year), and

$$N = 1.8F_1 \left[\frac{(M)^{0.2} - (2h)^{0.2}}{0.2} - LW \frac{(M)^{-1.8} - (2h)^{-1.8}}{1.8} - (L+W) \frac{(M)^{-0.8} - (2h)^{-0.8}}{0.8} \right]. \quad \text{(SCR.6)}$$

Conservatively using the size (933 km [550 mi]) of the largest known asteroid, Ceres (Tedesco 1992), for the maximum size considered and if it is assumed that the repository is located at a depth of 650 m (2,150 ft) and has a footprint area of 1.4 km × 1.6 km (0.9 mi × 1.0 mi) and that meteorites creating craters larger than 1 km in diameter hit the earth at a frequency (F_1) of 17×10^{-13} impacts/km^2/yr, then Equation (SCR.6) gives a frequency of approximately 5.6×10^{-11} impacts per year for impacts disrupting the repository. If impacts are randomly distributed over time, this corresponds to a probability of 5.6×10^{-7} over 10,000 years.

Similar calculations have been performed that indicate rates of impact of between 10^{-12} and 10^{-13} per year for meteorites large enough to disrupt a deep repository (see, for example, Hartmann 1979, Kärnbränslesakerhet 1978, Claiborne and Gera 1974, Cranwell et al. 1990, and Thorne 1992). Meteorite impact can thus be eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

Assuming a random or nearly random distribution of meteorite impacts, cratering at any location is inevitable given sufficient time. Although repository depth and host-rock lithology may reduce the consequences of a meteorite impact, there are no repository locations or engineered systems that can reduce the probability of impact over 10,000 years.

SCR-4.4.1.5 FEP Number: N41 and N42
FEP Titles: *Mechanical Weathering* (N41)
Chemical Weathering (N42)

SCR-4.4.1.5.1 Screening Decision: SO-C

The effects of *Chemical Weathering* and *Mechanical Weathering* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.5.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.4.1.5.3 Screening Argument

Mechanical weathering and chemical weathering are assumed to be occurring at or near the surface around the WIPP site through processes such as exfoliation and leaching. The extent of these processes is limited and they will contribute little to the overall rate of erosion in the area or to the availability of material for other erosional processes. The effects of chemical weathering and mechanical weathering have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.6 FEP Numbers: N43, N44, and N45
FEP Titles: *Aeolian Erosion* (N43)
Fluvial Erosion (N44)
Mass Wasting (N45)

SCR-4.4.1.6.1 Screening Decision: SO-C

The effects of *Fluvial Erosion*, *Aeolian Erosion*, and *Mass Wasting* in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.6.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.4.1.6.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes. Dunes are present in the area, and although some are stabilized by vegetation, aeolian erosion will occur as they migrate across the area. Old dunes will be replaced by new dunes, and no significant changes in the overall thickness of aeolian material are likely to occur.

Currently, precipitation in the region of the WIPP is too low (about 33 centimeters [cm] [13 inches (in.)] per year) to cause perennial streams, and the relief in the area is too low for

extensive sheet flood erosion during storms. An increase in precipitation to around 61 cm (24 in.) per year in cooler climatic conditions could result in perennial streams, but the nature of the relief and the presence of dissolution hollows and sinks will ensure that these streams remain small. Significant fluvial erosion is not expected during the next 10,000 years.

Mass wasting (the downslope movement of material caused by the direct effect of gravity) is important only in terms of sediment erosion in regions of steep slopes. In the vicinity of the WIPP, mass wasting will be insignificant under the climatic conditions expected over the next 10,000 years.

Erosion from wind, water, and mass wasting will continue in the WIPP region throughout the next 10,000 years at rates similar to those occurring at present. These rates are too low to affect the performance of the disposal system significantly. Thus the effects of fluvial erosion, aeolian erosion, and mass wasting have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.7 FEP Number: N50
FEP Title: *Soil Development*

SCR-4.4.1.7.1 Screening Decision: SO-C

Soil Development has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.4.1.7.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.4.1.7.3 Screening Argument

The Mescalero caliche is a well-developed calcareous remnant of an extensive soil profile across the WIPP site and adjacent areas. Although this unit may be up to 3 m (10 ft) thick, it is not continuous and does not prevent infiltration to the underlying formations. At Nash Draw, this caliche, dated in Lappin et al. (1989, pp. 2-4) at 410,000 to 510,000 years old, is present in collapse blocks, indicating some growth of Nash Draw in the late Pleistocene. Localized gypsite spring deposits about 25,000 years old occur along the eastern flank of Nash Draw, but the springs are not currently active. The Berino soil, interpreted as 333,000 years old (Rosholt and McKinney 1980, Table 5), is a thin soil horizon above the Mescalero caliche. The persistence of these soils on the Livingston Ridge and the lack of deformation indicates the relative stability of the WIPP region over the past half-million years.

Continued growth of caliche may occur in the future but will be of low consequence in terms of its effect on infiltration. Other soils in the area are not extensive enough to affect the amount of infiltration that reaches underlying aquifers. Soil development has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5 Surface Hydrological FEPs

SCR-4.5.1 Depositional Processes

SCR-4.5.1.1 FEP Numbers: N46, N47, N48, and N49
FEP Titles: *Aeolian Deposition* (N46)
Fluvial Deposition (47)
Lacustrine Deposition (N48)
Mass Waste (Deposition) (N49)

SCR-4.5.1.1.1 Screening Decision: SO-C

The effects of *Aeolian Deposition*, *Fluvial Deposition*, and *Lacustrine Deposition* and sedimentation in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.1.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.5.1.1.3 Screening Argument

The geomorphological regime on the Mescalero Plain (Los Medaños) in the region of the WIPP is dominated by aeolian processes, but although some dunes are stabilized by vegetation, no significant changes in the overall thickness of aeolian material are expected to occur. Vegetational changes during periods of wetter climate may further stabilize the dune fields, but aeolian deposition is not expected to significantly increase the overall thickness of the superficial deposits.

The limited extent of water courses in the region of the WIPP, under both present-day conditions and under the expected climatic conditions, will restrict the amount of fluvial deposition and lacustrine deposition in the region.

Mass wasting (deposition) may be significant if it results in dams or modifies streams. In the region around the WIPP, the Pecos River forms a significant water course some 19 km (12 mi) away, but the broadness of its valley precludes either significant mass wasting or the formation of large impoundments.

Sedimentation from wind, water, and mass wasting is expected to continue in the WIPP region throughout the next 10,000 years at the low rates similar to those occurring at present. These rates are too low to significantly affect the performance of the disposal system. Thus the effects of aeolian deposition, fluvial deposition, and lacustrine deposition and sedimentation resulting from mass wasting have been eliminated from PA calculations on the basis of low consequence.

SCR-4.5.2 Streams and Lakes

SCR-4.5.2.1 FEPs Number: N51
FEPs Title: *Stream and River Flow*

SCR-4.5.2.1.1 Screening Decision: SO-C

Stream and River Flow has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.2.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.5.2.1.3 Screening Argument

No perennial streams are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location since the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). The Pecos River is approximately 19 km (12 mi) from the WIPP site and more than 90 m (300 ft) lower in elevation. Stream and river flow has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.2.2 FEP Number: N52
FEP Title: *Surface Water Bodies*

SCR-4.5.2.2.1 Screening Decision: SO-C

The effects of *Surface Water Bodies* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.2.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.5.2.2.3 Screening Argument

No standing surface water bodies are present at the WIPP site, and there is no evidence in the literature indicating that such features existed at this location during or after the Pleistocene (see, for example, Powers et al. 1978; and Bachman 1974, 1981, and 1987b). In Nash Draw, lakes and spoil ponds associated with potash mines are located at elevations 30 m (100 ft) below the elevation of the land surface at the location of the waste panels. There is no evidence in the literature to suggest that Nash Draw was formed by stream erosion or was at any time the location of a deep body of standing water, although shallow playa lakes have existed there at various times. Based on these factors, the formation of large lakes is unlikely and the formation of smaller lakes and ponds is of little consequence to the performance of the disposal system.

The effects of surface water bodies have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.3 Groundwater Recharge and Discharge

SCR-4.5.3.1 FEP Numbers: N53, N54, and N55
FEP Titles: *Groundwater Discharge* (N53)
Groundwater Recharge (N54)
Infiltration (N55)

SCR-4.5.3.1.1 Screening Decision: UP

Groundwater Recharge, *Groundwater Discharge*, and *Infiltration* are accounted for in PA calculations.

SCR-4.5.3.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.5.3.1.3 Screening Argument

The groundwater basin described in the CCA, Chapter 2.0, Section 2.2.1.4 is governed by flow from areas where the water table is high to areas where the water table is low. The height of the water table is governed by the amount of groundwater recharge reaching the water table, which in turn is a function of the vertical hydraulic conductivity and the partitioning of precipitation between evapotranspiration, runoff, and Infiltration. Flow within the Rustler is also governed by the amount of groundwater discharge that takes place from the basin. In the region around the WIPP, the principal discharge areas are along Nash Draw and the Pecos River. Groundwater flow modeling accounts for infiltration, recharge, and discharge (the CCA, Chapter 2.0, Section 2.2.1.4 and Chapter 6.0, Section 6.4.10.2).

SCR-4.5.3.2 FEP Number: N56
FEP Title: *Changes in Groundwater Recharge and Discharge*

SCR-4.5.3.2.1 Screening Decision: UP

Changes in Groundwater Recharge and Discharge arising as a result of climate change are accounted for in PA calculations.

SCR-4.5.3.2.2 Summary of New Information

No new information has become available that would change the screening decision for this FEP.

SCR-4.5.3.2.3 Screening Argument

Changes in recharge may affect groundwater flow and radionuclide transport in units such as the Culebra and Magenta dolomites. Changes in the surface environment driven by natural climate

change are expected to occur over the next 10,000 years (see FEPs N59 to N63). Groundwater basin modeling (the CCA, Chapter 2.0, Section 2.2.1.4) indicates that a change in recharge will affect the height of the water table in the area of the WIPP, and that this will in turn affect the direction and rate of groundwater flow.

The present-day water table in the vicinity of the WIPP is within the Dewey Lake at about 980 m (3,215 ft) above mean sea level (the CCA, Chapter 2.0, Section 2.2.1.4.2.1). An increase in recharge relative to present-day conditions would raise the water table, potentially as far as the local ground surface. Similarly, a decrease in recharge could result in a lowering of the water table. The low transmissivity of the Dewey Lake and the Rustler ensures that any such lowering of the water table will be at a slow rate, and lateral discharge from the groundwater basin is expected to persist for several thousand years after any decrease in recharge. Under the anticipated changes in climate over the next 10,000 years, the water table will not fall below the base of the Dewey Lake, and dewatering of the Culebra is not expected to occur during this period (the CCA, Chapter 2.0, Section 2.2.1.4).

Changes in groundwater recharge and discharge is accounted for in PA calculations through definition of the boundary conditions for flow and transport in the Culebra (the CCA, Chapter 6.0, Section 6.4.9).

SCR-4.5.3.3 FEP Numbers: N57 and N58
FEP Titles: *Lake Formation* (N57)
River Flooding (N58)

SCR-4.5.3.3.1 Screening Decision: SO-C

The effects of *River Flooding* and *Lake Formation* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.5.3.3.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.5.3.3.3 Screening Argument

Intermittent flooding of stream channels and the formation of shallow lakes will occur in the WIPP region over the next 10,000 years. These may have a short-lived and local effect on the height of the water table, but are unlikely to affect groundwater flow in the Culebra.

Future occurrences of playa lakes or other longer-term floods will be remote from the WIPP and will have little consequence on system performance in terms of groundwater flow at the site. There is no reason to believe that any impoundments or lakes could form over the WIPP site itself. Thus river flooding and lake formation have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.6 Climate EPs

SCR-4.6.1 Climate and Climate Changes

SCR-4.6.1.1 FEP Numbers: N59 and N60
FEP Titles: *Precipitation* (N59)
Temperature (N60)

SCR-4.6.1.1.1 Screening Decision: UP

Precipitation and *Temperature* are accounted for in PA calculations.

SCR-4.6.1.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.6.1.1.3 Screening Argument

The climate and meteorology of the region around the WIPP are described in the CCA, Section 2.5.2. Precipitation in the region is low (about 33 cm [13 in.] per yr) and temperatures are moderate with a mean annual temperature of about 63 °F (17 °C). Precipitation and temperature are important controls on the amount of recharge that reaches the groundwater system and are accounted for in PA calculations by use of a sampled parameter for scaling flow velocity in the Culebra (see Appendix PA-2009, Section PA-2.1.4.6).

SCR-4.6.1.2 FEP Number: N61
FEP Title: *Climate Change*

SCR-4.6.1.2.1 Screening Decision: UP

Climate Change is accounted for in PA calculations.

SCR-4.6.1.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.6.1.2.3 Screening Argument

Climate changes are instigated by changes in the earth's orbit and by feedback mechanisms within the atmosphere and hydrosphere. Models of these mechanisms, combined with interpretations of the geological record, suggest that the climate will become cooler and wetter in the WIPP region during the next 10,000 years as a result of natural causes. Other changes, such as fluctuations in radiation intensity from the sun and variability within the many feedback mechanisms, will modify this climatic response to orbital changes. The available evidence suggests that these changes will be less extreme than those arising from orbital fluctuations.

The effect of a change to cooler and wetter conditions is considered to be an increase in the amount of recharge, which in turn will affect the height of the water table (see FEPs N53 through N56, Section SCR-4.5.3.1 and SCR-4.5.3.2). The height of the water table across the groundwater basin is an important control on the rate and direction of groundwater flow within the Culebra (see the CCA, Chapter 2.0, Section 2.2.1.4), and hence potentially on transport of radionuclides released to the Culebra through the shafts or intrusion boreholes. Climate change is accounted for in PA calculations through a sampled parameter used to scale groundwater flow velocity in the Culebra (see Appendix PA-2009, Section PA-4.8).

SCR-4.6.1.3 FEP Numbers: N62 and N63
FEP Titles: *Glaciation* (N62)
Permafrost (N63)

SCR-4.6.1.3.1 Screening Decision: SO-P

Glaciation and the effects of *Permafrost* have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-4.6.1.3.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.6.1.3.3 Screening Argument

No evidence exists to suggest that the northern part of the Delaware Basin has been covered by continental glaciers at any time since the beginning of the Paleozoic Era. During the maximum extent of continental glaciation in the Pleistocene Epoch, glaciers extended into northeastern Kansas at their closest approach to southeastern New Mexico. There is no evidence that alpine glaciers formed in the region of the WIPP during the Pleistocene glacial periods.

According to the theory that relates the periodicity of climate change to perturbations in the earth's orbit, a return to a full glacial cycle within the next 10,000 years is highly unlikely (Imbrie and Imbrie 1980, p. 951).

Thus glaciation has been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years. Similarly, a number of processes associated with the proximity of an ice sheet or valley glacier, such as permafrost and accelerated slope erosion (solifluction) have been eliminated from PA calculations on the basis of low probability of occurrence over the next 10,000 years.

SCR-4.7 Marine FEPs

SCR-4.7.1 Seas, Sedimentation, and Level Changes

SCR-4.7.1.1 FEP Numbers: N64 and N65
FEP Titles: *Seas and Oceans* (N64)
Estuaries (N65)

SCR-4.7.1.1.1 Screening Decision: SO-C

The effects of *Estuaries* and *Seas and Oceans* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.7.1.1.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and from the Gulf of Mexico. Estuaries and seas and oceans have therefore been eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-4.7.1.2 FEPs Numbers: N66 and N67
FEPs Titles: *Coastal Erosion* (N66)
Marine Sediment Transport and Deposition (N67)

SCR-4.7.1.2.1 Screening Decision: SO-C

Coastal Erosion and *Marine Sediment Transport and Deposition* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.2.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.7.1.2.3 Screening Argument

The WIPP site is more than 800 km (480 mi) from the Pacific Ocean and Gulf of Mexico. The effects of coastal erosion and marine sediment transport and deposition have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.3 FEP Number: N68
FEP Title: *Sea Level Changes*

SCR-4.7.1.3.1 Screening Decision: SO-C

The effects of both short-term and long-term *Sea Level Changes* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.7.1.3.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.7.1.3.3 Screening Argument

The WIPP site is some 1,036 m (3,400 ft) above sea level. Global sea level changes may result in sea levels as much as 140 m (460 ft) below that of the present day during glacial periods, according to Chappell and Shackleton (1986, p. 138). This can have marked effects on coastal aquifers. During the next 10,000 years, the global sea level can be expected to drop towards this glacial minimum, but this will not affect the groundwater system in the vicinity of the WIPP. Short-term changes in sea level, brought about by events such as meteorite impact, tsunamis, seiches, and hurricanes may raise water levels by several tens of meters. Such events have a maximum duration of a few days and will have no effect on the surface or groundwater systems at the WIPP site. Anthropogenic-induced global warming has been conjectured by Warrick and Oerlemans (1990, p. 278) to result in longer-term sea level rise. The magnitude of this rise, however, is not expected to be more than a few meters, and such a variation will have no effect on the groundwater system in the WIPP region. Thus the effects of both short-term and long-term sea level changes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8 Ecological FEPs

SCR-4.8.1 Flora and Fauna

SCR-4.8.1.1 FEP Numbers: N69 and N70
FEP Titles: *Plants* (N69)
Animals (N70)

SCR-4.8.1.1.1 Screening Decision: SO-C

The effects of the natural *Plants* and *Animals* (flora and fauna) in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-4.8.1.1.3 Screening Argument

The terrestrial and aquatic ecology of the region around the WIPP is described in the CCA, Chapter 2.0, Section 2.4.1. The plants in the region are predominantly shrubs and grasses. The most conspicuous animals in the area are jackrabbits and cottontail rabbits. The effects of this flora and fauna in the region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.2 FEP Number: N71
FEP Title: *Microbes*

SCR-4.8.1.2.1 Screening Decision: SO-C *UP for colloidal effects and gas generation*

The effects of *Microbes* on the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.2.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.8.1.2.3 Screening Argument

Microbes are presumed to be present with the thin soil horizons. Gillow et al. (2000) characterized the microbial distribution in Culebra groundwater at the WIPP site. Culebra groundwater contained $1.51 \pm 1.08 \times 10^5$ cells/milliliter (mL). The dimension of the cells are 0.75 micrometer (μm) in length and 0.58 μm in width, right at the upper limit of colloidal particle size. Gillow et al. (2000) also found that at pH 5.0, Culebra denitrifier CDn ($0.90 \pm 0.02 \times 10^8$ cells/mL) removed 32% of the U added to sorption experiments, which is equivalent to 180 ± 10 milligrams U/g of dry cells. Another isolate from the WIPP (Halomonas sp.) ($3.55 \pm 0.11 \times 10^8$ cells/mL) sorbed 79% of the added U. Because of their large sizes, microbial cells as colloidal particles will be rapidly filtered out in the Culebra formation. Therefore, the original FEP screening decision that microbes in groundwater have an insignificant impact on radionuclide transport in the Culebra formation remains valid. A similar conclusion has also been arrived at for Swedish repository environments (Pedersen 1999).

SCR-4.8.1.3 FEP Number: N72
FEP Title: *Natural Ecological Development*

SCR-4.8.1.3.1 Screening Decision: SO-C

The effects of *Natural Ecological Development* likely to occur in the region of the WIPP have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-4.8.1.3.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-4.8.1.3.3 Screening Argument

The region around the WIPP is sparsely vegetated as a result of the climate and poor soil quality. Wetter periods are expected during the regulatory period, but botanical records indicate that, even under these conditions, dense vegetation will not be present in the region (Swift 1992; see the CCA, Appendix CLI, p. 17). The effects of the indigenous fauna are of low consequence to the performance of the disposal system and no natural events or processes have been identified that would lead to a change in this fauna that would be of consequence to system performance. Natural ecological development in the region of the WIPP has therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.0 Screening of Human-Induced EPs

The following section presents screening arguments and decisions for human-induced EPs. Table SCR-2 provides summary information regarding changes to human-induced EPs since the CCA. Of the 58 human-induced EPs listed in the CRA-2004, 46 remain unchanged, 8 were updated with new information or were edited for clarity and completeness, 1 screening decision has been changed, and 3 EPs were split into 6 similar but more descriptive FEPs. Thus, for the CRA-2009, there are now 61 human-induced EPs in the FEPs baseline.

SCR-5.1 Human-Induced Geological EPs

SCR-5.1.1 Drilling

SCR-5.1.1.1 FEP Numbers: H1, H2, H4, H8, and H9
FEP Titles: *Oil and Gas Exploration* (H1)
Potash Exploration (H2)
Oil and Gas Exploitation (H4)
Other Resources (drilling for) (H8)
Enhanced Oil and Gas Recovery (drilling for) (H9)

SCR-5.1.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

The effects of historical, current, and near-future drilling associated with *Oil and Gas Exploration*, *Potash Exploration*, *Oil and Gas Exploitation*, *Drilling for Other Resources*, and *Drilling for Enhanced Oil and Gas Recovery* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system (see screening discussion for H21, H22, and H23). Oil and gas exploration, potash exploration, oil and gas exploitation, drilling for other resources, and enhanced oil and gas recovery in the future is accounted for in DP scenarios through incorporation of the rate of future drilling as specified in section 194.33.

SCR-5.1.1.1.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-5.1.1.1.3 Historical, Current, and Near-Future Human EPs

Resource exploration and exploitation are the most common reasons for drilling in the Delaware Basin and are the most likely reasons for drilling in the near future. The WIPP location has been evaluated for the occurrence of natural resources in economic quantities. Powers et al. (1978) (the CCA, Appendix GCR, Chapter 8) investigated the potential for exploitation of potash, hydrocarbons, caliche, gypsum, salt, uranium, sulfur, and lithium. Also, in 1995, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) performed a reevaluation of the mineral resources at and within 1.6 km (1 mi) around the WIPP site (New Mexico Bureau of Mines and Mineral Resources 1995). While some resources do exist at the WIPP site, for the HCN time frames, such drilling is assumed to only occur outside the WIPP site boundary. This

assumption is based on current federal ownership and management of the WIPP during operations, and assumed effectiveness of institutional controls for the 100-yr period immediately following site closure.

Drilling associated with oil and gas exploration and oil and gas exploitation currently takes place in the vicinity of the WIPP. For example, gas is extracted from reservoirs in the Morrow Formation, some 4,200 m (14,000 ft) below the surface, and oil is extracted from shallower units within the Delaware Mountain Group, some 2,150 to 2,450 m (7,000 to 8,000 ft) below the surface.

Potash resources in the vicinity of the WIPP are discussed in the CCA, Chapter 2.0, Section 2.3.1.1. Throughout the Carlsbad Potash District (CPD), commercial quantities of potash are restricted to the McNutt, which forms part of the Salado above the repository horizon. Potash exploration and evaluation boreholes have been drilled within and outside the controlled area. Such drilling will continue outside the WIPP land withdrawal boundary, but no longer occurs within the boundary because rights and controls have been transferred to the DOE. Moreover, drilling for the evaluation of potash resources within the boundary will not occur throughout the time period of active institutional controls (AICs).

Drilling for other resources has taken place within the Delaware Basin. For example, sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. In addition, brine wells have been in operation in and about the Delaware Basin for at least as long. Solution mining processes for sulfur, salt (brine), potash, or any other mineral are not addressed in this FEP; only the drilling of the borehole is addressed here. Resource extraction through solution mining and any potential effects are evaluated in Section SCR-5.2.2.3 (*Solution Mining for Potash* [H58]). Nonetheless, the drilling activity associated with the production of other resources is not notably different than drilling for petroleum exploration and exploitation.

Drilling for the purposes of reservoir stimulation and subsequent enhanced oil and gas recovery does take place within the Delaware Basin, although systematic, planned waterflooding has not taken place near the WIPP. Instead, injection near the WIPP consists of single-point injectors, rather than broad, grid-type waterflood projects (Hall et al. 2008). In the vicinity of the WIPP, fluid injection usually takes place using boreholes initially drilled as producing wells. Therefore, regardless of the initial intent of a deep borehole, whether in search of petroleum reserves or as an injection point, the drilling event and associated processes are virtually the same. These drilling-related processes are addressed more fully in Section SCR-5.2.1.1 (*Drilling Fluid Flow* [H21]), Section SCR-5.2.1.2 (*Drilling Fluid Loss* [H22]), and Section SCR-5.2.1.3 (*Blowouts* [H23]). Discussion on the effects subsequent to drilling a borehole for the purpose of enhancing oil and gas recovery is discussed in Section SCR-5.2.1.6 *(Enhanced Oil and Gas Production [H28]).*

In summary, drilling associated with oil and gas exploration, potash exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling associated with Other Resources has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in FEPs H25 through H36 (Section SCR-5.2.1.5, Section SCR-5.2.1.6,

Section SCR-5.2.1.7, Section SCR-5.2.1.8, Section SCR-5.2.1.9, Section SCR-5.2.1.10, Section SCR-5.2.1.11, Section SCR-5.2.1.12, and Section SCR-5.2.1.13), where low-consequence screening arguments are provided.

SCR-5.1.1.1.4 Future Human EPs

Criteria in section 194.33 require the DOE to examine the historical rate of drilling for resources in the Delaware Basin. Thus consistent with 40 CFR § 194.33(b)(3)(i), the DOE has used the historical record of deep drilling associated with oil and gas exploration, potash exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling associated with other resources (sulfur exploration) in the Delaware Basin in calculations to determine the rate of future deep drilling in the Delaware Basin (see Section 33 of this application).

SCR-5.1.1.2 FEP Numbers: H3 and H5
FEP Titles: *Water Resources Exploration* (H3)
Groundwater Exploitation (H5)

SCR-5.1.1.2.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of HCN and future drilling associated with *Water Resources Exploration* and *Groundwater Exploitation* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Historical shallow drilling associated with *Water Resources Exploration* and *Groundwater Exploitation* is accounted for in calculations to determine the rate of future shallow drilling.

SCR-5.1.1.2.2 Summary of New Information

The Delaware Basin Monitoring Program records and tracks the development of deep and shallow wells within the vicinity of the WIPP. Updated drilling data is reported annually in the Delaware Basin Monitoring Annual Report (U.S. Department of Energy 2007b). While this information has been updated since the last recertification, it does not result in a change in the screening arguments or decisions of these FEPs.

SCR-5.1.1.2.3 Screening Argument

Drilling associated with water resources exploration and groundwater exploitation has taken place and is expected to continue in the Delaware Basin. For the most part, water resources in the vicinity of the WIPP are scarce. Elsewhere in the Delaware Basin, potable water occurs in places while some communities rely solely on groundwater sources for drinking water. Even though water resources exploration and groundwater exploitation occur in the Basin, all such exploration/exploitation is confined to shallow drilling that extends no deeper than the Rustler. Thus it will not impact repository performance because of the limited drilling anticipated in the future and the sizeable thickness of low-permeability Salado salt between the waste panels and the shallow groundwaters. Given the limited groundwater resources and minimal consequence of shallow drilling on performance, the effects of HCN and future drilling associated with water resources exploration and groundwater exploitation have been eliminated from PA calculations

on the basis of low consequence to the performance of the disposal system. The screening argument therefore remains the same as given previously in the CCA.

Although shallow drilling for water resources exploration and groundwater exploitation have been eliminated from PA calculations, the Delaware Basin Drilling Surveillance Program (DBDSP) continues to collect drilling data related to water resources, as well as other shallow drilling activities. As shown in the DBDSP 2007 Annual Report (U.S. Department of Energy 2007b), the total number of shallow water wells in the Delaware Basin is currently 2,296, compared to 2,331 shallow water wells reported in the CCA. This decrease of 35 wells is attributed primarily to the reclassification of water wells to other types of shallow boreholes. Based on these data, the shallow drilling rate for water resources exploration and groundwater exploitation is essentially the same as reported in the CCA. The distribution of groundwater wells in the Delaware Basin was included in the CCA, Appendix USDW, Section USDW.3.

SCR-5.1.1.2.4 Historical, Current, and Near-Future Human EPs

Water is currently extracted from formations above the Salado, as discussed in the CCA, Chapter 2.0, Section 2.3.1.3. The distribution of groundwater wells in the Delaware Basin is included in the CCA, Appendix USDW, Section USDW.3. Water resources exploration and groundwater exploitation are expected to continue in the Delaware Basin.

In summary, drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources has taken place and is expected to continue in the Delaware Basin. The potential effects of existing and possible near-future boreholes on fluid flow and radionuclide transport within the disposal system are discussed in Section SCR-5.2, where low-consequence screening arguments are provided.

SCR-5.1.1.2.5 Future Human EPs

Criteria in section 194.33 require that, to calculate the rates of future shallow and deep drilling in the Delaware Basin, the DOE should examine the historical rate of drilling for resources in the Delaware Basin.

Shallow drilling associated with water, potash, sulfur, oil, and gas extraction has taken place in the Delaware Basin over the past 100 years. However, of these resources, only water and potash are present at shallow depths (less than 655 m (2,150 ft) below the surface) within the controlled area. Thus, consistent with 40 CFR § 194.33(b)(4), the DOE includes drilling associated with water resources exploration, potash exploration, and groundwater exploitation in calculations to determine the rate of future shallow drilling in the Delaware Basin. However, the effects of such events are not included in PA calculations because of low consequence to the performance of the disposal system.

SCR-5.1.1.3 FEP Numbers: H6, H7, H10, H11, and H12
FEP Titles: *Archeological Investigations* (H6)
Geothermal Energy Production (H7)
Liquid Waste Disposal (H10)
Hydrocarbon Storage (H11)
Deliberate Drilling Intrusion (H12)

SCR-5.1.1.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Drilling associated with *Archeological Investigations*, *Geothermal Energy Production*, *Liquid Waste Disposal*, *Hydrocarbon Storage*, and *Deliberate Drilling Intrusion* have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.1.3.2 Summary of New Information

No new information has been identified for these FEPs since the CRA-2004.

SCR-5.1.1.3.3 Screening Argument

SCR-5.1.1.3.3.1 Historic, Current, and Near-Future EPs

No drilling associated with archeology or geothermal energy production has taken place in the Delaware Basin. Consistent with the future states assumptions in 40 CFR § 194.25(a) (U.S. Environmental Protection Agency 1996), such drilling activities have been eliminated from PA calculations on regulatory grounds.

While numerous archeological sites exist at and near the WIPP site, drilling for archeological purposes has not occurred. Archeological investigations have only involved shallow surface disruptions, and do not require deeper investigation by any method, drilling or otherwise. Geothermal energy is not considered to be a potentially exploitable resource because economically attractive geothermal conditions do not exist in the northern Delaware Basin.

Oil and gas production byproducts are disposed of underground in the WIPP region, but such liquid waste disposal does not involve drilling of additional boreholes (see H27, Section SCR-5.2.1.6); therefore drilling of boreholes for the explicit purpose of disposal has not occurred.

Hydrocarbon storage takes place in the Delaware Basin, but it involves gas injection through existing boreholes into depleted reservoirs (see, for example, Burton et al. 1993, pp. 66-67). Therefore, drilling of boreholes for the explicit purpose of hydrocarbon storage has not occurred.

Consistent with section 194.33(b)(1), all near-future Human EPs relating to deliberate drilling intrusion into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.1.3.4 Future Human EPs

Consistent with section 194.33 and the future states assumptions in section 194.25(a), drilling for purposes other than resource recovery (such as WIPP site investigation) and drilling activities that have not taken place in the Delaware Basin over the past 100 years need not be considered in determining future drilling rates. Thus drilling associated with archeological investigations, geothermal energy production, liquid waste disposal, hydrocarbon storage, and deliberate drilling intrusion have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2 Excavation Activities

SCR-5.1.2.1 FEP Number: H13
FEP Title: *Conventional Underground Potash Mining*

SCR-5.1.2.1.1 Screening Decision: UP (HCN)
DP (Future)

As prescribed by section 194.32(b), the effects of HCN and future *Conventional Underground Potash Mining* are accounted for in PA calculations (see also FEP H37).

SCR-5.1.2.1.2 Summary of New Information

No new information has been identified for this FEP since the CRA-2004.

SCR-5.1.2.1.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining (see the CCA, Chapter 2.0, Section 2.3.1). Potash is mined extensively by conventional techniques in the region east of Carlsbad and up to 2.4 km (1.5 mi) from the boundaries of the controlled area of the WIPP. According to existing plans and leases (see the CCA, Chapter 2.0, Section 2.3.1.1), potash mining is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future, although there are no economical reserves above the WIPP waste panels (Griswold and Griswold 1999).

In summary, conventional underground potash mining is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. The potential effects of HCN and future conventional underground potash mining are accounted for in PA calculations as prescribed by section 194.32(b), and as further described in the supplementary information to Part 194 Subpart C, "Compliance Certification and Recertification" and in the Compliance Application Guidance (CAG), Subpart C, § 194.32, Scope of Performance Assessments.

SCR-5.1.2.2 FEP Number: H14
FEP Title: *Other Resources (mining for)*

SCR-5.1.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

HCN *Mining for Other Resources* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Mining for Other Resources* has been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.2.2 Summary of New Information

Since the CCA, no changes in the resources sought via mining have occurred.

SCR-5.1.2.2.3 Screening Argument

Potash is the only known economically viable resource in the vicinity of the WIPP that is recovered by underground mining. Potash is mined extensively in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. According to existing plans and leases, potash mining is expected to continue in the vicinity of the WIPP in the near future. The DOE assumes that all economically recoverable potash in the vicinity of the disposal system will be extracted in the near future. Excavation for resources other than potash and archaeological excavations have taken place or are currently taking place in the Delaware Basin. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations for the HCN timeframe on the basis of low consequence to the performance of the disposal system.

Potash is the only resource that has been identified within the controlled area in a quality similar to that currently mined elsewhere in the Delaware Basin. Future mining for other resources has been eliminated from PA calculations on the regulatory basis of section 194.25(a).

SCR-5.1.2.3 FEP Numbers: H15 and H16
FEP Titles: *Tunneling* (H15)
Construction of Underground Facilities (H16)

SCR-5.1.2.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Consistent with section 194.33(b)(1), near-future, human-induced EPs relating to *Tunneling* into the WIPP excavation and *Construction of Underground Facilities* have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with section 194.25(a), future human-induced EPs relating to *Tunneling* into the WIPP excavation and *Construction of Underground Facilities* have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.3.2 Summary

No new information has been identified for this FEP.

SCR-5.1.2.3.3 Screening Argument

No tunneling or construction of underground facilities (for example, storage, disposal, accommodation [i.e., dwellings]) has taken place in the Delaware Basin. Mining for potash occurs (a form of tunneling), but is addressed specifically in (Section SCR-5.1.2.1 (*Conventional Underground Potash Mining* [H13])). Gas storage does take place in the Delaware Basin, but it involves injection through boreholes into depleted reservoirs, and not excavation (see, for example, Burton et al. 1993, pp. 66–67).

On April 26, 2001, the DOE formally requested approval for the installation of the OMNISita astrophysics experiment in the core storage alcove of the WIPP underground repository. The purpose of the project is to develop a prototype neutrino detector to test proof-of-concept principles and measure background cosmic radiation levels within the WIPP underground repository. EPA approved the request on August 29, 2001. This project does not require additional tunneling or excavation beyond the current repository footprint, and therefore does not impact the screening argument for this FEP.

Because tunneling and construction of underground facilities (other than WIPP) have not taken place in the Delaware Basin, and consistent with the future-states assumptions in section 194.25(a), such excavation activities have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.4 FEP Number: H17
FEP Title: *Archeological Excavations*

SCR-5.1.2.4.1 Screening Decision: SO-C (HCN)
SO-R (Future)

HCN *Archaeological Excavations* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Archaeological Excavations* into the disposal system have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.4.2 Summary of New Information

No new information related to this FEP has been identified.

SCR-5.1.2.4.3 Screening Argument

Archeological excavations have occurred at or near the WIPP, but involved only minor surface disturbances. These archaeological excavations may continue into the foreseeable future as other archeological sites are discovered. These activities have not altered the geology of the controlled area significantly, and have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system for the HCN timeframe.

Also, consistent with section 194.32(a), which limits the scope of consideration of future human actions to mining and drilling, future archaeological excavations have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.5 FEP Number: H18
FEP Title: *Deliberate Mining Intrusion*

SCR-5.1.2.5.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Consistent with section 194.33(b)(1), near-future, human-induced EPs relating to *Deliberate Mining Intrusion* into the WIPP excavation have been eliminated from PA calculations on regulatory grounds. Furthermore, consistent with section 194.33(b)(1), future human-induced EPs relating to *Deliberate Mining Intrusion* into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.2.5.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.1.2.5.3 Screening Argument

Consistent with section 194.33(b)(1), all future human-related EPs relating to deliberate mining intrusion into the WIPP excavation have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3 Subsurface Explosions

SCR-5.1.3.1 FEPs Number: H19
FEP Title: *Explosions for Resource Recovery*

SCR-5.1.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical underground *Explosions for Resource Recovery* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future underground *Explosions for Resource Recovery* have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.1.3.1.3 Screening Argument

This section discusses subsurface explosions associated with resource recovery that may result in pathways for fluid flow between hydraulically conductive horizons. The potential effects of explosions on the hydrological characteristics of the disposal system are discussed in Section SCR-5.2.3.1 (*Changes in Groundwater Flow Due to Explosions* [H39]).

SCR-5.1.3.1.4 Historical, Current, and Near-Future Human EPs

Neither small-scale nor regional-scale explosive techniques to enhance the formation of hydraulic conductivity form a part of current mainstream oil- and gas-production technology. Instead, controlled perforating and hydrofracturing are used to improve the performance of oil and gas boreholes in the Delaware Basin. However, small-scale explosions have been used in the past to fracture oil- and natural-gas-bearing units to enhance resource recovery. The size of explosion used to fracture an oil- or gas-bearing unit is limited by the need to contain the damage within the unit being exploited. In the area surrounding the WIPP, the stratigraphic units with oil and gas resources are too deep for explosions to affect the performance of the disposal system. Thus the effects of explosions for resource recovery have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potash mining is currently taking place and is expected to continue in the vicinity of the WIPP in the near future. Potash is mined extensively in the region east of Carlsbad and up to 2.4 km (1.3 mi) from the boundaries of the controlled area. In earlier years conventional drill, blast, load, and rail-haulage methods were used. Today, continuous miners similar to those used in coal-mining have been adapted to fit the potash-salt formations. Hence, drilling and blasting technology is not used in the present day potash mines. Thus the effects of explosions for resource recovery have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Consistent with section 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, future underground explosions for resource recovery have been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3.2 FEPs Number: H20
FEP Title: *Underground Nuclear Device Testing*

SCR-5.1.3.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Historical *Underground Nuclear Device Testing* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Underground Nuclear Device Testing* has been eliminated from PA calculations on regulatory grounds.

SCR-5.1.3.2.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-5.1.3.2.3 Screening Argument

SCR-5.1.3.2.3.1 Historical, Current, and Near-Future Human EPs
The Delaware Basin has been used for an isolated nuclear test. This test, Project Gnome (Rawson et al. 1965), took place in 1961 at a location approximately 13 km (8 mi) southwest of the WIPP waste disposal region. Project Gnome was decommissioned in 1979.

The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1 kiloton nuclear device at a depth of 360 m (1,190 ft) in the bedded salt of the Salado. The explosion created an approximately spherical cavity of about 27,000 cubic meters (m^3) (950,000 cubic feet [ft^3]) and caused surface displacements in a radius of 360 m (1,180 ft). No earth tremors perceptible to humans were reported at distances over 40 km (25 mi) from the explosion. A zone of increased permeability was observed to extend at least 46 m (150 ft) laterally from and 105 m (344 ft) above the point of the explosion. The test had no significant effects on the geological characteristics of the WIPP disposal system. Thus historical underground nuclear device testing has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. There are no existing plans for underground nuclear device testing in the vicinity of the WIPP in the near future.

SCR-5.1.3.2.3.2 Future Human EPs

The criterion in section 194.32(a) relating to the scope of PAs limits the consideration of future human actions to mining and drilling. Therefore, future underground nuclear device testing has been eliminated from PA calculations on regulatory grounds.

SCR-5.2 Subsurface Hydrological and Geochemical EPs

SCR-5.2.1 Borehole Fluid Flow

SCR-5.2.1.1 FEP Number: H21
FEP Title: *Drilling Fluid Flow*

SCR-5.2.1.1.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Flow associated with historical, current, near-future, and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel, such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.

SCR-5.2.1.1.2 Summary of New Information

The screening argument for this FEP has been revised slightly to remove confusion and inconsistency as suggested by the EPA in "TSD for Section 194.25, 194.32, and 194.33" (U.S. Environmental Protection Agency 2006).

SCR-5.2.1.1.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (blowout) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide

transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone through a borehole into potential thief zones such as the Salado interbeds or the Culebra could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.1.3.1 Historical, Current, and Near-Future Human EPs

Drilling fluid flow is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. However, long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than a short-term event like drilling-induced flow outside the controlled area. Wallace (1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area, and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Thus the HCN of drilling fluid flow associated with boreholes outside the controlled area has been screened out on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H25 through H36 (Section SCR-5.2.1.5, Section SCR-5.2.1.6, Section SCR-5.2.1.7, Section SCR-5.2.1.8, Section SCR-5.2.1.9, Section SCR-5.2.1.10, Section SCR-5.2.1.11, Section SCR-5.2.1.12, and Section SCR-5.2.1.13), drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

SCR-5.2.1.1.3.2 Future Human EPs

For the future, drill holes may intersect the waste disposal region and their effects could be more profound. Thus the possibility of a future borehole penetrating a waste panel, so that drilling fluid flow and, potentially, blowout results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

Penetration of an underpressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus the consequences associated with radionuclide transport to an underpressurized unit below

the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of underpressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.2 FEP Number: H22
FEP Title: *Drilling Fluid Loss*

SCR-5.2.1.2.1 Screening Decision: SO-C (HCN)
DP (Future)

Drilling Fluid Loss associated with HCN and future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future *Drilling Fluid Loss* into waste panels is accounted for in PA calculations.

SCR-5.2.1.2.2 Summary of New Information

The screening argument for this FEP has been revised slightly to remove confusion and inconsistency as suggested by the EPA in "TSD for Section 194.25, 194.32, and 194.33" (U.S. Environmental Protection Agency 2006).

SCR-5.2.1.2.3 Screening Argument

Drilling fluid loss is a short-term event that can result in the flow of pressurized fluid from one geologic stratum to another. Large fluid losses would lead a driller to inject materials to reduce permeability, or it would lead to the borehole being cased and cemented to limit the loss of drilling fluid. Assuming such operations are successful, drilling fluid loss in the near future outside the controlled area will not significantly affect the hydrology of the disposal system. Thus drilling fluid loss associated with historical, current, and near-future boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

In evaluating the potential consequences of drilling fluid loss to a waste panel in the future, two types of drilling events need to be considered – those that intercept pressurized fluid in underlying formations such as the Castile (defined in the CCA, Chapter 6.0, Section 6.3.2.2 as E1 events), and those that do not (E2 events). A possible hydrological effect would be to make a greater volume of brine available for gas generation processes and thereby increase gas volumes at particular times in the future. For either type of drilling event, on the basis of current drilling practices, the driller is assumed to pass through the repository rapidly. Relatively small amounts of drilling fluid loss might not be noticed and might not give rise to concern. Larger fluid losses would lead to the driller injecting materials to reduce permeability, or to the borehole being cased and cemented, to limit the loss of drilling fluid.

For boreholes that intersect pressurized brine reservoirs, the volume of fluid available to flow up a borehole will be significantly greater than the volume of any drilling fluid that could be lost.

This greater volume of brine is accounted for in PA calculations, and is allowed to enter the disposal room (see the CCA, Chapter 6.0, Section 6.4.7). Thus the effects of drilling fluid loss will be small by comparison to the potential flow of brine from pressurized brine reservoirs. Therefore, the effects of drilling fluid loss for E1 drilling events have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The consequences of drilling fluid loss into waste panels in the future are accounted for in PA calculations for E2 events.

SCR-5.2.1.2.3.1 Historical, Current, and Near-Future Human EPs

Drilling fluid flow will not affect hydraulic conditions in the disposal system significantly unless there is substantial drilling fluid loss to a thief zone, such as the Culebra. Typically, zones into which significant borehole circulation fluid is lost are isolated through injection of materials to reduce permeability or through casing and cementing programs. Assuming such operations are successful, drilling fluid loss in the near future outside the controlled area will not affect the hydrology of the disposal system significantly and be of no consequence.

SCR-5.2.1.2.3.2 Future Human EPs

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. Hydraulic and geochemical conditions in the waste panel could be affected as a result of drilling fluid loss to the panel.

Penetration of an underpressurized unit underlying the Salado could result in flow and radionuclide transport from the waste panel to the underlying unit during drilling, although drillers would minimize such fluid loss to a thief zone through the injection of materials to reduce permeability or through the use of casing and cementing. Also, the permeabilities of formations underlying the Salado are less than the permeability of the Culebra (Wallace 1996a). Thus the consequences associated with radionuclide transport to an underpressurized unit below the waste panels during drilling will be less significant, in terms of disposal system performance, than the consequences associated with radionuclide transport to the land surface or to the Culebra during drilling. Through this comparison, drilling events that result in penetration of underpressurized units below the waste-disposal region have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

For boreholes that do not intersect pressurized brine reservoirs (but do penetrate the waste-disposal region), the treatment of the disposal room implicitly accounts for the potential for greater gas generation resulting from drilling fluid loss. Thus the hydrological effects of drilling fluid loss for E2 drilling events are accounted for in PA calculations within the conceptual model of the disposal room for drilling intrusions.

SCR-5.2.1.3 FEP Number: H23
FEP Title: *Blowouts*

SCR-5.2.1.3.1 Screening Decision: SO-C (HCN)
DP (Future)

Blowouts associated with HCN and future boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The possibility of a future deep borehole penetrating a waste panel such that drilling-induced flow results in transport of radionuclides to the land surface or to overlying hydraulically conductive units is accounted for in PA calculations. The possibility of a deep borehole penetrating both the waste disposal region and a Castile brine reservoir is accounted for in PA calculations.

SCR-5.2.1.3.2 Summary of New Information

No new information is available for this FEP.

SCR-5.2.1.3.3 Screening Argument

Blowouts are short-term events that can result in the flow of pressurized fluid from one geologic stratum to another. For the near future, a blowout may occur in the vicinity of the WIPP but is not likely to affect the disposal system because of the distance from the well to the waste panels, assuming that AICs are in place which restrict borehole installation to outside the WIPP boundary. *Blowouts* associated with HCN and future boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. For the future, the drill holes may intersect the waste disposal region and these effects could be more profound. Thus *blowouts* are included in the assessment of future activities and their consequences are accounted for in PA calculations.

Fluid could flow from pressurized zones through the borehole to the land surface (*blowout*) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Movement of brine from a pressurized zone through a borehole into potential thief zones such as the Salado interbeds or the Culebra could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.3.3.1 Historical, Current, and Near-Future Human EPs

Drilling associated with water resources exploration, groundwater exploitation, potash exploration, oil and gas exploration, oil and gas exploitation, enhanced oil and gas recovery, and drilling to explore other resources has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future.

Naturally occurring brine and gas pockets have been encountered during drilling in the Delaware Basin. Brine pockets have been intersected in the Castile (as discussed in the CCA, Chapter 2.0, Section 2.2.1.3) and in the Salado above the WIPP horizon (the CCA, Section 2.2.1.2.2). Gas blowouts have occurred during drilling in the Salado. Usually, such events result in brief

interruptions in drilling while the intersected fluid pocket is allowed to depressurize through flow to the surface (for a period lasting from a few hours to a few days). Drilling then restarts with an increased drilling mud weight. Under these conditions, blowouts in the near future will cause isolated hydraulic disturbances, but will not affect the hydrology of the disposal system significantly.

Potentially, the most significant disturbance to the disposal system could occur if an uncontrolled blowout during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra over the long term, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analyzed the potential effects of flow through abandoned boreholes in the future within the controlled area and concluded that interconnections between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence. Long-term flow through abandoned boreholes would have a greater hydrological impact in the Culebra than short-term, drilling-induced flow outside the controlled area. Thus the effects of fluid flow during drilling in the near future have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

In summary, blowouts associated with historical, current, and near-future boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.3.3.2 Future Human EPs—Boreholes that Intersect the Waste Disposal Region

The consequences of drilling within the controlled area in the future will depend primarily on the location of the borehole. Potentially, future deep drilling could penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of drilling fluid flow: releases to the accessible environment may occur as material entrained in the circulating drilling fluid is brought to the surface. Also, during drilling, contaminated brine may flow up the borehole and reach the surface, depending on fluid pressure within the waste disposal panels; blowout conditions could prevail if the waste panel were sufficiently pressurized at the time of intrusion.

SCR-5.2.1.3.3.3 Hydraulic Effects of Drilling-Induced Flow

The possibility of a future borehole penetrating a waste panel, so that drilling fluid flow and, potentially, blowout results in transport of radionuclides to the land surface or to overlying hydraulically conductive units, is accounted for in PA calculations.

The units intersected by the borehole may provide sources for fluid flow (brine, oil, or gas) to the waste panel during drilling. In the vicinity of the WIPP, the Castile that underlies the Salado contains isolated volumes of brine at fluid pressures greater than hydrostatic. A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. The possibility of a deep borehole penetrating both a waste panel and a brine reservoir is accounted for in PA calculations.

Future boreholes could affect the hydraulic conditions in the disposal system. Intersection of pockets of pressurized gas and brine would likely result in short-term, isolated hydraulic disturbances, and will not affect the hydrology of the disposal system significantly. Potentially the most significant hydraulic disturbance to the disposal system could occur if an uncontrolled blowout during drilling resulted in substantial flow through the borehole from a pressurized zone to a thief zone. For example, if a borehole penetrates a brine reservoir in the Castile, brine could flow through the borehole to the Culebra, and, as a result, could affect hydraulic conditions in the Culebra. The potential effects of such an event can be compared to the effects of long-term fluid flow from deep overpressurized units to the Culebra through abandoned boreholes. Wallace (1996a) analyzed the potential effects of such interconnections in the future within the controlled area, concluding that flow through abandoned boreholes between the Culebra and deep units could be eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.4 FEP Number: H24
FEP Title: *Drilling-Induced Geochemical Changes*

SCR-5.2.1.4.1 Screening Decision: UP (HCN)
DP (Future)

Drilling-Induced Geochemical Changes that occur within the controlled area as a result of HCN and future drilling-induced flow are accounted for in PA calculations.

SCR-5.2.1.4.2 Summary of New Information

No new information is available for this FEP.

SCR-5.2.1.4.3 Screening Argument

Borehole circulation fluid could be lost to thief zones encountered during drilling, or fluid could flow from pressurized zones through the borehole to the land surface (blowout) or to a thief zone. Such drilling-related EPs could influence groundwater flow and, potentially, radionuclide transport in the affected units. Future drilling within the controlled area could result in direct releases of radionuclides to the land surface or transport of radionuclides between hydraulically conductive units.

Movement of brine from a pressurized zone through a borehole and into potential thief zones such as the Salado interbeds or the Culebra, could result in geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.1 Historical, Current, and Near-Future Human EPs

Drilling associated with resource exploration, exploitation, and recovery has taken place or is currently taking place outside the controlled area in the Delaware Basin. These drilling activities are expected to continue in the vicinity of the WIPP in the near future. Chemical changes induced by such drilling are discussed below.

SCR-5.2.1.4.3.2 Geochemical Effects of Drilling-Induced Flow–HCN

Radionuclide migration rates are governed by the coupled effects of hydrological and geochemical processes (see discussions in FEPs W77 through W100, Section SCR-6.6.1.1, Section SCR-6.6.1.2, Section SCR-6.6.2.1, Section SCR-6.6.3.1, Section SCR-6.6.3.2, Section SCR-6.6.4.1, Section SCR-6.7.1.1, Section SCR-6.7.2.1, Section SCR-6.7.3.1, Section SCR-6.7.4.1, Section SCR-6.7.4.2, Section SCR-6.7.4.3, Section SCR-6.7.5.1, Section SCR-6.7.5.2, Section SCR-6.7.5.3, and Section SCR-6.7.5.4). Human EPs outside the controlled area could affect the geochemistry of units within the controlled area if they occur sufficiently close to the edge of the controlled area. Movement of brine from a pressurized reservoir in the Castile through a borehole into potential thief zones, such as the Salado interbeds or the Culebra, could cause drilling-induced geochemical changes resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption (colloid transport may enhance radionuclide migration, while radionuclide migration may be retarded by sorption).

The treatment of colloids in PA calculations is described in the CCA, Chapter 6.0, Section 6.4.3.6 and Section 6.4.6.2.2. The repository and its contents provide the main source of colloids in the disposal system. By comparison, Castile brines have relatively low total colloid concentrations. Therefore, changes in colloid transport in units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Sorption within the Culebra is accounted for in PA calculations as discussed in the CCA, Chapter 6.0, Section 6.4.6.2. The sorption model comprises an equilibrium, sorption isotherm approximation, employing K_ds applicable to dolomite in the Culebra (the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.2). The cumulative distribution functions (CDFs) of K_ds used are derived from a suite of experimental studies that include measurements of K_ds for actinides in a range of chemical systems including Castile brines, Culebra brines, and Salado brines. Therefore, any changes in sorption geochemistry in the Culebra within the controlled area as a result of HCN drilling-induced flow are accounted for in PA calculations.

Sorption within the Dewey Lake is accounted for in PA calculations, as discussed in the CCA, Chapter 6.0, Section 6.4.6.6. It is assumed that the sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter the Dewey Lake from being released over 10,000 years (Wallace et al. 1995). Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of changes in sorption in the Dewey Lake and other units within the controlled area as a result of HCN drilling-induced flow have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.4.3.3 Future Human EPs — Boreholes that Intersect the Waste Disposal Region

The consequences of drilling within the controlled area in the future will primarily depend on the location of the borehole. Future deep drilling could potentially penetrate the waste disposal region. If the borehole intersects the waste in the disposal rooms, radionuclides could be transported as a result of drilling fluid flow and geochemical conditions in the waste panel could be affected as a result of drilling induced geochemical changes.

SCR-5.2.1.4.3.4 Geochemical Effects of Drilling-Induced Flow-Future

Drilling fluid loss to a waste panel could modify the chemistry of disposal room brines in a manner that would affect the solubility of radionuclides and the source term available for subsequent transport from the disposal room. The majority of drilling fluids used are likely to be locally derived, and their bulk chemistry will be similar to fluids currently present in the disposal system. In addition, the presence of the MgO chemical conditioner in the disposal rooms will buffer the chemistry across a range of fluid compositions, as discussed in detail in Appendix SOTERM-2009, Section SOTERM-2.3.2. Furthermore, for E1 drilling events, the volume of Castile brine that flows into the disposal room will be greater than that of any drilling fluids; Castile brine chemistry is accounted for in PA calculations. Thus the effects on radionuclide solubility of drilling fluid loss to the disposal room have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could result in geochemical changes in the receiving units, and thus alter radionuclide migration rates in these units through their effects on colloid transport and sorption.

The repository and its contents provide the main source of colloids in the disposal system. Thus colloid transport in the Culebra within the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region is accounted for in PA calculations, as described in the CCA, Chapter 6.0, Section 6.4.3.6 and Section 6.4.6.2.1. The Culebra is the most transmissive unit in the disposal system, and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of drilling fluid loss associated with boreholes that intersect the waste disposal region, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, and SCR-5.2.1.3), sorption within the Culebra is accounted for in PA calculations. The sorption model used incorporates the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, and SCR-5.2.1.3), the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of drilling-induced flow associated with boreholes that intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.4.3.5 Future Human EPs — Boreholes That Do Not Intersect the Waste Disposal Region

Future boreholes that do not intersect the waste disposal region could nevertheless encounter contaminated material by intersecting a region into which radionuclides have migrated from the disposal panels, or could affect hydrogeological conditions within the disposal system.

Consistent with the containment requirements in 40 CFR § 191.13(a), PAs need not evaluate the effects of the intersection of contaminated material outside the controlled area.

Movement of brine from a pressurized reservoir in the Castile, through a borehole and into thief zones such as the Salado interbeds or the Culebra could result in drilling-induced geochemical changes and altered radionuclide migration rates in these units.

SCR-5.2.1.4.3.6 Geochemical Effects of Drilling-Induced Flow

Movement of brine from a pressurized reservoir in the Castile through a borehole into thief zones, such as the Salado interbeds or the Culebra, could cause geochemical changes resulting in altered radionuclide migration rates in these units through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus consistent with the discussion in FEPs H21, H22, and H23 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, and SCR-5.2.1.3), colloid transport as a result of drilling-induced flow associated with future boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21, H22, and H23 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, and SCR-5.2.1.3), sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region.

Consistent with the screening discussion in FEPs H21, H22, and H23 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, and SCR-5.2.1.3), the effects of changes in sorption in the Dewey Lake within the controlled area as a result of drilling-induced flow associated with boreholes that do not intersect the waste disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

In summary, the effects of drilling-induced geochemical changes that occur within the controlled area as a result of HCN and future drilling-induced flow are accounted for in PA calculations. Those that occur outside the controlled area have been eliminated from PA calculations.

SCR-5.2.1.5 FEP Numbers: H25 and H26
FEP Titles: *Oil and Gas Extraction*
Groundwater Extraction

SCR-5.2.1.5.1 Screening Decision: SO-C (HCN)
SO-R (Future)

HCN *Groundwater Extraction* and *Oil and Gas Extraction* outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the

disposal system. *Groundwater Extraction* and *Oil and Gas Extraction* through future boreholes has been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.5.2 Summary of New Information

The screening argument for this FEP has been updated with new information relating to a new water well used for ranching purposes near WIPP. No change to the screening decisions is merited.

SCR-5.2.1.5.2.1 Screening Argument

The extraction of fluid could alter fluid-flow patterns in the target horizons, or in overlying units as a result of a failed borehole casing. Also, the removal of confined fluid from oil- or gas-bearing units can cause compaction in some geologic settings, potentially resulting in subvertical fracturing and surface subsidence.

SCR-5.2.1.5.2.2 Historical, Current, and Near-Future Human EPs

As discussed in FEPs H25 through H36, water, oil, and gas production are the only activities involving fluid extraction through boreholes that have taken place or are currently taking place in the vicinity of the WIPP. These activities are expected to continue in the vicinity of the WIPP in the near future.

Groundwater extraction outside the controlled area from formations above the Salado could affect groundwater flow. The Dewey Lake contains a productive zone of saturation south of the WIPP site. Several wells operated by the J.C. Mills Ranch south of the WIPP produce water from the Dewey Lake to supply livestock (see the CCA, Chapter 2.0, Section 2.2.1.4.2.1). Water has also been extracted from the Culebra at the Engle Well approximately 9.66 km (6 mi) south of the controlled area to provide water for livestock. In addition, a new water well was drilled in 2007 at the Sandia National Laboratories (SNL)-14 wellpad to provide livestock water for the Mills ranch. This well is approximately 3,000 ft (0.9 km) from the WIPP site boundary.

If contaminated water intersects a well while it is producing, then contaminants could be pumped to the surface. Consistent with the containment requirements in section 191.13(a), PAs need not evaluate radiation doses that might result from such an event. However, compliance assessments must include any such events in dose calculations for evaluating compliance with the individual protection requirements in section 191.15. As discussed in the CCA, Chapter 8.0, under undisturbed conditions, there are no calculated radionuclide releases to units containing producing wells.

Pumping from wells at the J.C. Mills Ranch may have resulted in reductions in hydraulic head in the Dewey Lake within southern regions of the controlled area, leading to increased hydraulic head gradients. However, these changes in the groundwater flow conditions in the Dewey Lake will have no significant effects on the performance of the disposal system, primarily because of the sorptive capacity of the Dewey Lake (see the CCA, Chapter 6.0, Section 6.4.6.6). Retardation of any radionuclides that enter the Dewey Lake will be such that no radionuclides will migrate through the Dewey Lake to the accessible environment within the 10,000-yr regulatory period.

The effects of groundwater extraction from the Culebra from a well 9.66 km (6 mi) south of the controlled area have been evaluated by Wallace (1996b), using an analytical solution for Darcian fluid flow in a continuous porous medium. Wallace (1996b) showed that such a well pumping at about 0.5 gallon (gal) (1.9 liters [L]) per minute for 10,000 years will induce a hydraulic head gradient across the controlled area of about 4×10^{-5}. The hydraulic head gradient across the controlled area currently ranges from between 0.001 to 0.007. Therefore, pumping from the Engle Well will have only minor effects on the hydraulic head gradient within the controlled area even if pumping were to continue for 10,000 years. Thus the effects of HCN groundwater extraction outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Oil and gas extraction outside the controlled area could affect the hydrology of the disposal system. However, the horizons that act as oil and gas reservoirs are sufficiently below the repository for changes in fluid-flow patterns to be of low consequence, unless there is fluid leakage through a failed borehole casing. Also, oil and gas extraction horizons in the Delaware Basin are well-lithified rigid strata, so oil and gas extraction is not likely to result in compaction and subsidence (Brausch et al. 1982, pp. 52, 61). Furthermore, the plasticity of the salt formations in the Delaware Basin will limit the extent of any fracturing caused by compaction of underlying units. Thus, neither the extraction of gas from reservoirs in the Morrow Formation (some 4,200 m (14,000 ft) below the surface), nor extraction of oil from the shallower units within the Delaware Mountain Group (about 1,250 to 2,450 m (about 4,000 to 8,000 ft) below the surface) will lead to compaction and subsidence. In summary, historical, current, and near-future oil and gas extraction outside the controlled area has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.5.2.3 Future Human EPs

Consistent with section 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, groundwater extraction and oil and gas extraction through future boreholes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.6 FEP Numbers: H27, H28, and H29

FEP Titles: *Liquid Waste Disposal – OB* (H27)
Enhanced Oil and Gas Production – OB (H28)
Hydrocarbon Storage – OB (H29)

SCR-5.2.1.6.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The hydrological effects of HCN fluid injection (*Liquid Waste Disposal*, *Enhanced Oil and Gas Production*, and *Hydrocarbon Storage*) through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. *Liquid Waste Disposal*, *Enhanced Oil and Gas Production*, and *Hydrocarbon Storage* in the future have been eliminated from PA calculations based on low consequence.

SCR-5.2.1.6.2 Summary of New Information

These FEPs are specific to activities outside the WIPP boundary, although past descriptions have sometimes confused these activities with possible events occurring inside the WIPP boundary, or IB. Section 194.33(d) excludes activities subsequent to drilling the borehole from further consideration in PA. It has historically been understood that this exclusion implicitly applies to activities within the WIPP boundary, and not those outside the boundary, or OB. Therefore, three new FEPs have been created to address analogous IB activities (see Section SCR-5.2.1.7, FEPs H60, *Liquid Disposal–IB*; *H61 Enhanced Oil and Gas Production–IB*; and *H62 Hydrocarbon Storage–IB*).

Recent monitoring activities have identified a salt water disposal well that had hardware failure resulting in migration of the injected fluid away from the wellbore in a shallow freshwater producing zone. This leak may have persisted up to 22 months, based on inspection and test records on file with the New Mexico Oil Conservation Division. Once the failure was identified, the well was repaired and returned to service. Details of this event are discussed in Hall (2008).

Fluid injection modeling conducted since the CCA has demonstrated that injection of fluids will not have a significant effect upon the WIPP's ability to contain radioactive materials (Stoelzel and Swift 1997). Conservative assumptions used by Stoelzel and Swift include a leaking well that persists for many years (150) with pressures above maximum allowable permitted pressures in the area. Therefore, current modeling conservatively bounds the effects of the recent injection well failure mentioned above. Neither liquid waste disposal nor waterflooding conducted in wells outside the controlled area have the potential to affect the disposal system in any significant way.

SCR-5.2.1.6.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.6.3.1 Historical, Current, and Near-Future Human EPs

The only historical and current activities involving fluid injection through boreholes in the Delaware Basin are enhanced oil and gas production (waterflooding or carbon dioxide (CO_2) injection), hydrocarbon storage (gas reinjection), and liquid waste disposal (byproducts from oil and gas production). These fluid injection activities are expected to continue in the vicinity of the WIPP in the near future.

Hydraulic fracturing of oil- or gas-bearing units is currently used to improve the performance of hydrocarbon reservoirs in the Delaware Basin. Fracturing is induced during a short period of high-pressure fluid injection, resulting in increased hydraulic conductivity near the borehole. Normally, this controlled fracturing is confined to the pay zone and is unlikely to affect overlying strata.

Secondary production techniques, such as waterflooding, that are used to maintain reservoir pressure and displace oil are currently employed in hydrocarbon reservoirs in the Delaware Basin (Brausch et al. 1982, pp. 29-30). Tertiary recovery techniques, such as CO_2 miscible flooding, have been implemented with limited success in the Delaware Basin, but CO_2 miscible flooding is not an attractive recovery method for reservoirs near the WIPP (Melzer 2008). Even if CO_2 flooding were to occur, the effects, if any, would be very similar to those associated with waterflooding.

Reinjection of gas for storage currently takes place at one location in the Delaware Basin in a depleted gas field in the Morrow Formation at the Washington Ranch near Carlsbad Caverns (Burton et al. 1993, pp. 66-67; the CRA-2004, Appendix DATA, Attachment A). This field is too far from the WIPP site to have any effect on WIPP groundwaters under any circumstances. Disposal of liquid by-products from oil and gas production involves injection of fluid into depleted reservoirs. Such fluid injection techniques result in repressurization of the depleted target reservoir and mitigates any effects of fluid withdrawal.

The most significant effects of fluid injection would arise from substantial and uncontrolled fluid leakage through a failed borehole casing. The highly saline environment of some units can promote rapid corrosion of well casings and may result in fluid loss from boreholes.

SCR-5.2.1.6.3.2 Hydraulic Effects of Leakage through Injection Boreholes

The Vacuum Field (located in the Capitan Reef, some 30 km [20 mi] northeast of the WIPP site) and the Rhodes-Yates Field (located in the back reef of the Capitan, some 70 km (45 mi) southeast of the WIPP site) have been waterflooded for 40 years with confirmed leaking wells, which have resulted in brine entering the Salado and other formations above the Salado (see, for example, Silva 1994, pp. 67-68). Currently, saltwater disposal takes place in the vicinity of the WIPP into formations below the Castile. However, leakages from saltwater disposal wells or waterflood wells in the near future in the vicinity of the WIPP are unlikely to occur because of the following:

- There are significant differences between the geology and lithology in the vicinity of the disposal system and that of the Vacuum and Rhodes-Yates Fields. The WIPP is located in the Delaware Basin in a fore-reef environment, where a thick zone of anhydrite and halite (the Castile) exists. In the vicinity of the WIPP, oil is produced from the Brushy Canyon Formation at depths greater than 2,100 m (7,000 ft). By contrast, the Castile is not present at either the Vacuum or the Rhodes-Yates Field, which lie outside the Delaware Basin. Oil production at the Vacuum Field is from the San Andres and Grayburg Formations at depths of approximately 1,400 m (4,500 ft), and oil production at the Rhodes-Yates Field is from the Yates and Seven Rivers Formations at depths of approximately 900 m (3,000 ft). Waterflooding at the Rhodes-Yates Field involves injection into a zone only 60 m (200 ft) below the Salado. There are more potential thief zones below the Salado near the WIPP than at the Rhodes-Yates or Vacuum Fields; the Salado in the vicinity of the WIPP is therefore less likely to receive any fluid that leaks from an injection borehole. Additionally, the oil pools in the vicinity of the WIPP are characterized by channel sands with thin net pay zones, low permeabilities, high irreducible water saturations, and high residual oil saturations. Therefore, waterflooding

of oil fields in the vicinity of the WIPP on the scale of that undertaken in the Vacuum or the Rhodes-Yates Field is unlikely.

- New Mexico state regulations require the emplacement of a salt isolation casing string for all wells drilled in the potash enclave, which includes the WIPP area, to reduce the possibility of petroleum wells leaking into the Salado. Also, injection pressures are not allowed to exceed the pressure at which the rocks fracture. The injection pressure gradient must be kept below 4.5×10^3 pascals per meter above hydrostatic if fracture pressures are unknown. Such controls on fluid injection pressures limit the potential magnitude of any leakages from injection boreholes.

- Recent improvements in well completion practices and reservoir operations management have reduced the occurrences of leakages from injection wells. For example, injection pressures during waterflooding are typically kept below about 23×10^3 pascals per meter to avoid fracture initiation. Also, wells are currently completed using cemented and perforated casing, rather than the open-hole completions used in the early Rhodes-Yates wells. A recent report (Hall et al. 2008) concludes that injection well operations near the WIPP have a low failure rate, and that failures are remedied as soon as possible after identification.

Any injection well leakages that do occur in the vicinity of the WIPP in the near future are more likely to be associated with liquid waste disposal than waterflooding. Disposal typically involves fluid injection though old and potentially corroded well casings and does not include monitoring to the same extent as waterflooding. Such fluid injection could affect the performance of the disposal system if sufficient fluid leaked into the Salado interbeds to affect the rate of brine flow into the waste disposal panels.

Stoelzel and O'Brien (1996) evaluated the potential effects on the disposal system of leakage from a hypothetical salt water disposal borehole near the WIPP. Stoelzel and O'Brien (1996) used the two-dimensional BRAGFLO model (vertical north-south cross-section) to simulate saltwater disposal to the north and to the south of the disposal system. The disposal system model included the waste disposal region, the marker beds (MBs) and anhydrite intervals near the excavation horizon, and the rock strata associated with local oil and gas developments. A worst-case simulation was run using high values of borehole and anhydrite permeability and a low value of halite permeability to encourage flow to the disposal panels via the anhydrite. The boreholes were assumed to be plugged immediately above the Salado (consistent with the plugging configurations described in the CCA, Chapter 6.0, Section 6.4.7.2). Saltwater disposal into the Upper Bell Canyon was simulated, with annular leakage through the Salado. A total of approximately 7×10^5 m^3 (2.47×10^7 ft^3) of brine was injected through the boreholes during a 50-year simulated disposal period. In this time, approximately 50 m^3 (1,765.5 ft^3) of brine entered the anhydrite interval at the horizon of the waste disposal region. For the next 200 years, the boreholes were assumed to be abandoned (with open-hole permeabilities of 1×10^{-9} square meters (m^2) (4×10^{-8} $in.^2$)). Cement plugs (of permeability 1×10^{-17} m^2 (4×10^{-16} $in.^2$)) were assumed to be placed at the injection interval and at the top of the Salado. Subsequently, the boreholes were prescribed the permeability of silty sand (see the CCA, Chapter 6.0, Section 6.4.7.2), and the simulation was continued until the end of the 10,000-yr regulatory period. During this period, approximately 400 m^3 (14,124 ft^3) of brine entered the waste disposal region

from the anhydrite interval. This value of cumulative brine inflow is within the bounds of the values generated by PA calculations for the UP scenario. During the disposal well simulation, leakage from the injection boreholes would have had no significant effect on the inflow rate at the waste panels.

Stoelzel and Swift (1997) expanded on Stoelzel and O'Brien's (1996) work by considering injection for a longer period of time (up to 150 years) and into deeper horizons at higher pressures. They developed two computational models (a modified cross-sectional model and an axisymmetric radial model) that are alternatives to the cross-sectional model used by Stoelzel and O'Brien (1996). Rather than repeat the conservative and bounding approach used by Stoelzel and O'Brien (1996), Stoelzel and Swift (1997) focused on reasonable and realistic conditions for most aspects of the modeling, including setting parameters that were sampled in the CCA at their median values. Model results indicate that, for the cases considered, the largest volume of brine entering MB 139 (the primary pathway to the WIPP) from the borehole is approximately 1,500 m^3 (52,974 ft^3), which is a small enough volume that it would not affect Stoelzel and O'Brien's (1996) conclusion even if it somehow all reached the WIPP. Other cases showed from 0 to 600 m^3 (21,190 ft^3) of brine entering MB 139 from the injection well. In all cases, high-permeability fractures created in the Castile and Salado anhydrite layers by the modeled injection pressures were restricted to less than 400 m (1,312 ft) from the wellbore, and did not extend more than 250 m in MB 138 and MB 139.

No flow entered MB 139, nor was fracturing of the unit calculated to occur away from the borehole, in cases in which leaks in the cement sheath had permeabilities of $10^{-12.5}$ m^2 (corresponding to the median value used to characterize fully degraded boreholes in the CCA) or lower. The cases modeled in which flow entered MB 139 from the borehole and fracturing occurred away from the borehole required injection pressures conservatively higher than any currently in use near the WIPP and either 150 years of leakage through a fully degraded cement sheath or 10 years of simultaneous tubing and casing leaks from a waterflood operation. These conditions are not likely to occur in the future. If leaks like these do occur from brine injection near the WIPP, however, results of the Stoelzel and Swift (1997) modeling study indicate that they will not affect the performance of the repository.

Thus the hydraulic effects of leakage through HCN boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.3 Effects of Density Changes Resulting from Leakage Through Injection Boreholes

Leakage through a failed borehole casing during a fluid injection operation in the vicinity of the WIPP could alter fluid density in the affected unit, which could result in changes in fluid flow rates and directions within the disposal system. Disposal of oil and gas production byproducts through boreholes could increase fluid densities in transmissive units affected by leakage in the casing. Operations such as waterflooding use fluids derived from the target reservoir, or fluids with a similar composition, to avoid scaling and other reactions. Therefore, the effects of leakage from waterflood boreholes would be similar to leakage from disposal wells.

Denser fluids have a tendency to sink relative to less dense fluids, and, if the hydrogeological unit concerned has a dip, there will be a tendency for the dense fluid to travel in the downdip direction. If this direction is the same as the direction of the groundwater pressure gradient, there would be an increase in flow velocity, and conversely, if the downdip direction is opposed to the direction of the groundwater pressure gradient, there would be a decrease in flow velocity. In general terms, taking account of density-related flow will cause a rotation of the flow vector towards the downdip direction that is dependent on the density contrast and the dip.

Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an injection borehole outside the controlled area will not affect fluid flow in the Culebra significantly. Potash mining activities assumed on the basis of regulatory criteria to occur in the near future outside the controlled area will have a more significant effect on modeled Culebra hydrology. The distribution of existing leases suggests that near-future mining will take place to the north, west, and south of the controlled area (see the CCA, Chapter 2.0, Section 2.3.1.1). The effects of such potash mining are accounted for in calculations of UP of the disposal system (through an increase in the transmissivity of the Culebra above the mined region, as discussed in FEPs H37, H38, and H39 [Section SCR-5.2.2.1, Section SCR-5.2.2.2, and Section SCR-5.2.3.1]). Groundwater modeling that accounts for potash mining shows a change in the fluid pressure distribution and a consequent shift of flow directions towards the west in the Culebra within the controlled area (Wallace 1996c). A localized increase in fluid density in the Culebra resulting from leakage from an injection borehole would rotate the flow vector towards the downdip direction (towards the east).

Wilmot and Galson (1996) compared the relative magnitudes of the freshwater head gradient and the gravitational gradient and showed that the density effect is of low consequence to the performance of the disposal system. According to Darcy's Law, flow in an isotropic porous medium is governed by the gradient of fluid pressure and a gravitational term

$$\bar{v} = -\frac{k}{\mu}\left[\nabla p - \rho \bar{g}\right] \qquad \text{(SCR.7)}$$

where

v	=	Darcy velocity vector	($m\ s^{-1}$)
k	=	intrinsic permeability	(m^2)
μ	=	fluid viscosity	(Pa s)
∇p	=	gradient of fluid pressure	($Pa\ m^{-1}$)
ρ	=	fluid density	($kg\ m^{-3}$)
g	=	gravitational acceleration vector	($m\ s^{-2}$)

The relationship between the gravity-driven flow component and the pressure-driven component can be shown by expressing the velocity vector in terms of a freshwater head gradient and a density-related elevation gradient

$$\bar{v} = -K\left[\nabla H_f + \frac{\Delta\rho}{\rho_f}\nabla E\right] \qquad \text{(SCR.8)}$$

where

K = hydraulic conductivity ($m\ s^{-1}$)
∇H_f = gradient of freshwater head
$\Delta\rho$ = difference between actual fluid density and reference fluid density ($kg\ m^{-3}$)
ρ_f = density of freshwater ($kg\ m^{-3}$)
∇E = gradient of elevation

Davies (1989, p. 28) defined a driving force ratio (DFR) to assess the potential significance of the density gradient

$$DFR = \frac{\Delta\rho\left|\nabla E\right|}{\rho_f\left|\nabla H_f\right|} \qquad \text{(SCR.9)}$$

and concluded that a DFR of 0.5 can be considered an approximate threshold at which density-related gravity effects may become significant (Davies 1989, p. 28).

The dip of the Culebra in the vicinity of the WIPP is about 0.44 degrees or 8 m/km (26 ft/mi) to the east (Davies 1989, p. 42). According to Davies (1989, pp. 47–48), freshwater head gradients in the Culebra between the waste panels and the southwestern and western boundaries of the accessible environment range from 4 m/km (13 ft/mi) to 7 m/km (23 ft/mi). Only small changes in gradient arise from the calculated effects of near-future mining. Culebra brines have densities ranging from 998 to 1,158 kilograms per cubic meter (kg/m^3) (998 to 1,158 parts per million [ppm]) (Cauffman et al. 1990, Table E1.b). Assuming the density of fluid leaking from a waterflood borehole or a disposal well to be 1,215 kg/m^3 (1,215 ppm) (a conservative high value similar to the density of Castile brine [Popielak et al. 1983, Table C-2]) leads to a DFR of between 0.07 and 0.43. These values of the DFR show that density-related effects caused by leakage of brine into the Culebra during fluid injection operations are not significant.

In summary, the effects of HCN fluid injection (liquid waste disposal, enhanced oil and gas production, and hydrocarbon storage) through boreholes outside the controlled area have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.4 Geochemical Effects of Leakage through Injection Boreholes

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such fluid injection-induced geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs discussion for H21

through H24, Section SCR-5.2.1.1, Section SCR-5.2.1.2, Section SCR-5.2.1.3, and SCR-5.2.1.4). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, Section SCR-5.2.1.3, and SCR-5.2.1.4), sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Nonlocally derived fluids could be used during hydraulic fracturing operations. However, such fluid-injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.6.3.5 Future Human EPs

Consistent with section 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole within the site boundary. Liquid waste disposal (byproducts from oil and gas production), enhanced oil and gas production, and hydrocarbon storage are techniques associated with resource recovery and are expected to continue into the future outside the site boundary. Analyses have shown that these activities have little consequence on repository performance (Stoelzel and Swift 1997). Therefore, activities such as liquid waste disposal, enhanced oil and gas production, and hydrocarbon storage outside the site boundary have been eliminated from PA calculations on the basis of low consequence.

SCR-5.2.1.7 FEP Numbers: H60, H61, and H62

FEP Titles: *Liquid Waste Disposal – IB* (H60)
Enhanced Oil and Gas Production – IB (H61)
Hydrocarbon Storage – IB (H62)

SCR-5.2.1.7.1 Screening Decision: SO-R (HCN)
SO-R (Future)

The hydrological effects of HCN fluid injection (*Liquid Waste Disposal*, *Enhanced Oil and Gas Production*, and *Hydrocarbon Storage*) through boreholes inside the controlled area have been eliminated from PA calculations on regulatory grounds (section 194.25(a)). *Liquid Waste Disposal*, *Enhanced Oil and Gas Production*, and *Hydrocarbon Storage* (within the controlled area) in the future have been eliminated from PA calculations on regulatory grounds (section 194.33(d)).

SCR-5.2.1.7.2 Summary of New Information

These FEPs are specific to activities inside the WIPP boundary, or IB, although past discussions have sometimes confused these activities with possible events occurring outside the WIPP boundary or OB. Section 194.33(d) excludes activities subsequent to drilling the borehole from further consideration in PA. It has historically been understood that this exclusion applies only to IB activities, and not those OB. Therefore, these FEPs deal specifically with IB activities. These three new FEPs have been created to address IB activities analogous to FEPs H27, *Liquid Disposal-OB*; H28 *Enhanced Oil and Gas Production-OB*; and H29 *Hydrocarbon Storage-OB*. The descriptions of the OB activities (H27 – H29, Section SCR-5.2.1.6) have been clarified to be specifically related to activities OB.

SCR-5.2.1.7.3 Screening Argument

The injection of fluids in a borehole within the WIPP boundary could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole within the WIPP boundary could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.7.3.1 Historical, Current, and Near-Future Human EPs

Injection of fluids for the purposes of liquid disposal, enhanced oil and gas production, or hydrocarbon storage has not occurred within the WIPP boundary. Therefore, based on the future states assumption provided by section 194.25(a), it is assumed that such activities will not occur within the near-future time frame, which includes the period of WIPP AICs. These activities are excluded from PA calculations on regulatory grounds.

SCR-5.2.1.7.3.2 Future Human EPs

The provisions of section 194.33(d) state, "that performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole." Therefore, the future injection of fluids for the purposes of liquid disposal, enhanced oil and gas production, and hydrocarbon storage within the WIPP boundary have been excluded from PA calculations on regulatory grounds.

SCR-5.2.1.8 FEP Number: H30
FEP Title: *Fluid Injection-Induced Geochemical Changes*

SCR-5.2.1.8.1 Screening Decision: UP (HCN)
SO-R (Future)

Geochemical changes that occur inside the controlled area as a result of fluid flow associated with HCN fluid injection are accounted for in PA calculations. Geochemical changes resulting from fluid injection in the future inside the controlled area have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.8.2 Summary of New Information

No new information regarding this FEP has been identified.

SCR-5.2.1.8.3 Screening Argument

The injection of fluids could alter fluid-flow patterns in the target horizons or, if there is accidental leakage through a borehole casing, in any other intersected hydraulically conductive zone. Injection of fluids through a leaking borehole could also result in geochemical changes and altered radionuclide migration rates in the thief units.

SCR-5.2.1.8.3.1 Geochemical Effects of Leakage through Injection Boreholes

Injection of fluids through a leaking borehole could affect the geochemical conditions in thief zones, such as the Salado interbeds or the Culebra. Such fluid injection-induced geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area through their effects on colloid transport and sorption.

The majority of fluids injected (for example, during brine disposal) have been extracted locally during production activities. Because they have been derived locally, their compositions are similar to fluids currently present in the disposal system, and they will have low total colloid concentrations compared to those in the waste disposal panels (see FEPs H21 through H24, Section SCR-5.2.1.1, Section SCR-5.2.1.2, Section SCR-5.2.1.3, and SCR-5.2.1.4). The repository will remain the main source of colloids in the disposal system. Therefore, colloid transport as a result of HCN fluid injection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in FEPs H21 through H24 (Section SCR-5.2.1.1, Section SCR-5.2.1.2, Section SCR-5.2.1.3, and SCR-5.2.1.4), sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of any changes in sorption in the Culebra as a result of leakage through HCN injection boreholes.

Consistent with the screening discussion in FEPs H21 through H24, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of leakage through HCN injection boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

Nonlocally derived fluids could be used during hydraulic fracturing operations. However, such fluid injection operations would be carefully controlled to minimize leakage to thief zones. Therefore, any potential geochemical effects of such leakages have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.8.3.2 Future Human EPs

Consistent with section 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Liquid waste disposal

(byproducts from oil and gas production), enhanced oil and gas production, and hydrocarbon storage are techniques associated with resource recovery. Therefore, the use of future boreholes for such activities and fluid injection-induced geochemical changes have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.9 FEP Number: H31
FEP Title: *Natural Borehole Fluid Flow* (H31)

SCR-5.2.1.9.1 Screening Decision: SO-C (HCN)
SO-C (Future, holes not penetrating waste panels)
DP (Future, holes through waste panels)

The effects of *Natural Borehole Fluid Flow* through existing or near-future abandoned boreholes, known or unknown, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. *Natural Borehole Fluid Flow* through a future borehole that intersects a waste panel is accounted for in PA calculations. The effects of *Natural Borehole Fluid Flow* through a future borehole that does not intersect the waste-disposal region have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.9.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.1.9.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.9.3.1 Historical, Current, and Near-Future Human EPs

Abandoned water, potash, oil, and gas exploration and production boreholes exist within and outside the controlled area. Most of these boreholes have been plugged in some way, but some have simply been abandoned. Over time, even the boreholes that have been plugged may provide hydraulic connections among the units they penetrate as the plugs degrade. The DOE

assumes that records of past and present drilling activities in New Mexico are largely accurate and that evidence of most boreholes would be included in these records. However, the potential effects of boreholes do not change depending on whether their existence is known, hence flow through undetected boreholes and flow through detected boreholes can be evaluated together.

SCR-5.2.1.9.3.2 Hydraulic Effects of Flow through Abandoned Boreholes

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep, overpressurized or underpressurized units, or if boreholes provide interconnections for flow between shallow units.

SCR-5.2.1.9.3.3 Connections Between the Culebra and Deeper Units

Fluid flow and radionuclide transport within the Culebra could be affected if deep boreholes result in hydraulic connections between the Culebra and deep, overpressurized or underpressurized units. Over the past 80 years, a large number of deep boreholes have been drilled within and around the controlled area (see the CCA, Chapter 6.0, Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deep units depends on the locations of the boreholes. In some cases, changes in the Culebra flow field caused by interconnections with deep units could decrease lateral radionuclide travel times to the accessible environment.

As part of an analysis to determine the impact of such interconnections, Wallace (1996a) gathered information on the pressures, permeabilities, and thicknesses of potential oil- or gas-bearing sedimentary units; such units exist to a depth of about 5,500 m (18,044 ft) in the vicinity of the WIPP. Of these units, the Atoka, some 4,000 m (13,123 ft) below the land surface, has the highest documented pressure of about 64 megapascals (MPa) (9,600 pounds per square inch [psi]), with permeability of about 2×10^{-14} m^2 (2.1×10^{-13} square feet [ft^2]) and thickness of about 210 m (689 ft). The Strawn, 3,900 m (12,795 ft) below the land surface, has the lowest pressures (35 MPa [5,000 psi], which is lower than hydrostatic) and highest permeability (10^{-13} m^2 [1.1×10^{-12} ft^2]) of the deep units, with a thickness of about 90 m (295 ft).

PA calculations indicate that the shortest radionuclide travel times to the accessible environment through the Culebra occur when flow in the Culebra in the disposal system is from north to south. Wallace (1996a) ran the steady-state SECOFL2D model with the PA data that generated the shortest radionuclide travel times (with and without mining in the controlled area) but perturbed the flow field by placing a borehole connecting the Atoka to the Culebra just north of the waste disposal panels and a borehole connecting the Culebra to the Strawn just south of the controlled area. The borehole locations were selected to coincide with the end points of the fastest flow paths modeled, which represents an unlikely worst-case condition. Although the Atoka is primarily a gas-bearing unit, Wallace (1996a) assumed that the unit is brine saturated. This assumption is conservative because it prevents two-phase flow from occurring in the Culebra, which would decrease the water permeability and thereby increase transport times. It was conservatively assumed that the pressure in the Atoka would not have been depleted by production before the well was plugged and abandoned. Furthermore, it was conservatively assumed that all flow from the Atoka would enter the Culebra and not intermediate or shallower units, and that flow from the Culebra could somehow enter the Strawn despite intermediate zones having higher pressures than the Culebra. The fluid flux through each borehole was determined using Darcy's Law, assuming a borehole hydraulic conductivity of 10^{-4} m/s (for a

permeability of about 10^{-11} m^2 [1.1×10^{-10} ft^2]) representing silty sand, a borehole radius of 0.25 m (.82 ft), and a fluid pressure in the Culebra of 0.88 MPa (132 psi) at a depth of about 200 m (650 ft). With these parameters, the Atoka was calculated to transmit water to the Culebra at about 1.4×10^{-5} m^3/s (0.22 gallons per minute [gpm]), and the Strawn was calculated to receive water from the Culebra at about 1.5×10^{-6} m^3/s (0.024 gpm).

Travel times through the Culebra to the accessible environment were calculated using the SECOFL2D velocity fields for particles released to the Culebra above the waste panels, assuming no retardation by sorption or diffusion into the rock matrix. Mean Darcy velocities were then determined from the distance each radionuclide traveled, the time taken to reach the accessible environment, and the effective Culebra porosity. The results show that, at worst, interconnections between the Culebra and deep units under the unrealistically conservative assumptions listed above could cause less than a twofold increase in the largest mean Darcy velocity expected in the Culebra in the absence of such interconnections.

These effects can be compared to the potential effects of climate change on gradients and flow velocities through the Culebra. As discussed in the CCA, Chapter 6.0, Section 6.4.9 (and Corbet and Knupp 1996), the maximum effect of a future, wetter climate would be to raise the water table to the ground surface. This would raise heads and gradients in all units above the Salado. For the Culebra, the maximum change in gradient was estimated to be about a factor of 2.1. The effect of climate change is incorporated in compliance calculations through the Climate Index, which is used as a multiplier for Culebra groundwater velocities. The Climate Index has a bimodal distribution, with the range from 1.00 to 1.25 having a 75% probability, and the range from 1.50 to 2.25 having a 25% probability. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and deeper units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.9.3.4 Connections Between the Culebra and Shallower Units

Abandoned boreholes could also provide interconnections for long-term fluid flow between shallow units (overlying the Salado). Abandoned boreholes could provide pathways for downward flow of water from the Dewey Lake and/or Magenta to the Culebra because the Culebra hydraulic head is lower than the hydraulic heads of these units. Magenta freshwater heads are as much as 45 m (148 ft) higher than Culebra freshwater heads. Because the Culebra is generally at least one order of magnitude more transmissive than the Magenta at any location, a connection between the Magenta and Culebra would cause proportionally more drawdown in the Magenta head than rise in the Culebra head. For example, for a one-order-of-magnitude difference in transmissivity and a 45-m (148-ft) difference in head, the Magenta head would decrease by approximately 40 m (131 ft) while the Culebra head increased by 5 m (16 ft). This head increase in the Culebra would also be a localized effect, decreasing with radial distance from the leaking borehole. The primary flow direction in the Culebra across the WIPP site is from north to south, with the Culebra head decreasing by approximately 20 m (66 ft) across this distance. A 5-m (16-ft) increase in Culebra head at the northern WIPP boundary would, therefore, increase gradients by at most 25%.

The Dewey Lake freshwater head at the WQSP-6 pad is 55 m (180 ft) higher than the Culebra freshwater head. Leakage from the Dewey Lake could have a greater effect on Culebra head

than leakage from the Magenta if the difference in transmissivity between the Dewey Lake and Culebra observed at the WQSP-6 pad, where the Dewey Lake is two orders of magnitude more transmissive than the Culebra (Beauheim and Ruskauff 1998), persists over a wide region. However, the saturated, highly transmissive zone in the Dewey Lake has only been observed south of the WIPP disposal panels. A connection between the Dewey Lake and the Culebra south of the panels would tend to decrease the north-south gradient in the Culebra across the site, not increase it.

In any case, leakage of water from overlying units into the Culebra could not increase Culebra heads and gradients as much as might result from climate change, discussed above. Because implementation of the Climate Index leads to radionuclide releases through the Culebra that are orders of magnitude lower than the regulatory limits, the effects of flow between the Culebra and shallower units through abandoned boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.9.3.5 Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes

Leakage from historical, current, and near-future abandoned boreholes that penetrate pressurized brine pockets in the Castile could give rise to fluid density changes in affected units. Wilmot and Galson (1996) showed that brine density changes in the Culebra resulting from leakage through an abandoned borehole would not have a significant effect on the Culebra flow field. A localized increase in fluid density in the Culebra resulting from leakage from an abandoned borehole would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the freshwater head gradient and the gravitational gradient, based on an analysis similar to that presented in Section SCR-5.2.1.6 (FEPs H27, H28, and H29), shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.1.9.3.6 Future Human EPs

The EPA provides criteria for analysis of the consequences of future drilling events in section 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete, the borehole is plugged according to current practice in the Delaware Basin (see the CCA, Chapter 6.0, Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.9.3.7 Hydraulic Effects of Flow Through Abandoned Boreholes

A future borehole that penetrates a Castile brine reservoir could provide a connection for brine flow from the reservoir to the waste panel, thus increasing fluid pressure and brine volume in the waste panel. Long-term natural borehole fluid flow through such a borehole is accounted for in PA calculations (see the CCA, Chapter 6.0, Section 6.4.8).

Deep, abandoned boreholes that intersect the Salado interbeds near the waste disposal panels could provide pathways for long-term radionuclide transport from the waste panels to the land surface or to overlying units. The potential significance of such events were assessed by the WIPP PA Department (1991, B-26 to B-27), which examined single-phase flow and transport

between the waste panels and a borehole intersecting MB 139 outside the DRZ. The analysis assumed an in situ pressure of 11 MPa in MB 139, a borehole pressure of 6.5 MPa (975 psi) (hydrostatic) at MB 139, and a constant pressure of 18 MPa (2,700 psi) as a source term in the waste panels representing gas generation. Also, MB 139 was assigned a permeability of approximately 3×10^{-20} m^2 (3.2×10^{-19} ft^2) and a porosity of 0.01%. The disturbed zone was assumed to exist in MB 139 directly beneath the repository only and was assigned a permeability of 1.0×10^{-17} m^2 (1.1×10^{-16} ft^2) and a porosity of 0.055%. Results showed that the rate of flow through a borehole located just 0.25 m (0.8 ft) outside the DRZ would be more than two orders of magnitude less than the rate of flow through a borehole located within the DRZ because of the contrast in permeability. Thus any releases of radionuclides to the accessible environment through deep boreholes that do not intersect waste panels would be insignificant compared to the releases that would result from transport through boreholes that intersect waste panels. Thus radionuclide transport through deep boreholes that do not intersect waste panels has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.9.3.8 Fluid Flow and Radionuclide Transport in the Culebra

Fluid flow and radionuclide transport within the Culebra could be affected if future boreholes result in hydraulic connections between the Culebra and either deeper or shallower units. Over the 10,000-yr regulatory period, a large number of deep boreholes could be drilled within and around the controlled area (see the CCA, Chapter 6.0, Section 6.4.12.2). The effects on the performance of the disposal system of long-term hydraulic connections between the Culebra and deeper or shallower units would be the same as those discussed above for historic, current, and near-future conditions. Thus the effects of flow between the Culebra and deeper or shallower units through abandoned future boreholes can be screened out on the basis of low consequence.

SCR-5.2.1.9.3.9 Changes in Fluid Density Resulting from Flow Through Abandoned Boreholes

A future borehole that intersects a pressurized brine reservoir in the Castile could also provide a source for brine flow to the Culebra in the event of borehole casing leakage, with a consequent localized increase in fluid density in the Culebra. The effect of such a change in fluid density would be to increase any density-driven component of groundwater flow. If the downdip direction, along which the density-driven component would be directed, is different from the direction of the groundwater pressure gradient, there would be a slight rotation of the flow vector towards the downdip direction. The groundwater modeling presented by Davies (1989, p. 50) indicates that a borehole that intersects a pressurized brine pocket and causes a localized increase in fluid density in the Culebra above the waste panels would result in a rotation of the flow vector slightly towards the east. However, the magnitude of this effect would be small in comparison to the magnitude of the pressure gradient (see screening argument for FEPs H27, H28, and H29, Section SCR-5.2.1.6, where this effect is screened out on the basis of low consequence).

SCR-5.2.1.10 FEP Number: H32
FEP Title: *Waste-Induced Borehole Flow*

SCR-5.2.1.10.1 Screening Decision: SO-R (HCN)
DP (Future)

Waste-induced flow through boreholes drilled in the near future has been eliminated from PA calculations on regulatory grounds. *Waste-Induced Borehole Flow* through a future borehole that intersects a waste panel are accounted for in PA calculations.

SCR-5.2.1.10.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.1.10.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Continued resource exploration and production in the near future will result in the occurrence of many more abandoned boreholes in the vicinity of the controlled area. Institutional controls will prevent drilling (other than that associated with the WIPP development) from taking place within the controlled area in the near future. Therefore, no boreholes will intersect the waste disposal region in the near future, and waste-induced borehole flow in the near future has been eliminated from PA calculations on regulatory grounds.

SCR-5.2.1.10.3.1 Future Human EPs
The EPA provides criteria concerning analysis of the consequences of future drilling events in section 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete, the borehole is plugged according to current practice in the Delaware Basin (see the CCA, Chapter 6.0, Section 6.4.7.2). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.10.3.2 Hydraulic Effects of Flow Through Abandoned Boreholes
An abandoned future borehole that intersects a waste panel could provide a connection for contaminant transport away from the repository horizon. If the borehole has degraded casing and/or plugs, and the fluid pressure within the waste panel is sufficient, radionuclides could be transported to the land surface. Additionally, if brine flows through the borehole to overlying units, such as the Culebra, it may carry dissolved and colloidal actinides that can be transported laterally to the accessible environment by natural groundwater flow in the overlying units. Long-term waste-induced borehole flow is accounted for in PA calculations (see Appendix PA-2009, Section PA-2.1.4.5).

SCR-5.2.1.11 **FEP Number:** H34
FEP Title: *Borehole-Induced Solution and Subsidence*

SCR-5.2.1.11.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of *Borehole-Induced Solution and Subsidence* associated with existing, near-future, and future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.1.11.3 Screening Argument

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.11.3.1 Historical, Current, and Near-Future Human EPs
SCR-5.2.1.11.3.1.1 Borehole-Induced Solution and Subsidence
During the period covered by HCN FEPs, drilling within the land withdrawn for the WIPP will be controlled, and boreholes will be plugged according to existing regulations. Under these circumstances and during this time period, borehole-induced solution and subsidence at WIPP is eliminated from PA calculations on the basis of no consequence to the disposal system.

Outside the area withdrawn for the WIPP, drilling has been regulated, but conditions of historical and existing boreholes are highly variable. Borehole-induced solution and subsidence may occur in these areas, although it is expected to be limited and should not affect the disposal system, as discussed in the following paragraphs.

Three features are required for significant borehole-induced solution and subsidence to occur: a borehole, an energy gradient to drive unsaturated (with respect to halite) water through the evaporite-bearing formations, and a conduit to allow migration of brine away from the site of dissolution. Without these features, minor amounts of halite might be dissolved in the immediate vicinity of a borehole, but percolating water would become saturated with respect to halite and stagnant in the bottom of the drillhole, preventing further dissolution.

At, and in the vicinity of, the WIPP site, drillholes penetrating into, but not through, the evaporite-bearing formations have little potential for dissolution. Brines coming from the Salado and Castile, for example, have high total dissolved solids and are likely to precipitate halite, not dissolve more halite during passage through the borehole. Water infiltrating from the surface or near-surface units may not be saturated with halite. For drillholes with a total depth in halite-

bearing formations, there is little potential for dissolution because the halite-bearing units have very low permeability and provide little outlet for the brine created as the infiltrating water fills the drillhole. ERDA-9 is the deepest drillhole in the immediate vicinity of the waste panels at the WIPP; the bottom of the drillhole is in the uppermost Castile, with no known outlet for brine at the bottom.

Drillholes penetrating through the evaporite-bearing formations provide possible pathways for circulation of water. Underlying units in the vicinity of the WIPP site with sufficient potentiometric levels or pressures to reach or move upward through the halite units generally have one of two characteristics: (1) high-salinity brines, which limit or eliminate the potential for dissolution of evaporites, or (2) are gas producers. Wood et al. (1982) analyzed natural processes of dissolution of the evaporites by water from the underlying Bell Canyon. They concluded that brine removal in the Bell Canyon is slow, limiting the movement of dissolution fronts or the creation of natural collapse features. Existing drillholes that are within the boundaries of the withdrawn land and also penetrate through the evaporites are not located in the immediate vicinity of the waste panels or WIPP workings.

There are three examples in the region that appear to demonstrate the process for borehole-induced solution and subsidence, but the geohydrologic setting and drillhole completions differ from those at or near the WIPP.

An example of borehole-induced solution and subsidence occurred in 1980 about 160 km (100 mi) southeast of the WIPP site (outside the Delaware Basin) at the Wink Sink (Baumgardner et al. 1982; Johnson 1989), where percolation of shallow groundwater through abandoned boreholes, dissolution of the Salado, and subsidence of overlying units led to a surface collapse feature 110 m (360 ft) in width and 34 m (110 ft) deep. At the Wink Sink, the Salado is underlain by the Tansill, Yates, and Capitan Formations, which contain vugs and solution cavities through which brine could migrate. Also, the hydraulic head of the Santa Rosa (the uppermost aquifer) is greater than those of the deep aquifers (Tansill, Yates, and Capitan), suggesting downward flow if a connection were established. A second sink (Wink Sink 2) formed in May 2002, near the earlier sink (Johnson et al. 2003). Its origin is similar to the earlier sink. By February 2003, Wink Sink 2 had enlarged by surface collapse to a length of about 305 m (1,000 ft) and a width of about 198 m (650 ft).

A similar, though smaller, surface collapse occurred in 1998 northwest of Jal, New Mexico (Powers 2000). The most likely cause of collapse appears to be dissolution of Rustler, and possibly Salado, halite as relatively low salinity water from the Capitan Reef circulated through breaks in the casing of a deep water supply well. Much of the annulus behind the casing through the evaporite section was uncemented, and work in the well at one time indicated bent and ruptured casing. The surface collapse occurred quickly, and the sink was initially about 23 m (75 ft) across and a little more than 30 m (100 ft) deep. By 2001, the surface diameter was about 37 m (120 ft), and the sink was filled with collapse debris to about 18 m (60 ft) below the ground level (Powers, in press).

The sinkholes near Wink, Texas and Jal, New Mexico, occurred above the Capitan Reef (which is by definition outside the Delaware Basin), and the low-salinity water and relatively high potentiometric levels of the Capitan Reef appear to be integral parts of the process that formed

these sinkholes. They are reviewed as examples of the process of evaporite dissolution and subsidence related to circulation in drillholes. Nevertheless, the factors of significant low salinity water and high potentiometric levels in units below the evaporites do not appear to apply at the WIPP site.

Beauheim (1986) considered the direction of natural fluid flow through boreholes in the vicinity of the WIPP. Beauheim (1986, p. 72) examined hydraulic heads measured using drill stem tests in the Bell Canyon and the Culebra at well DOE-2 and concluded that the direction of flow in a cased borehole open only to the Bell Canyon and the Culebra would be upward. Bell Canyon waters in the vicinity of the WIPP site are saline brines (e.g., Lambert 1978; Beauheim et al. 1983; Mercer et al. 1987), limiting the potential for dissolution of the overlying evaporites. However, dissolution of halite in the Castile and the Salado would increase the relative density of the fluid in an open borehole, causing a reduction in the rate of upward flow. The direction of borehole fluid flow could potentially reverse, but such a flow could be sustained only if sufficient driving pressure, porosity, and permeability exist for fluid to flow laterally within the Bell Canyon. A further potential sink for Salado-derived brine is the Capitan Limestone. However, the subsurface extent of the Capitan Reef is approximately 16 km (10 mi) from the WIPP at its closest point, and this unit will not provide a sink for brine derived from boreholes in the vicinity of the controlled area. A similar screening argument is made for natural deep dissolution in the vicinity of the WIPP (see N16 and N18, Section SCR-4.1.5.1 and Section SCR-4.1.5.2).

The effects of borehole-induced solution and subsidence through a waste panel are considered below. The principal effects of borehole-induced solution and subsidence in the remaining parts of the disposal system should be to change the hydraulic properties of the Culebra and other rocks in the system. The features are local (limited lateral dimensions) and commonly nearly circular. If subsidence occurs along the expected travel path and the transmissivity of the Culebra is increased, as in the calculations conducted by Wallace (1996c), the travel times should increase. If the transmissivity along the expected flow path decreased locally as a result of such a feature, the flow path should be lengthened by travel around the feature. Thus the effects of borehole-induced solution and subsidence around existing abandoned boreholes, and boreholes drilled and abandoned in the near-future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.11.3.2 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in section 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Appendix PA-2009, Section PA-2.1.4.5). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.11.3.2.1 Borehole-Induced Solution and Subsidence

Future boreholes that do not intersect the WIPP excavation do not differ in long-term behavior or consequences from existing boreholes, and can be eliminated from PA on the basis of low consequence to the performance of the disposal system.

The condition of more apparent concern is a future borehole that intersects the WIPP excavation. Seals and casings are assumed to degrade, connecting the excavation to various units. For a drillhole intersecting the excavation, but not connecting to a brine reservoir or to formations below the evaporites, downward flow is limited by the open volume of the disposal room(s), which is dependent with time, gas generation, or brine inflow to the disposal system from the Salado.

Maximum dissolution, and maximum increase in borehole diameter, will occur at the top of the Salado; dissolution will decrease with depth as the percolating water becomes salt saturated. Eventually, degraded casing and concrete plug products, clays, and other materials will fill the borehole. Long-term flow through a borehole that intersects a waste panel is accounted for in DP calculations by assuming that the borehole is eventually filled by such materials, which have the properties of a silty sand (see Appendix PA-2009, Section PA-2.1.4.5). However, these calculations assume that the borehole diameter does not increase with time. Under the conditions assumed in the CCA for an E2 drilling event at 1,000 years, about 1,000 m^3 (35,316 ft^3) would be dissolved from the lower Rustler and upper Salado. If the dissolved area is approximately cylindrical or conical around the borehole, and the collapse/subsidence propagates upward as occurred in breccia pipes (e.g., Snyder and Gard 1982), the diameter of the collapsed or subsided area through the Culebra and other units would be a few tens of meters across. Changes in hydraulic parameters for this small zone should slow travel times for any hypothesized radionuclide release, as discussed for HCN occurrences. This does not change the argument for low consequence due to borehole-induced solution and subsidence for these circumstances.

If a drillhole through a waste panel and into deeper evaporites intercepts a Castile brine reservoir, the brine has little or no capability of dissolving additional halite. The Castile brine flow is considered elsewhere as part of DP. There is, however, no *Borehole-Induced Solution and Subsidence* under this circumstance, and therefore there is no effect on performance because of this EP.

If a borehole intercepts a waste panel and also interconnects with formations below the evaporite section, fluid flow up or down is determined by several conditions and may change over a period of time (e.g., as dissolution increases the fluid density in the borehole). Fluid flow downward is not a concern for performance, as fluid velocities in units such as the Bell Canyon are slow and should not be of concern for performance (Wilson et al., 1996). As with boreholes considered for HCN, the local change in hydraulic parameters, if it occurs along the expected flow path, would be expected to cause little change in travel time and should increase the travel time.

In summary, the effects of borehole-induced solution and subsidence around future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.12 FEP Number: H35
FEP Title: *Borehole-Induced Mineralization*

SCR-5.2.1.12.1 Screening Decision: SO-C (HCN)
SO-C (Future)

The effects of *Borehole-Induced Mineralization*, associated with existing, near-future, and future abandoned boreholes, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.12.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.1.12.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units, such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

Potentially, boreholes could provide pathways for surface-derived water or groundwater to percolate through low-permeability strata and into formations containing soluble minerals. Large-scale dissolution through this mechanism could lead to subsidence and to changes in groundwater flow patterns. Also, fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation.

SCR-5.2.1.12.3.1 Borehole-Induced Mineralization

Fluid flow between hydraulically conductive horizons through a borehole may result in changes in permeability in the affected units through mineral precipitation. For example:

- Limited calcite precipitation may occur as the waters mix in the Culebra immediately surrounding the borehole, and calcite dissolution may occur as the brines migrate away from the borehole as a result of variations in water chemistry along the flow path.

- Gypsum may be dissolved as the waters mix in the Culebra immediately surrounding the borehole but may precipitate as the waters migrate through the Culebra.

The effects of these mass transfer processes on groundwater flow depend on the original permeability structure of the Culebra rocks and the location of the mass transfer. The volumes of minerals that may precipitate or dissolve in the Culebra as a result of the injection of Castile or

Salado brine through a borehole will not affect the existing spatial variability in the permeability field significantly.

Predicted radionuclide transport rates in the Culebra assume that the dolomite matrix is diffusively accessed by the contaminants. The possible inhibition of matrix diffusion by secondary mineral precipitation on fracture walls as a result of mixing between brines and Culebra porewater was addressed by Wang (1998). Wang showed that the volume of secondary minerals precipitated because of this mechanism was too small to significantly affect matrix porosity and accessibility.

Consequently, the effects of borehole-induced mineralization on permeability and groundwater flow within the Culebra, as a result of brines introduced via any existing abandoned boreholes and boreholes drilled and abandoned in the near future, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.12.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in section 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Appendix PA-2009, Section PA-2.1.4.5). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.12.4.1 Borehole-Induced Mineralization

Fluid flow between hydraulically conductive horizons through a future borehole may result in changes in permeability in the affected units through mineral precipitation. However, the effects of mineral precipitation as a result of flow through a future borehole in the controlled area will be similar to the effects of mineral precipitation as a result of flow through an existing or near-future borehole (see FEP H32, Section SCR-5.2.1.10). Thus borehole-induced mineralization associated with flow through a future borehole has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.1.13 **FEP Number:** H36
FEP Title: *Borehole-Induced Geochemical Changes*

SCR-5.2.1.13.1 Screening Decision: UP (HCN)
DP (Future)
SO-C for units other than the Culebra

Geochemical changes that occur inside the controlled area as a result of long-term flow associated with HCN and future abandoned boreholes are accounted for in PA calculations.

SCR-5.2.1.13.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.1.13.3 Screening Argument

Abandoned boreholes could provide pathways for fluid flow and, potentially, contaminant transport between any intersected zones. For example, such boreholes could provide pathways for vertical flow between transmissive units in the Rustler, or between the Culebra and units below the Salado, which could affect fluid densities, flow rates, and flow directions.

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra, and thus alter radionuclide migration rates in these units.

SCR-5.2.1.13.3.1 Geochemical Effects of Borehole Flow

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units if they occur sufficiently close to the edge of the controlled area, or if they occur as a result of flow through existing boreholes within the controlled area through their effects on colloid transport and sorption.

The contents of the waste disposal panels provide the main source of colloids in the disposal system. Thus, consistent with the discussion in Section SCR-5.2.1.4 (*Borehole-Induced Geochemical Changes* [H24]), colloid transport as a result of flow through existing and near-future abandoned boreholes has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in H24, sorption within the Culebra is accounted for in PA calculations. The sorption model used accounts for the effects of changes in sorption in the Culebra as a result of flow through existing and near-future abandoned boreholes.

Consistent with the screening discussion in Section SCR-5.2.1.4, the effects of changes in sorption in the Dewey Lake inside the controlled area as a result of flow through existing and near-future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.1.13.4 Future Human EPs

The EPA provides criteria concerning analysis of the consequences of future drilling events in section 194.33(c). Consistent with these criteria, the DOE assumes that after drilling is complete the borehole is plugged according to current practice in the Delaware Basin (see Appendix PA-2009, Section PA-2.1.4.5). Degradation of casing and/or plugs may result in connections for fluid flow and, potentially, contaminant transport between connected hydraulically conductive

zones. The long-term consequences of boreholes drilled and abandoned in the future will primarily depend on the location of the borehole and the borehole casing and plugging methods used.

SCR-5.2.1.13.4.1 Geochemical Effects of Flow Through Abandoned Boreholes

Movement of fluids through abandoned boreholes could result in borehole-induced geochemical changes in the receiving units, such as the Salado interbeds or Culebra. Such geochemical changes could alter radionuclide migration rates within the disposal system in the affected units through their effects on colloid transport and sorption.

The waste disposal panels provide the main source of colloids in the disposal system. Colloid transport within the Culebra as a result of long-term flow associated with future abandoned boreholes that intersect the waste disposal region are accounted for in PA calculations, as described in the CCA, Chapter 6.0, Section 6.4.3.6 and Section 6.4.6.2.1. Consistent with the discussion in Section SCR-5.2.1.4, colloid transport as a result of flow through future abandoned boreholes that do not intersect the waste disposal region has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The Culebra is the most transmissive unit in the disposal system and it is the most likely unit through which significant radionuclide transport could occur. Therefore, colloid transport in units other than the Culebra, as a result of flow through future abandoned boreholes, has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

As discussed in Section SCR-5.2.1.4, sorption within the Culebra is accounted for in PA calculations. The sorption model accounts for the effects of changes in sorption in the Culebra as a result of flow through future abandoned boreholes.

Consistent with the screening discussion in Section SCR-5.2.1.4, the effects of changes in sorption in the Dewey Lake within the controlled area as a result of flow through future abandoned boreholes have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Sorption within other geological units of the disposal system has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-5.2.2 Excavation-Induced Flow

SCR-5.2.2.1 FEP Number: H37
FEP Title: *Changes in Groundwater Flow Due to Mining*

SCR-5.2.2.1.1 Screening Decision: UP (HCN)
DP (Future)

Changes in Groundwater Flow due to *Mining* (HCN and future) are accounted for in PA calculations.

SCR-5.2.2.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.2.1.3 Screening Argument

Excavation activities may result in hydrological disturbances of the disposal system. Subsidence associated with excavations may affect groundwater flow patterns through increased hydraulic conductivity within and between units. Fluid flow associated with excavation activities may also result in changes in brine density and geochemistry in the disposal system.

SCR-5.2.2.1.3.1 Historical, Current, and Near-Future Human EPs

Currently, potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (3.1 mi) from the boundaries of the controlled area. Mining of the McNutt Potash Zone in the Salado is expected to continue in the vicinity of the WIPP (see the CCA, Chapter 2.0, Section 2.3.1.1): the DOE assumes that all economically recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.1.3.2 Hydrogeological Effects of Mining

Potash mining in the Delaware Basin typically involves constructing vertical shafts to the elevation of the ore zone and then extracting the minerals in an excavation that follows the trend of the ore body. Potash has been extracted using conventional room-and-pillar mining, secondary mining where pillars are removed, and modified long-wall mining methods. Mining techniques used include drilling and blasting (used for mining langbeinite) and continuous mining (commonly used for mining sylvite). The DOE (Westinghouse 1994, pp. 2-17 to 2-19) reported investigations of subsidence associated with potash mining operations located near the WIPP. The reported maximum total subsidence at potash mines is about 1.5 m (5 ft), representing up to 66% of initial excavation height, with an observed angle of draw from the vertical at the edge of the excavation of 58 degrees. The DOE (Westinghouse 1994 pp. 2-22 to 2-23) found no evidence that subsidence over local potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the surface. However, subsidence and fracturing associated with mining in the McNutt in the vicinity of the WIPP may allow increased recharge to the Rustler units and affect the lateral hydraulic conductivity of overlying units, such as the Culebra, which could influence the direction and magnitude of fluid flow within the disposal system. Such changes in groundwater flow due to mining are accounted for in calculations of UP of the disposal system. The effects of any increased recharge that may be occurring are, in effect, included by using heads measured in 2000 (which should reflect that recharge) to calibrate Culebra transmissivity fields (T fields) and calculate transport through those fields (Beauheim 2002). Changes (increases) in Culebra transmissivity are incorporated directly in the modeling of flow and transport in the Culebra (see the CCA, Chapter 6.0, Section 6.4.6.2.3).

Potash mining, and the associated processing outside the controlled area, have changed fluid densities within the Culebra, as demonstrated by the areas of higher densities around boreholes WIPP-27 and WIPP-29 (Davies 1989, p. 43). Transient groundwater flow calculations (Davies 1989, pp. 77–81) show that brine density variations to the west of the WIPP site caused by historical and current potash processing operations will not persist because the rate of groundwater flow in this area is fast enough to flush the high-density groundwaters to the Pecos River. These calculations also show that accounting for the existing brine density variations in

the region east of the WIPP site, where hydraulic conductivities are low, would have little effect on the direction or rate of groundwater flow. Therefore, changes in fluid densities from historical and current human EPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The distribution of existing leases and potash grades suggests that near-future mining will take place to the north, west, and south of the controlled area (see the CCA, Appendix DEL). A localized increase in fluid density in the Culebra, in the mined region or elsewhere outside the controlled area, would rotate the flow vector towards the downdip direction (towards the east). A comparison of the relative magnitudes of the pressure gradient and the density gradient (based on an analysis identical to that presented for fluid leakage to the Culebra through boreholes) shows that the density effect is of low consequence to the performance of the disposal system.

SCR-5.2.2.1.4 Future Human EPs

Consistent with section 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in the CCA, Chapter 2.0, Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in section 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with section 194.32(b), changes in groundwater flow due to mining within the controlled area are accounted for in calculations of the DP of the disposal system (see the CCA, Chapter 6.0, Section 6.4.6.2.3).

SCR-5.2.2.2 FEP Number: H38
FEP Title: *Changes in Geochemistry Due to Mining*

SCR-5.2.2.2.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in Geochemistry due to Mining (HCN) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Changes in Geochemistry due to Mining* have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.2.2.3 Screening Argument

SCR-5.2.2.2.3.1 Historical, Current, and Near-Future Human EPs

Potash mining is the only excavation activity currently taking place in the vicinity of the WIPP that could affect hydrogeological or geochemical conditions in the disposal system. Potash is mined in the region east of Carlsbad and up to 5 km (1.5 mi) from the boundaries of the controlled area. Mining of the McNutt in the Salado is expected to continue in the vicinity of the WIPP (see the CCA, Chapter 2.0, Section 2.3.1.1): the DOE assumes that all economically

recoverable potash in the vicinity of the WIPP (outside the controlled area) will be extracted in the near future.

SCR-5.2.2.2.3.2 Geochemical Effects of Mining

Fluid flow associated with excavation activities may result in geochemical disturbances of the disposal system. Some waters from the Culebra reflect the influence of current potash mining, having elevated potassium to sodium ratios. However, potash mining has had no significant effect on the geochemical characteristics of the disposal system. Solution mining, which involves the injection of freshwater to dissolve the ore body, can be used for extracting sylvite. The impact on the WIPP of neighboring potash mines was examined in greater detail by D'Appolonia (1982). D'Appolonia noted that attempts to solution mine sylvite in the Delaware Basin failed because of low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. See discussion in Section SCR-5.1.2.1 (*Conventional Underground Potash Mining* [H13]). Thus changes in geochemistry due to mining (HCN) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.2.2.3.3 Future Human EPs

Consistent with section 194.32(b), consideration of future mining may be limited to potash mining within the disposal system. Within the controlled area, the McNutt provides the only potash of appropriate quality. The extent of possible future potash mining within the controlled area is discussed in the CCA, Chapter 2.0, Section 2.3.1.1. Criteria concerning the consequence modeling of future mining are provided in section 194.32(b): the effects of future mining may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system. Thus, consistent with section 194.32(b), changes in groundwater flow as a result of mining within the controlled area are accounted for in calculations of the DP of the disposal system (see the CCA, Chapter 6.0, Section 6.4.6.2.3). Other potential effects, such as changes in geochemistry due to mining, have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.2.3 FEP Number H58
FEP Title: *Solution Mining for Potash*

SCR-5.2.2.3.1 Screening Decision: SO-R (HCN)
SO-R (Future)

HCN and future *Solution Mining for Potash* has been eliminated from PA calculations on regulatory grounds. HCN and future solution mining for other resources has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.2.3.2 Summary of New Information

Plans for the development of a potash solution mine in the region continue, although the solution process has not begun; the project remains in the permitting and planning stage. The project lies outside the Delaware Basin, but the DOE maintains communication with the leaseholder and the U.S. Bureau of Land Management to monitor project status.

SCR-5.2.2.3.3 Screening Argument

Currently, no solution mining for potash occurs in the CPD. The prospect of using solution-mining techniques for extracting potash has been identified in the region, but has not been implemented. A pilot plant for secondary solution mining of sylvite in the Clayton Basin, just north of the Delaware Basin was permitted, and concept planning took place during the mid-1990s and was noted by the EPA in their Response to Comments to the CCA (U.S. Environmental Agency 1998c). Continued progress has been made towards initiating this project, but as of the submittal of this recertification application, the project has not begun. The project intends to solution mine sylvite from retired underground mine workings at the old Potash Corporation of America lease. To date, discharge permits have been filed with the State of New Mexico, but are pending. Therefore, it is premature to consider this an operational solution mining activity. More importantly, the proposed site is outside the Delaware Basin.

The potash reserves evaluated by Griswold and Griswold (1999) and New Mexico Bureau of Mines and Mineral Resources (1995) at the WIPP are of economic importance in only two ore zones; the 4^{th} and the 10^{th} contain two minerals of economic importance, langbeinite and sylvite. The ore in the 10^{th} ore zone is primarily sylvite with some langbeinite and the ore in the 4th zone is langbeinite with some sylvite. Langbeinite falls between gypsum and polyhalite in solubility and dissolves at a rate 1000 times slower than sylvite (Heyn 1997). Halite, the predominate gangue mineral present, is much more soluble than the langbeinite. Because of the insolubility of langbeinite, sylvite is the only potash ore in the WIPP vicinity that could be mined using a solution mining process. Mining for sylvite by solutioning would cause the langbeinite to be lost because conventional mining could not be done in conjunction with a solution mining process.

Communiqués with IMC Global (Heyn 1997, Prichard 2003) indicate that rock temperature is critical to the success of a solution-mining endeavor. IMC Global's solution mines in Michigan and Saskatchewan are at depths of around 914 m (3,000 ft) or greater, at which rock temperatures are higher. The ore zones at the WIPP are shallow, at depths of 457 to 549 m (1,500 to 1,800 ft), with fairly cool rock temperatures. Prichard (2003) states that solution mining is energy intensive and the cool temperature of the rock would add to the energy costs. In addition, variable concentrations of confounding minerals (such as kainite and leonite) will cause problems with the brine chemistry.

Typically, solution mining is used for potash

- When deposits are at depths in excess of 914 m (3,000 ft) and rock temperatures are high, or are geologically too complex to mine profitably using conventional underground mining techniques
- To recover the potash pillars at the end of a mine's life
- When a mine is unintentionally flooded with waters from underlying or overlying rock strata and conventional mining is no longer feasible

Douglas W. Heyn (chief chemist of IMC Kalium) provided written testimony to the EPA related to the Agency's rulemaking activities on the CCA. Heyn concluded that "the rational choice for

extracting WIPP potash ore reserves would be by conventional room and pillar mechanical means" (Heyn 1997). It is the opinion of IMC Global that no company will ever attempt solution mining of the ores in or near the WIPP (Heyn 1997, Prichard 2003).

The impact on the WIPP of neighboring potash mines and the possible effects of solution mining for potash or other evaporite minerals were examined in detail by D'Appolonia (1982). According to D'Appolonia (1982), and in agreement with Heyn (1997) of IMC Global, Inc., solution mining of langbeinite is not technically feasible because the ore is less soluble than the surrounding evaporite minerals. Solution mining of sylvite was unsuccessfully attempted in the past by the Potash Company of America and Continental Potash. Both ore bodies are currently owned by Mississippi Chemical. Failure of solution mining was attributed to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. Unavailability of water in the area would also impede implementation of this technique. For these reasons, solution mining is not currently used in the CPD.

Serious technical and economic obstacles exist that render solution mining for potash very unlikely in the vicinity of the WIPP. Expectedly, no operational example of this technology exists in the CPD; that is, solution mining for potash in not considered a current practice in the area. For this reason, consideration of solution mining on the disposal system in the future may be excluded on regulatory grounds. For example, the EPA stated in their Response to Comments, Section 8, Issue GG (EPA 1998c):

> …However, the Agency emphasizes that, in accordance with the WIPP compliance criteria, solution mining does not need to be included in the PA. As previously discussed, potash solution mining is not an ongoing activity in the Delaware Basin. Section 194.32(b) of the rule limits assessment of mining effects to excavation mining. Thus the solution mining scenarios proposed are excluded on regulatory grounds after repository closure. Prior to or soon after disposal, solution mining is an activity that could be considered under Section 194.32(c). However, DOE found that potash solution mining is not an ongoing activity in the Delaware Basin; and one pilot project examining solution mining in the Basin is not substantive evidence that such mining is expected to occur in the near future. (Even if mining were assumed to occur in the near future, the proposed scenarios would not be possible because, even though solution mining might occur, there would be no intruding borehole to provide a pathway into the repository: active institutional controls would preclude such drilling during the first 100 years after disposal.) Furthermore, Section 194.33(d) states that PA need not analyze the effects of techniques used for resource recovery (e.g. solution mining) after a borehole is drilled in the future.

No new data or information have become available that compromise, reduce, or invalidate the project's position on whether solution mining for potash should be included in the PA calculations. Therefore, conventional mining activities will continue to be incorporated into the WIPP PA as directed by the EPA CAG (U.S. Environmental Protection Agency 1996b). It remains to be seen if a viable potash solution mining project (or others like it) ever progress beyond the planning phase. Construction of a facility for solution mining is an expensive undertaking, and its use as a final recovery method implies that marginal (residual) ore quantities are available. Because the CPD mines are in their mature (declining) stages of production, the significant financing required for a solution mining facility may not become available. Nonetheless, at the time of this FEP reassessment, this technology is not being employed. Therefore, a screening based on the future states assumption at section 194.25(a) is appropriate

for this mining technique. Further, the proposed site is outside the Delaware Basin, making it outside the scope of consideration.

SCR-5.2.2.4 FEP Number: H59
FEP Title: *Solution Mining for Other Resources*

SCR-5.2.2.4.1 Screening Decision: SO-C (HCN)
SO-C (Future)

HCN and future *Solution Mining for Other Resources* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.2.4.2 Summary of New Information

Brine well information provided in Table SCR-3 has been updated based on new information from the Delaware Basin Monitoring Program (U.S. Department of Energy 2007b). Since the CRA-2004, active brine wells have increased from 11 to 12 wells.

SCR-5.2.2.4.3 Screening Argument

Brine wells (solution mining for brine) exist within the Delaware Basin, although none within the vicinity of the WIPP. Sulfur extraction using the Frasch process began in 1969 and continued for three decades at the Culberson County Rustler Springs mine near Orla, Texas. Solution mining for the purposes of creating a storage cavity has not occurred within the New Mexico portion of the Delaware Basin.

SCR-5.2.2.4.4 Solution Mining for Brine

Oil and gas reserves in the Delaware Basin are located in structures within the Delaware Mountain Group and lower stratigraphic units. Boreholes drilled to reach these horizons pass through the Salado and Castile that comprise thick halite and other evaporite units. To avoid dissolution of the halite units during drilling and prior to casing of the borehole, the fluid used for lubrication, rotating the drilling-bit cutters, and transporting cuttings (drilling mud) must be saturated with respect to halite. Most oil- and gas-field drilling operations in the Delaware Basin therefore use saturated brine (10 to 10.5 pounds per gallon [lb/gal]) as a drilling fluid until reaching the Bell Canyon, where intermediate casing is set.

One method of providing saturated brine for drilling operations is solution mining, whereby fresh water is pumped into the Salado, allowed to reach saturation with respect to halite, and then recovered. This manufactured brine is then transported to the drilling site by water tanker.

Two principal techniques are used for solution mining: single-borehole operations and doublet or two-borehole operations.

Table SCR-3. Delaware Basin Brine Well Status

County	Location	API No.	Well Name and No.	Operator	Status
Eddy	22S-26E-36	3001521842	City of Carlsbad #WS-1	Key Energy Services	Brine Well
Eddy	22S-27E-03	3001520331	Tracy #3	Ray Westall	Plugged Brine Well
Eddy	22S-27E-17	3001522574	Eugenie #WS-1	I & W Inc	Brine Well
Eddy	22S-27E-17	3001523031	Eugenie #WS-2	I & W Inc	Plugged Brine Well
Eddy	22S-27E-23	3001528083	Dunaway #1	Mesquite SWD, Inc.	Brine Well
Loving	Blk 29-03	4230110142	Lineberry Brine Station #1	Chance Properties	Brine Well
Loving	Blk 01-82	4230130680	Chapman Ford #BR1	Herricks & Son Co.	Plugged Brine Well
Loving	Blk 33-80	4230180318	Mentone Brine Station #1D	Basic Energy Services	Brine Well
Loving	Blk 29-28	4230180319	East Mentone Brine Station #1	Permian Brine Sales, Inc.	Plugged Brine Well
Loving	Blk 01-83	4230180320	North Mentone #1	Chance Properties	Brine Well
Reeves	Blk 56-30	4238900408	Orla Brine Station #1D	Mesquite SWD Inc.	Brine Well
Reeves	Blk 04-08	4238920100	North Pecos Brine Station #WD-1	Chance Properties	Brine Well
Reeves	Blk 07-21	4238980476	Coyanosa Brine Station #1	Chance Properties	Brine Well
Ward	Blk 17-20	4247531742	Pyote Brine Station #WD-1	Chance Properties	Brine Well
Ward	Blk 01-13	4247534514	Quito West Unit #207	Seaboard Oil Co.	Brine Well
Ward	Blk 34-174	4247582265	Barstow Brine Station #1	Chance Properties	Brine Well

In single-borehole operations, a borehole is drilled into the upper part of the halite unit. After casing and cementing this portion of the borehole, the borehole is extended, uncased, into the halite formation. An inner pipe is installed from the surface to the base of this uncased portion of the borehole. During operation, fresh water is pumped down the annulus of the borehole. This dissolves halite over the uncased portion of the borehole, and saturated brine is forced up the inner tube to the surface.

In doublet operations, a pair of boreholes are drilled, cased, and cemented into the upper part of the halite unit. The base of the production well is set some feet below the base of the injection well. In the absence of natural fractures or other connections between the boreholes, hydrofracturing is used to induce fractures around the injection well. During operation, fresh water is pumped down the injection well. This initially dissolves halite from the walls of the fractures and the resulting brine is then pumped from the production well. After a period of operation a cavity develops between the boreholes as the halite between fractures is removed. Because of its lower density, fresh water injected into this cavity will rise to the top and dissolve

halite from the roof of the cavity. As the brine density increases it sinks within the cavern and saturated brine is extracted from the production well.

SCR-5.2.2.4.4.1 Current Brine Wells within the Delaware Basin

Brine wells are classified as Class II injection wells. In the Delaware Basin, the process includes injecting fresh water into a salt formation to create a saturated brine solution which is then extracted and utilized as a drilling agent. These wells are tracked by the DBDSP on a continuing basis. Supplemental information provided to the EPA in 1997 showed 11 brine wells in the Delaware Basin. Since that time, additional information has shown that there are 16 brine wells within the Delaware basin, of which 4 are plugged and abandoned. This results in 12 currently active brine wells. Table SCR-3 provides information on these wells.

While these wells are within the Delaware Basin, none are within the vicinity of the WIPP. The nearest brine well to the WIPP is the Eugenie #WS-1, located within the city limits of Carlsbad, New Mexico. This well is approximately 48 km (30 mi) from the WIPP site.

SCR-5.2.2.4.5 Solution Mining for Other Minerals

Currently, there are no ongoing solution mining activities within the vicinity of the WIPP. The Rustler Springs sulfur mine located in Culberson County, Texas, began operations in 1969 and continued until it was officially closed in 1999. This mine used the Frasch process (superheated water injection) to extract molten sulfur (Cunningham 1999).

SCR-5.2.2.4.6 Solution Mining for Gas Storage

No gas storage cavities have been solution mined within the New Mexico portion of the Delaware Basin. Five gas storage facilities exist within the general vicinity of the WIPP; however, only one is within the Delaware basin. This one New Mexico Delaware Basin facility uses a depleted gas reservoir for storage and containment; it was not solution mined (see the CRA-2004, Appendix DATA, Attachment A, Section DATA-A-5.4).

SCR-5.2.2.4.7 Solution Mining for Disposal

Solution mining can be used to create a disposal cavity in bedded salt. Such disposal cavities can be used for the disposal of naturally occurring radioactive material or other wastes. No such cavities have been mined or operated within the vicinity of the WIPP.

SCR-5.2.2.4.8 Effects of Solution Mining

SCR-5.2.2.4.8.1 Subsidence

Regardless of whether the single-borehole or two-borehole technique is used for solution mining, the result is a subsurface cavity which could collapse and lead to subsidence of overlying strata. Gray (1991) quoted earlier analyses that show cavity stability is relatively high if the cavity has at least 15 m (50 ft) of overburden per million cubic feet of cavity volume (26.9 m per 50,000 m^3). There are two studies – discussed below – on the size of solution-mining cavities in the Carlsbad, New Mexico region. These studies concern the Carlsbad Eugenie Brine Wells and

the Carlsbad Brine Well and show that neither of these cavities are currently close to this critical ratio, but that subsidence in the future, given continued brine extraction, is a possibility.

Hickerson (1991) considered the potential for subsidence resulting from operation of the Carlsbad Eugenie Brine wells, where fresh water is injected into a salt section at a depth of 178 m (583 ft) and brine is recovered through a borehole at a depth of 179 m (587 ft). The boreholes are 100 m (327 ft) apart. Hickerson noted that the fresh water, being less dense than brine, tends to move upwards, causing the dissolution cavern to grow preferentially upwards. Thus the dissolution cavern at the Carlsbad Eugenie Brine wells is approximately triangular in cross-section, being bounded by the top of the salt section and larger near the injection well. Hickerson estimated that brine production from 1979 until 1991 had created a cavern of about 9.6×10^4 m^3 (3.4×10^6 ft^3). The size of this cavern was estimated as 107 m (350 ft) by 47 m (153 ft) at the upper surface of the cavern with a depth of 39 m (127 ft).

Gray (1991) investigated the potential for collapse and subsidence at the Carlsbad Brine Well. Based on estimated production rates between 1976 and 1991, approximately 9.6×10^4 m^3 (3.4×10^6 ft^3) of salt has been dissolved at this site. The well depth is 216 m (710 ft), and thus there are about 64 m (210 ft) of overburden per million cubic feet of capacity (112 m of overburden per 50,000 m^3 of capacity).

Gray (1991) also estimated the time required for the cavity at the Carlsbad Brine Well to reach the critical ratio. At an average cavity growth rate of 6.4×10^3 m^3 per year (2.25×10^5 ft^3 per year), a further 50 years of operation would be required before cavity stability was reduced to levels of concern. A similar calculation for the Carlsbad Eugenie Brine well, based on an overburden of 140 m (460 ft) and an estimated average cavity growth rate of 7.9×10^3 m^3 per year (2.8×10^5 ft^3 per year), shows that a further 15 years of operation is required before the cavity reaches the critical ratio.

SCR-5.2.2.4.8.2 Hydrogeological Effects

In regions where solution mining takes place, the hydrogeology could be affected in a number ways:

- Subsidence above a large dissolution cavity could change the vertical and lateral hydraulic conductivity of overlying units.
- Extraction of fresh water from aquifers for solution mining could cause local changes in pressure gradients.
- Loss of injected fresh water or extracted brine to overlying units could cause local changes in pressure gradients.

The potential for subsidence to take place above solution mining operations in the region of Carlsbad, New Mexico is discussed above. Some subsidence could occur in the future if brine operations continue at existing wells. Resulting fracturing may change permeabilities locally in overlying formations. However, because of the restricted scale of the solution mining at a particular site, and the distances between such wells, such fracturing will have no significant effect on hydrogeology near the WIPP.

Solution mining operations in the Delaware Basin extract water from shallow aquifers so that, even if large drawdowns are permitted, the effects on the hydrogeology will be limited to a relatively small area around the operation. Since all the active operations are more than 32 km (20 mi) from the WIPP, there will be no significant effects on the hydrogeology near the WIPP.

Discharge plans for solution mining operations typically include provision for annual mechanical integrity tests at one and one-half the normal operating pressure for four hours (New Mexico Oil Conservation Division 1994). Thus the potential for loss of integrity and consequent leakage of freshwater or brine to overlying formations is low. If, despite these annual tests, large water losses did take place from either injection or production wells, the result would be low brine yields and remedial actions would most likely be taken by the operators.

SCR-5.2.2.4.8.3 Geochemical Effects

Solution mining operations could affect the geochemistry of surface or subsurface water near the operation if there were brine leakage from storage tanks or production wells. Discharge plans for solution mining operations specify the measures to be taken to prevent leakage and to mitigate the effects of any that do take place. These measures include berms around tanks and annual mechanical integrity testing of wells (New Mexico Oil Conservation Division 1994). The potential for changes in geochemistry is therefore low, and any brine losses that did take place would be limited by remedial actions taken by the operator. In the event of leakage from a production well, the effect on geochemistry of overlying formation waters would be localized and, given the distance of such wells from the WIPP site, such leakage would have no significant effect on geochemistry near the WIPP.

SCR-5.2.2.4.9 Conclusion of Low Consequence

Brine production through solution mining takes place in the Delaware Basin, and the DOE assumes it will continue in the near future. Because of the existence of these solution operations, it is not possible to screen this activity based on the provisions of section 194.25(a). However, despite oil and gas exploration and production taking place in the vicinity of the WIPP site, the nearest operating solution mine is more than 32 km (20 mi) from the WIPP site. These locations are too far from the WIPP site for any changes in hydrogeology or geochemistry, from subsidence or fresh water or brine leakage, to affect the performance of the disposal system. Thus the effects of HCN and future solution mining for other resources in the Delaware Basin can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3 Explosion-Induced Flow

SCR-5.2.3.1 FEP Number: H39
FEPs Title: Changes in Groundwater Flow Due to Explosions

SCR-5.2.3.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

Changes in Groundwater Flow due to Explosions (HCN) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Changes in groundwater flow that may be caused by future explosions have been eliminated from PA calculations on regulatory grounds.

SCR-5.2.3.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.2.3.1.3 Screening Argument

SCR-5.2.3.1.3.1 Historical, Current, and Near-Future Human EPs

The small-scale explosions that have been used in the Delaware Basin to fracture oil- and natural-gas-bearing units to enhance resource recovery have been too deep to have disturbed the hydrology of the disposal system (see FEP H19, Section SCR-5.1.3.1).

Also, as discussed in Section SCR-5.1.3.2 (*Underground Nuclear Device Testing* [H20]), the Delaware Basin has been used for an isolated nuclear test (Project Gnome), approximately 13 km (8 mi) southwest of the WIPP waste disposal region. An induced zone of increased permeability was observed to extend 46 m (150 ft) laterally from the point of the explosion. The increase in permeability was primarily associated with motions and separations along bedding planes, the major preexisting weaknesses in the rock. This region of increased permeability is too far from the WIPP site to have had a significant effect on the hydrological characteristics of the disposal system. Thus changes in groundwater flow due to explosions in the past have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.2.3.1.3.2 Future Human EPs

The criterion in section 194.32(a) relating to the scope of PAs limits the consideration of future human actions to mining and drilling. Also, consistent with section 194.33(d), PAs need not analyze the effects of techniques used for resource recovery subsequent to the drilling of a future borehole. Therefore, changes in groundwater flow due to explosion*s* in the future have been eliminated from PA calculations on regulatory grounds.

SCR-5.3 Geomorphological EPS

SCR-5.3.1 Land Use Changes

SCR-5.3.1.1 FEP Number: H40
FEP Title: *Land Use Changes*

SCR-5.3.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Land Use Changes have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.3.1.1.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46 (Section SCR-5.4.1.1, Section SCR-5.4.1.2, and Section SCR-5.4.1.3).

SCR-5.3.1.1.4 Historical, Current, and Near-Future Human EPs

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of archeological investigations have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP), and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the Mississippi Potash Inc. (MPI) East tailings pile, approximately 10 km (6 mi) due north of the WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra T fields developed for the CRA used water levels measured in 2000 to define model boundary conditions. Thus the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

The Delaware Basin monitoring program monitors land use activities in the WIPP vicinity. This program has not identified new planned uses for land in the vicinity of the WIPP (U.S. Department of Energy 2007b). Therefore, consistent with the criteria in section 194.32(c) and 40 CFR § 194.54(b) (U.S. Environmental Protection Agency 1996a), land use changes in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.1.5 Future Human EPs

The criterion in section 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions." Therefore, no

future land use change*s* need be considered in the vicinity of the WIPP, and they have been eliminated from PA calculations on regulatory grounds.

SCR-5.3.1.2 FEP Number: H41
FEP Title: *Surface Disruptions*

SCR-5.3.1.2.1 Screening Decision: UP (HCN)
SO-C (Future)

The effects of HCN *Surface Disruptions* are accounted for in PA calculations. The effects of future *Surface Disruptions* have been eliminated from PA calculations on the basis of low consequence.

SCR-5.3.1.2.2 Summary of New Information

The screening decision has been changed from SO-R to SO-C. The EPA's TSD for Features, Events, and Processes (U.S. Environmental Protection Agency 2006) identified an inconsistency between the screening decision and the screening rationale. After review, it has been determined that SO-C is the correct screening decision and the previous classification of SO-R is not correct.

SCR-5.3.1.2.3 Screening Argument

This section discusses surface activities that could affect the geomorphological characteristics of the disposal system and result in changes in infiltration and recharge conditions. The potential effects of water use and control on disposal system performance are discussed in FEPs H42 through H46.

SCR-5.3.1.2.4 Historical, Current, and Near-Future Human EPs

Most surface activities have no potential to affect the disposal system and are, therefore, screened out on the basis of low consequence (e.g., archaeological excavations andarable farming). However, the effects of activities capable of altering the disposal system (disposal of potash effluent) are included in the modeling of current conditions (i.e., heads) at and around the site. Discussion regarding these anthropogenic effects is found in the CRA-2004, Chapter 2.0, Section 2.2.1.4.2.2.

Surface activities that take place at present in the vicinity of the WIPP site include those associated with potash mining, oil and gas reservoir development, water extraction, and grazing. Additionally, a number of archeological investigations have taken place within the controlled area that were aimed at protecting and preserving cultural resources. Elsewhere in the Delaware Basin, sand, gravel, and caliche are produced through surface quarrying. The only surface activity that has the potential to affect the disposal system is potash tailings, salt tailings (both potash and WIPP), and effluent disposal. Potash tailings ponds may act as sources of focused recharge to the Dewey Lake and Rustler units.

Three potash tailings piles/ponds are in operation that might be influencing groundwater flow at the WIPP site. These are the MPI East tailings pile, approximately 10 km (6 mi) due north of the

WIPP, the MPI West tailings pile in the northwest arm of Nash Draw, and the IMC Kalium tailings pile, approximately 10 km (6 mi) due west of the WIPP in Nash Draw. These tailings piles have been in operation for decades—disposal at the MPI East site, the youngest of the piles, began in 1965. Brine disposal at these locations affects Rustler groundwaters in Nash Draw, as shown by the hydrochemical facies D waters described by Siegel et al. (1991, p. 2-61). Brine disposal also affects heads in Nash Draw, and these head effects likely propagate to the WIPP site as well. These effects, however, predate water-level monitoring for the WIPP and have been implicitly included when defining boundary heads for Culebra flow models. The Culebra T fields developed for the CRA used water levels measured in 2000 to define model boundary conditions. Thus the effects of brine disposal at the tailings piles can be considered to be included in PA calculations. These effects are expected to continue in the near future.

SCR-5.3.1.2.5 Future Human EPs

Future tailings ponds, if situated in Nash Draw, are expected to change Culebra (and Magenta) heads, similar to existing ones. Future tailings ponds outside of Nash Draw would not be expected to alter Culebra heads because leakage from the ponds would not be able to propagate through the low-permeability lower Dewey Lake clastics and Rustler anhydrites overlying the Culebra during the 100 years or less that such a pond might be in operation. Because PA calculations already include the present-day effects of tailings ponds in Nash Draw on heads, as well as the effects of future potash mining on the permeability of the Culebra (which has much greater potential to alter flow than changes in head), future surface disruptions affecting hydrologic or geologic conditions (such as potash tailings ponds) may be screened out on the basis of low consequence.

SCR-5.4 Surface Hydrological EPs

SCR-5.4.1 Water Control and Use

SCR-5.4.1.1 FEP Numbers: H42, H43, and H44
FEP Titles: *Damming of Streams and Rivers* (H42)
Reservoirs (H43)
Irrigation (H44)

SCR-5.4.1.1.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN *Damming of Streams and Rivers*, *Reservoirs*, and *Irrigation* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Damming of Streams and Rivers*, *Reservoirs*, and *Irrigation* have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-5.4.1.1.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake.

SCR-5.4.1.1.4 Historical, Current, and Near-Future Human EPs

In the WIPP area, two topographically low features, the Pecos River and Nash Draw, are sufficiently large to warrant consideration for damming. Dams and reservoirs already exist along the Pecos River. However, the Pecos River is far enough from the waste panels (19 km [12 mi]) that the effects of damming of streams and rivers and reservoirs can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Nash Draw is not currently dammed, and based on current hydrological and climatic conditions, there is no reason to believe it will be dammed in the near future.

Irrigation uses water from rivers, lakes, impoundments, and wells to supplement the rainfall in an area to grow crops. Irrigation in arid environments needs to be efficient and involves the spreading of a relatively thin layer of water for uptake by plants, so little water would be expected to infiltrate beyond the root zone. However, some water added to the surface may infiltrate and reach the water table, affecting groundwater flow patterns. Irrigation currently takes place on a small scale within the Delaware Basin but not in the vicinity of the WIPP, and the extent of irrigation is not expected to change in the near future. Such irrigation has no significant effect on the characteristics of the disposal system. Thus the effects of irrigation have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-5.4.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in section 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future damming of streams and rivers, reservoirs, and irrigation have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.2 FEP Number: H45
FEP Title: *Lake Usage*

SCR-5.4.1.2.1 Screening Decision: SO-R (HCN)
SO-R (Future)

The effects of *Lake Usage* have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.2.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-5.4.1.2.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry. Note that the potential effects of geomorphological changes through land use are discussed in Section SCR-5.3.1.1 and Section SCR-5.3.1.2.

SCR-5.4.1.2.4 Historical, Current, and Near-Future Human EPs

As discussed in the CCA, Chapter 2.0, Section 2.2.2, there are no major natural lakes or ponds within 8 km (5 mi) of the site. To the northwest, west, and southwest, Red Lake, Lindsey Lake, and Laguna Grande de la Sal are more than 8 km (5 mi) from the site, at elevations of 914 to 1,006 m (3,000 to 3,300 ft). Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 16 km (10 mi) north and are at elevations of 1,050 m (3,450 ft) or higher.

Waters from these lakes are of limited use. Therefore human activities associated with lakes have been screened out of PA calculations based on regulatory grounds supported by section 194.32(c) and section 194.54(b).

SCR-5.4.1.2.5 Future Human EPs

The EPA has provided criteria relating to future human activities in section 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future lake usage have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.3 FEP Number: H46
FEP Title: *Altered Soil or Surface Water Chemistry by Human Activities*

SCR-5.4.1.3.1 Screening Decision: SO-C (HCN)
SO-R (Future)

The effects of HCN *Altered Soil or Surface Water Chemistry by Human Activities* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Future *Altered Soil or Surface Water Chemistry by Human Activities* have been eliminated from PA calculations on regulatory grounds.

SCR-5.4.1.3.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-5.4.1.3.3 Screening Argument

Irrigation and damming, as well as other forms of water control and use, could lead to localized changes in recharge, possibly leading to increased heads locally, thereby affecting flow

directions and velocities in the Rustler and Dewey Lake. Surface activities, such as those associated with potash mining, could also affect soil and surface water chemistry.

SCR-5.4.1.3.4 Historical, Current, and Near-Future Human EPs

Potash mining effluent and runoff from oil fields have altered soil and surface water chemistry in the vicinity of the WIPP. However, the performance of the disposal system will not be sensitive to soil and surface water chemistry. Therefore, altered soil or surface water chemistry by human activities has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The effects of effluent from potash processing on groundwater flow are discussed in H37 (Section SCR-5.2.2.1).

SCR-5.4.1.3.5 Future Human EPs

The EPA has provided criteria relating to future human activities in section 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future altered soil or surface water chemistry by human activities have been eliminated from PA calculations on regulatory grounds.

SCR-5.5 Climatic EPs

SCR-5.5.1 Anthropogenic Climate Change

SCR-5.5.1.1 FEP Numbers: H47, H48, and H49
FEP Titles: *Greenhouse Gas Effects* (H47)
Acid Rain (H48)
Damage to the Ozone Layer (N49)

SCR-5.5.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

The effects of anthropogenic climate change (*Acid Rain*, *Greenhouse Gas Effects*, and *Damage to the Ozone Layer*) have been eliminated from PA calculations on regulatory grounds.

SCR-5.5.1.1.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-5.5.1.1.3 Anthropogenic Climate Change

The effects of the current climate and natural climatic change are accounted for in PA calculations, as discussed in the CCA, Chapter 6.0, Section 6.4.9 and Appendix PA-2009, Section PA-4.8. However, human activities may also affect the future climate and thereby influence groundwater recharge in the WIPP region. The effects of anthropogenic climate change may be on a local to regional scale (acid rain) or on a regional to global scale (greenhouse gas effects and damage to the ozone layer). Of these anthropogenic effects, only the greenhouse gas effect could influence groundwater recharge in the WIPP region. However,

consistent with the future states assumptions in section 194.25, compliance assessments and PAs need not consider indirect anthropogenic effects on disposal system performance. Therefore, the effects of anthropogenic climate change have been eliminated from PA calculations on regulatory grounds.

SCR-5.6 Marine EPs

SCR-5.6.1 Marine Activities

SCR-5.6.1.1 FEP Numbers: H50, H51, and H52
FEP Titles: *Costal Water Use* (H50)
Seawater Use (H51)
Estuarine Water Use (H52)

SCR-5.6.1.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

HCN, and future *Coastal Water Use*, *Seawater Use*, and *Estuarine Water Use* have been eliminated from PA calculations on regulatory grounds.

SCR-5.6.1.1.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-5.6.1.1.3 Screening Argument

This section discusses the potential for human EPs related to marine activities to affect infiltration and recharge conditions in the vicinity of the WIPP.

SCR-5.6.1.1.4 Historical, Current, and Near-Future Human EPs

The WIPP site is more than 800 km (480 mi) from the nearest seas, and hydrological conditions in the vicinity of the WIPP have not been affected by marine activities. Furthermore, consistent with the criteria in section 194.32(c) and section 194.54(b), consideration of HCN human activities is limited to those activities that have occurred or are expected to occur in the vicinity of the disposal system. Therefore, Human EPs related to marine activities (such as coastal water use, seawater use, and estuarine water use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.6.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in section 194.32(a) that limit the scope of consideration of future human actions in PAs to mining and drilling. Therefore, the effects of future marine activities (such as coastal water use, seawater use, and estuarine water use) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7 Ecological EPs

SCR-5.7.1 Agricultural Activities

SCR-5.7.1.1 FEP Numbers: H53, H54, and H55
FEP Titles: *Arable Farming* (H53)
Ranching (H54)
Fish Farming (H55)

SCR-5.7.1.1.1 Screening Decision: SO-C (HCN) (H53, H54)
SO-R (HCN) (H55)
SO-R (Future) (H53, H54, H55)

The effects of HCN *Ranching* and *Arable Farming* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The effects of changes in future *Ranching* and *Arable Farming* practices have been eliminated from PA calculations on regulatory grounds. *Fish Farming* has been eliminated from PA calculations on regulatory grounds.

SCR-5.7.1.1.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-5.7.1.1.3 Screening Argument

Agricultural activities could affect infiltration and recharge conditions in the vicinity of the WIPP. Also, application of acids, oxidants, and nitrates during agricultural practice could alter groundwater geochemistry.

SCR-5.7.1.1.4 Historical, Current, and Near-Future Human EPs

Grazing leases exist for all land sections immediately surrounding the WIPP and grazing occurs within the controlled area (see the CCA, Chapter 2.0, Section 2.3.2.2). Although grazing and related crop production have had some control on the vegetation at the WIPP site, these activities are unlikely to have affected subsurface hydrological or geochemical conditions. The climate, soil quality, and lack of suitable water sources all mitigate against agricultural development of the region in the near future. Therefore, the effects of HCN ranching and arable farming have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Consistent with the criteria in section 194.32(c) and section 194.54(b), agricultural activities, such as fish farming, that have not taken place and are not expected to take place in the near future in the vicinity of the WIPP have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.1.1.5 Future Human EPs

The EPA has provided criteria relating to future human activities in section 194.32(a) that limit the scope of consideration of future human activities in PAs to mining and drilling. Also, the

criterion in section 194.25(a) concerned with predictions of the future states of society requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, the effects of changes in future agricultural practices (such as ranching, arable farming, and fish farming) have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2 Social and Technological Development

SCR-5.7.2.1 FEP Number: H56
FEP Title: *Demographic Change and Urban Development*

SCR-5.7.2.1.1 Screening Decision: SO-R (HCN)
SO-R (Future)

Demographic Change and Urban Development in the near future and in the future have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.7.2.1.3 Screening Argument

Social and technological changes in the future could result in the development of new communities and new activities in the vicinity of the WIPP that could have an impact on the performance of the disposal system.

Demography in the WIPP vicinity is discussed in the CCA, Chapter 2.0, Section 2.3.2.1. The community nearest to the WIPP site is the town of Loving, 29 km (18 mi) west-southwest of the site center. There are no existing plans for urban developments in the vicinity of the WIPP in the near future. Furthermore, the criterion in section 194.25(a), concerned with predictions of the future states of society, requires that compliance assessments and PAs "shall assume that characteristics of the future remain what they are at the time the compliance application is prepared." Therefore, demographic change and urban development in the vicinity of the WIPP and technological developments have been eliminated from PA calculations on regulatory grounds.

SCR-5.7.2.2 FEP Number: H57
FEP Title: *Loss of Records*

SCR-5.7.2.2.1 Screening Decision: **Not Applicable** (N/A) (HCN)
DP (Future)

Loss of Records in the future is accounted for in PA calculations.

SCR-5.7.2.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-5.7.2.2.3 Screening Argument

Because the DOE will maintain control for the current period throughout the active institutional period (100 years after closure), inadvertent drilling intrusion resulting from the loss of records is not applicable during the HCN period. However, PAs must consider the potential effects of human activities that might take place within the controlled area at a time when institutional controls cannot be assumed to eliminate completely the possibility of human intrusion. Consistent with 40 CFR § 194.41(b) (U.S. Environmental Protection Agency 1996a), the DOE assumes no credit for AICs for more than 100 years after disposal. Also, consistent with 40 CFR § 194.43(c) (U.S. Environmental Protection Agency 1996a), the DOE originally assumed in the CCA that passive institutional controls (PICs) do not eliminate the likelihood of future human intrusion entirely. The provisions at section 194.43(c) allow credit for PICs by reducing the likelihood of human intrusions for several hundred years. In U.S. Department of Energy 1996a, the DOE took credit for these controls that include records retention by reducing the probability of intrusion for the first 600 years after active controls cease. The EPA disallowed this credit during the original certification (U.S. Environmental Protection Agency 1998a). The DOE no longer takes credit for PICs in PA, effectively assuming that all public records and archives relating to the repository are lost 100 years after closure. Therefore, the DOE continues to include the loss of records FEP within PA and does not include credit for PICs.

SCR-6.0 Waste and Repository-Induced FEPs

This section presents screening arguments and decisions for waste- and repository-induced FEPs. There are 114 waste- and repository-induced FEPs used in the CRA-2009. Of these, 74 remain unchanged since the CRA-2004 and 26 were updated with new information. Further, 7 FEPs have been split into 14 similar, but more descriptive, FEPs since the CRA-2004.

SCR-6.1 Waste and Repository Characteristics

SCR-6.1.1 Repository Characteristics

SCR-6.1.1.1 FEP Number: W1
FEP Title: *Disposal Geometry*

SCR-6.1.1.1.1 Screening Decision: UP

The WIPP repository *Disposal Geometry* is accounted for in PA calculations.

SCR-6.1.1.1.2 Summary of New Information

Representation of the repository within the PA has not changed since the CRA-2004; the screening argument and decision remain unchanged. Disposal geometry is accounted for in PA calculations.

SCR-6.1.1.2 Screening Argument

Disposal geometry is described in the CRA-2004, Chapter 3.0, Section 3.2 and is accounted for in the setup of PA calculations (the CRA-2004, Chapter 6.0, Section 6.4.2).

SCR-6.1.2 Waste Characteristics

SCR-6.1.2.1 FEP Number: W2 and W3
FEP Title: *Waste Inventory*
Heterogeneity of Waste Forms

SCR-6.1.2.1.1 Screening Decision: UP (W2)
DP (W3)

The *Waste Inventory* and *Heterogeneity of Waste Forms* are accounted for in PA calculations.

SCR-6.1.2.1.2 Summary of New Information

The waste inventory used for the CRA-2009 PA calculations is the same as used for the CRA-2004 Performance Assessment Baseline Calculation (PABC) (see Clayton 2008 and Leigh et al. 2005). Since these FEPs are accounted for (UP) in PA, the implementation may differ from that used in the in previous PAs; however, the screening decision has not changed.

SCR-6.1.2.1.3 Screening Argument

Waste characteristics, comprising the waste inventory and heterogeneity of waste forms, are described in the CCA, Appendix BIR. The waste inventory is accounted for in PA calculations in deriving the dissolved actinide source term (see the CRA-2004, Appendix SOTERM) and gas generation rates (see Leigh, Trone, and Fox 2005, Section 2.3). The distribution of contact-handled (CH) transuranic (TRU) (CH-TRU) and remote-handled (RH) transuranic (TRU) (RH-TRU) waste within the repository leads to room-scale heterogeneity of the waste forms, which is accounted for in PA calculations when considering the potential activity of waste material encountered during inadvertent borehole intrusion (Appendix PA-2009, Section PA-3.8).

SCR-6.1.3 Container Characteristics

SCR-6.1.3.1 FEP Number: W4
FEP Title: *Container Form*

SCR-6.1.3.1.1 Screening Decision: SO-C – Beneficial

The *Container Form* has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.3.1.2 Summary of New Information

The physical form of the containers is conservatively ignored in performance calculations. Some inventory information has been updated since the CRA-2004. This inventory is slightly different than that used for the CRA-2004, although no changes affect the container form. As such, changes represented in the inventory used for this application do not affect this FEP or its screening decision.

SCR-6.1.3.1.3 Screening Argument

The container form has been eliminated from PA calculations on the basis of its beneficial effect on retarding radionuclide release. The PA assumes instantaneous container failure and waste dissolution consistent with the source-term model, even though WIPP performance calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see Helton et al. 1998). All these undegraded container materials will (1) prevent contact between brine and radionuclides; (2) decrease the rate and extent of radionuclide transport because of high tortuosity along the flow pathways and, as a result, increase opportunities for metallic iron (Fe) and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, the container form can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. In the CCA, Appendix WCL, a minimum quantity of metallic Fe was specified to ensure sufficient reactants to reduce radionuclides to lower and less soluble oxidation states. This requirement is met as long as there are no substantial changes in container materials. The inventory used for the CRA-2009 indicates that the density of steel in container materials currently reported by the sites has an average value of 170 kg/m^3. This is the same value used for the CRA-2004, but represents an increase over what was reported for the CCA (139 to 230 kg/m^3) (8.6 to 14.3 lb/ft^3). Therefore, the current

inventory estimates indicate that there is a sufficient quantity of metallic iron to ensure reduction of radionuclides to lower and less soluble oxidation states.

SCR-6.1.3.2 FEP Number: W5
FEP Title: *Container Material Inventory*

SCR-6.1.3.2.1 Screening Decision: UP

The *Container Material Inventory* is accounted for in PA calculations.

SCR-6.1.3.2.2 Summary of New Information

No new information has been identified that relates to this FEP.

SCR-6.1.3.2.3 Screening Argument

The container material inventory is described in Leigh, Trone, and Fox (2005), and is accounted for in PA calculations through the estimation of gas generation rates (see Appendix PA-2009, Section PA-4.2.5).

SCR-6.1.4 Seal Characteristics

SCR-6.1.4.1 FEP Numbers: W6, W7, W109, and W110
FEP Titles: *Shaft Seal Geometry* (W6)
Shaft Seal Physical Properties (W7)
Panel Closure Geometry (W109)
Panel Closure Physical Properties (W110)

SCR-6.1.4.1.1 Screening Decision: UP

The *Shaft Seal Geometry*, *Shaft Seal Physical Properties*, *Panel Closure Geometry*, and *Panel Closure Properties* are accounted for in PA calculations.

SCR-6.1.4.1.2 Summary of New Information

FEPs related to seals (generic) have been renamed to differentiate between panel closures and shaft seals. While analyzing the impacts of redesigned panel closures on the FEPs baseline, it was concluded that the current FEPs do not accurately represent these seal types (Kirkes 2006). Because a redesigned panel closure system has not been approved or implemented, new screening arguments are not appropriate at this time, but if the request for a redesigned panel closure system is approved, revised screening arguments may be warranted to better describe the panel closure physical properties (i.e., crushed salt versus concrete).

SCR-6.1.4.1.3 Screening Argument

Seal (shaft seals, panel closures, and drift closures) characteristics, including shaft seal geometry, panel closure geometry, seal physical properties, and panel closure physical properties are

described in the CCA, Chapter 3.0, Section 3.3.2 and are accounted for in PA calculations through the representation of the seal system and panel closures in BRAGFLO and the permeabilities assigned to the shaft seal and panel closure materials (see Appendix PA-2009, Section PA-4.2.7 and Section PA-4.2.8).

SCR-6.1.4.2 FEP Numbers: W8, W111
FEP Titles: *Shaft Seal Chemical Composition* (W8)
Panel Closure Chemical Composition (W111)

SCR-6.1.4.2.1 Screening Decision: SO-C Beneficial

The *Shaft Seal Chemical Composition* has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.2 Summary of New Information

These FEPs have been retitled as a result of the FEPs analysis conducted for the Panel Closure Redesign planned change request (Kirkes 2006).

SCR-6.1.4.2.3 Screening Argument

The effect of shaft seal chemical composition and panel closure chemical composition on actinide speciation and mobility has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.4.2.4 Repository Seals (Shaft and Panel Closures)

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical speciation of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315 – 325). At high pH values, the speciation and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form.

Several publications describe strong actinide (or actinide analog) sorption by cement (Altenheinhaese et al. 1994; Wierczinski et al. 1998; Pointeau et al. 2001), or sequestration by incorporation into cement alteration phases (Gougar et al. 1996, Dickson and Glasser 2000). These provide support for the screening argument that chemical interactions between the cement seals and the brine will be of beneficial consequence to the performance of the disposal system.

The effects of cementitious materials in shaft seals and panel closures on groundwater chemistry have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.1.5 Backfill Characteristics

SCR-6.1.5.1 FEP Number: W9
FEP Title: *Backfill Physical Properties*

SCR-6.1.5.1.1 Screening Decision: SO-C

Backfill Physical Properties have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.1.5.1.2 Summary of New Information

No new information related to this FEP has been identified.

SCR-6.1.5.1.3 Screening Argument

A chemical backfill is being added to the disposal room to buffer the chemical environment. The backfill characteristics were previously described in the CCA, Appendix BACK with additional information contained in the CRA-2004, Appendix BARRIERS, Section BARRIERS-2.3.4.3. The mechanical and thermal effects of backfill are discussed in W35 (Section SCR-6.3.5.4) and W72 (Section SCR-6.3.4.1) respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Backfill will result in an initial permeability for the disposal room lower than that of an empty cavity, so neglecting the hydrological effects of backfill is a conservative assumption with regard to brine inflow and radionuclide migration. Thus backfill physical properties have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.1.5.2 FEP Number: W10
FEP Title: *Backfill Chemical Composition*

SCR-6.1.5.2.1 Screening Decision: UP

The *Backfill Chemical Composition* is accounted for in PA calculations.

SCR-6.1.5.2.2 Summary of New Information

No new information related to this FEP has been identified.

SCR-6.1.5.2.3 Screening Argument

A chemical backfill is added to the disposal room to buffer the chemical environment. The backfill characteristics are described in Appendix MgO-2009, Section MgO-3.0. The mechanical and thermal effects of backfill are discussed in W35 (Section SCR-6.3.5.4) and W72 (Section SCR-6.3.4.1), respectively, where they have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Backfill chemical composition is accounted for in PA calculations in deriving the dissolved and colloidal actinide

source terms (see Appendix SOTERM-2009, Section SOTERM-5.0 and Appendix MgO-2009, Section MgO-5.0).

SCR-6.1.6 Post-Closure Monitoring Characteristics

SCR-6.1.6.1 FEPs Number: W11
FEP Title: *Post-Closure Monitoring*

SCR-6.1.6.1.1 Screening Decision: SO-C

The potential effects of *Post-Closure Monitoring* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.1.6.1.2 Summary of New Information

No new information has been identified that relates to this FEP.

SCR-6.1.6.1.3 Screening Argument

Post-closure monitoring is required by 40 CFR § 191.14(b) (U.S. Environmental Protection Agency 1993) as an assurance requirement to "detect substantial and detrimental deviations from expected performance." The DOE has designed the monitoring program (see the CCA, Appendix MON) so that the monitoring methods employed are not detrimental to the performance of the disposal system (40 CFR § 194.42(d)) (U.S. Environmental Protection Agency 1996a). Nonintrusive monitoring techniques are used so that post-closure monitoring would not impact containment or require remedial activities. In summary, the effects of monitoring have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2 Radiological FEPs

SCR-6.2.1 Radioactive Decay and Heat

SCR-6.2.1.1 FEP Number: W12
FEP Title: *Radionuclide Decay and Ingrowth*

SCR-6.2.1.1.1 Screening Decision: UP

Radionuclide decay and ingrowth are accounted for in PA calculations.

SCR-6.2.1.1.2 Summary of New Information

No new information related to this FEP has been identified.

SCR-6.2.1.1.3 Screening Argument

Radionuclide decay and ingrowth are accounted for in PA calculations (see Appendix PA-2009, Section PA-4.3).

SCR-6.2.1.2 FEP Number: W13
FEP Title: *Heat From Radioactive Decay*

SCR-6.2.1.2.1 Screening Decision: SO-C

The effects of temperature increases as a result of *Heat From Radioactive Decay* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2.1.2.2 Summary of New Information

The radionuclide inventory used for the CRA-2009 PA calculations (Leigh, Trone, and Fox 2005a) is lower than previously estimated for the CCA. Thus all CRA-2009 radioactive decay heat screening arguments are bounded by the previous CCA screening arguments.

SCR-6.2.1.3 Screening Argument

Radioactive decay of the waste emplaced in the repository will generate heat. The importance of heat from radioactive decay depends on the effects that the induced temperature changes would have on mechanics (W29 - W31, Section SCR-6.3.4.1), fluid flow (W40 and W41, Section SCR-6.4.1.1), and geochemical processes (W44 through W75, Section SCR-6.5.1.1, Section SCR-6.5.1.2, Section SCR-6.5.1.3, Section SCR-6.5.1.4, Section SCR-6.5.1.5, Section SCR-6.5.1.6, Section SCR-6.5.1.7, Section SCR-6.5.1.8, Section SCR-6.5.1.9, Section SCR-6.5.2.1, Section SCR-6.5.2.2, Section SCR-6.5.3.1, Section SCR-6.5.4.1, Section SCR-6.5.5.1, Section SCR-6.5.5.2, Section SCR-6.5.5.3, Section SCR-6.5.6.1, Section SCR-6.5.7.1, Section SCR-6.5.7.1, and Section SCR-6.5.7.2). For example, extreme temperature increases could result in thermally induced fracturing, regional uplift, or thermally driven flow of gas and brine in the vicinity of the repository.

The design basis for the WIPP requires that the thermal loading does not exceed 10 kilowatts (kW) per acre. Transportation restrictions also require that the thermal power generated by waste in an RH-TRU container shall not exceed 300 watts (U.S. Nuclear Regulatory Commission 2002).

The DOE has conducted numerous studies related to heat from radioactive decay. The following presents a brief summary of these past analyses. First, a numerical study to calculate induced temperature distributions and regional uplift is reported in DOE (1980, pp. 9-149 through 9-150). This study involved estimation of the thermal power of CH-TRU waste containers. The DOE (1980, p. 9-149) analysis assumed the following:

- All CH-TRU waste drums and boxes contain the maximum permissible quantity of Pu. The fissionable radionuclide content for CH-TRU waste containers was assumed to be no

greater than 200 grams (g) per 0.21 m^3 (7 ounces [oz] per 7.4 ft^3) drum and 350 g/1.8 m^3 (12.3 oz/63.6 ft^3) standard waste box (^{239}Pu fissile gram equivalents).

- The Pu in CH-TRU waste containers is weapons grade material producing heat at 0.0024 watts per gram (W/g). Thus the thermal power of a drum is approximately 0.5 W, and that of a box is approximately 0.8 W.

- Approximately 3.7×10^5 m^3 (1.3×10^7 ft^3) of CH-TRU waste are distributed within a repository enclosing an area of 7.3×10^5 m^2 (7.9×10^6 ft^2). This is a conservative assumption in terms of quantity and density of waste within the repository, because the maximum capacity of the WIPP is 1.756×10^5 m^3 (6.2×10^6 ft^3) for all waste (as specified by the LWA) to be placed in an enclosed area of approximately 5.1×10^5 m^2 (16 mi^2).

- Half of the CH-TRU waste volume is placed in drums and half in boxes so that the repository will contain approximately 900,000 drums and 900,000 boxes. Thus a calculated thermal power of 0.7 W/m^2 (2.8 kW/acre) of heat is generated by the CH-TRU waste.

- Insufficient RH-TRU waste would be emplaced in the repository to influence the total thermal load.

Under these assumptions, Thorne and Rudeen (1981) estimated the long-term temperature response of the disposal system to waste emplacement. Calculations assumed a uniform initial power density of 2.8 kW/acre (0.7 W/m^2) which decreases over time. Thorne and Rudeen (1981) attributed this thermal load to RH-TRU waste, but the DOE (1980) more appropriately attributed this thermal load to CH-TRU waste based on the assumptions listed above. Thorne and Rudeen (1981) estimated the maximum rise in temperature at the center of a repository to be 1.6 °C (2.9 °F) at 80 years after waste emplacement.

More recently, Sanchez and Trellue (1996) estimated the maximum thermal power of an RH-TRU waste container. The Sanchez and Trellue (1996) analysis involved inverse shielding calculations to evaluate the thermal power of an RH-TRU container corresponding to the maximum permissible surface dose of 1,000 rem per hour (rem/hr). The following calculational steps were taken in the Sanchez and Trellue (1996) analysis:

- Calculate the absorbed dose rate for gamma radiation corresponding to the maximum surface dose equivalent rate of 1,000 rem/hr. Beta and alpha radiation are not included in this calculation because such particles will not penetrate the waste matrix or the container in significant quantities. Neutrons are not included in the analysis because the maximum dose rate from neutrons is 270 millirems/hr, and the corresponding neutron heating rate will be insignificant.

- Calculate the exposure rate for gamma radiation corresponding to the absorbed dose rate for gamma radiation.

- Calculate the gamma flux density at the surface of a RH-TRU container corresponding to the exposure rate for gamma radiation. Assuming the gamma energy is 1.0 megaelectron volts, the maximum allowable gamma flux density at the surface of a RH-TRU container is about 5.8×10^8 gamma rays/cm^2/seconds (s).

- Determine the distributed gamma source strength, or gamma activity, in an RH-TRU container from the surface gamma flux density. The source is assumed to be shielded such that the gamma flux is attenuated by the container and by absorbing material in the container. The level of shielding depends on the matrix density. Scattering of the gamma flux, with loss of energy, is also accounted for in this calculation through inclusion of a gamma buildup factor. The distributed gamma source strength is determined assuming a uniform source in a right cylindrical container. The maximum total gamma source (gamma curies [Ci]) is then calculated for a RH-TRU container containing 0.89 m^3 (31.4 ft^3) of waste. For the waste of greatest expected density (about 6,000 kg/m^3 (360 lb/ft^3), the gamma source is about 2×10^4 Ci/m^3 (566 Ci/ft^3).

- Calculate the total Ci load of a RH-TRU container (including alpha and beta radiation) from the gamma load. The ratio of the total Ci load to the gamma Ci load was estimated through examination of the radionuclide inventory presented in the CCA, Appendix BIR. The gamma Ci load and the total Ci load for each radionuclide listed in the WIPP BIR were summed. Based on these summed loads the ratio of total Ci load to gamma Ci load of RH-TRU waste was calculated to be 1.01.

- Calculate the thermal load of a RH-TRU container from the total Ci load. The ratio of thermal load to Ci load was estimated through examination of the radionuclide inventory presented in the CCA, Appendix BIR. The thermal load and the total Ci load for each radionuclide listed in the WIPP inventory were summed. Based on these summed loads the ratio of thermal load to Ci load of RH-TRU waste was calculated to be about 0.0037 watts per curie (W/Ci). For a gamma source of 2×10^4 Ci/m^3 (566 Ci/ft^3), the maximum permissible thermal load of a RH-TRU container is about 70 W/m^3 (2 W/ft^3). Thus the maximum thermal load of a RH-TRU container is about 60 W, and the transportation limit of 300 W will not be achieved.

Note that Sanchez and Trellue (1996) calculated the average thermal load for a RH-TRU container to be less than 1 W. Also, the total RH-TRU heat load is less than 10% of the total heat load in the WIPP. Thus the total thermal load of the RH-TRU waste will not significantly affect the average rise in temperature in the repository resulting from decay of CH-TRU waste.

Temperature increases will be greater at locations where the thermal power of an RH-TRU container is 60 W, if any such containers are emplaced. Sanchez and Trellue (1996) estimated the temperature increase at the surface of a 60 W RH-TRU waste container. Their analysis involved solution of a steady-state thermal conduction problem with a constant heat source term of 70 W/m^3 (2 W/ft^3). These conditions represent conservative assumptions because the thermal load will decrease with time as the radioactive waste decays. The temperature increase at the surface of the container was calculated to be about 3 °C (5.4 °F).

In summary, previous analyses have shown that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH- and RH-TRU waste will be less than 2 °C (3.6 °F). Temperature increases of about 3 °C (5.4 °F) may occur in the vicinity of RH-TRU containers with the highest allowable thermal load of about 60 W (based on the maximum allowable surface dose equivalent for RH-TRU containers). Potential heat generation from nuclear criticality is discussed in Section SCR-6.2.1.4 and exothermic reactions and the effects of repository temperature changes on mechanics are discussed in the set of FEPs grouped as W29, W30, W31, W72, and W73 (Section SCR-6.3.4.1). These FEPs have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Additionally, WIPP transportation restrictions and WIPP design basis loading configurations do not allow the thermal load of the WIPP to exceed 10 kW/acre (NRC 2002). Transportation requirements restrict the thermal load from RH-TRU waste containers to no more than 30 W per container (NRC 2002). However, the limit on the surface dose equivalent rate of the RH-TRU containers (1,000 rem/hr) is more restrictive and equates to a thermal load of only about 60 W per container. Based on the thermal loads permitted, the maximum temperature rise in the repository from radioactive decay heat should be less than 2 °C (3.6 °F).

The previous FEPs screening arguments for the CCA used a bounding radioactivity heat load of 0.5 W/drum for the CH-TRU waste containers. With a total CH-TRU volume of 168,500 m^3 (~5,950,000 ft^3) this corresponds to approximately 810,000 55-gal drum equivalents with a corresponding heat load of > 400 kW used for the CCA FEPs screening arguments. From Sanchez and Trellue (1996), it can be seen that a realistic assessment of the heat load, based on radionuclide inventory data in the Transuranic Waste Baseline Inventory Report (TWBIR) is less than 100 kW. Thus the CCA FEPs incorporate a factor of safety of at least four, and heat loads from the CRA-2009 inventory would be even less.

SCR-6.2.1.4 FEPs Number: W14
FEPs Title: Nuclear Criticality: Heat

SCR-6.2.1.4.1 Screening Decision: SO-P

Nuclear Criticality has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.2.1.4.2 Summary of New Information

Appendix PA-2009, Section PA-2.2 states that the inventory used for the CRA-2009 PA is based on Leigh, Trone, and Fox (2005). This is the same inventory used for the CRA-2004 PABC. Leigh, Trone, and Fox (2005) show that the disposal inventory of fissile material continues to decrease below that used for the CCA. Thus CRA-2009 criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.1.4.3 Screening Argument

Nuclear criticality refers to a sustained fission reaction that may occur if fissile radionuclides reach both a sufficiently high concentration and total mass (where the latter parameter includes the influence of enrichment of the fissile radionuclides). In the subsurface, the primary effect of a nuclear reaction is the production of heat.

Nuclear criticality (near and far field) was eliminated from PA calculations for the WIPP for waste contaminated with TRU radionuclides. The probability for criticality within the repository is low (there are no mechanisms for concentrating fissile radionuclides dispersed amongst the waste). Possible mechanisms for concentration in the waste disposal region include high solubility, compaction, sorption, and precipitation. First, the maximum solubility of ^{239}Pu in the WIPP repository, the most abundant fissile radionuclide, is orders of magnitude lower than necessary to create a critical solution. The same is true for ^{235}U, the other primary fissile radionuclide. Second, the waste is assumed to be compacted by repository processes to one fourth its original volume. This compaction is still an order of magnitude too disperse (many orders of magnitude too disperse if neutron absorbers that prevent criticality (for example, ^{238}U) are included). Third, any potential sorbents in the waste would be fairly uniformly distributed throughout the waste disposal region; consequently, concentration of fissile radionuclides in localized areas through sorption is improbable. Fourth, precipitation requires significant localized changes in brine chemistry; small local variations are insufficient to separate substantial amounts of ^{239}Pu from other actinides in the waste disposal region (for example, 11 times more ^{238}U is present than ^{239}Pu).

Criticality away from the repository (following an inadvertent human intrusion) has a low probability because (1) the amount of fissile material transported from the repository is small; (2) host rock media have small porosities (insufficient for the generation of a sizable precipitation zone); and (3) no credible mechanism exists for concentrating fissile material during transport (the natural tendency is for transported material to be dispersed). As discussed in the CRA-2004, Chapter 6.0, Section 6.4.6.2 and the CRA-2004, Appendix PA, Attachment MASS, Section MASS-15.0, the dolomite porosity consists of intergranular porosity, vugs, microscopic fractures, and macroscopic fractures. As discussed in the CRA-2004, Chapter 6.0, Section 6.4.5.2, porosity in the MBs consists of partially healed fractures that may dilate as pressure increases. Advective flow in both units occurs mostly through macroscopic fractures. Consequently, any potential deposition through precipitation or sorption is constrained by the depth to which precipitation and sorption occur away from fractures. This geometry is not favorable for fission reactions and eliminates the possibility of criticality. Thus nuclear criticality has been eliminated from PA calculations on the basis of low probability of occurrence.

Additionally, screening arguments made in Rechard et al. (1996) are represented in greater detail in Rechard et al. (2000, 2001). A major finding among the analysis results in the screening arguments is the determination that fissile material would need to be reconcentrated by three orders of magnitude in order to be considered in a criticality scenario. Because inventory estimates reported in Leigh, Trone and Fox (2005) are below that used in previous calculations, screening analyses for nuclear criticality are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.2.2 Radiological Effects on Material Properties

SCR-6.2.2.1 FEP Numbers: W15, W16, W17, and W112
FEP Titles: *Radiological Effects on Waste* (W15)
Radiological Effects on Containers (W16)
Radiological Effects on Shaft Seals (W17)
Radiological Effects on Panel Closures (W112)

SCR-6.2.2.1.1 Screening Decision: SO-C

Radiological Effects on the properties of the *Waste*, *Containers*, *Shaft Seals*, and *Panel Closures* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.2.2.1.2 Summary of New Information

These FEPs have been retitled as a result of the FEPs analysis conducted for the Panel Closure Redesign planned change request (Kirkes 2006), and the screening arguments for these FEPs have been updated to include references to the radionuclide inventory used for CRA-2009 PA calculations.

SCR-6.2.2.1.3 Screening Argument

Ionizing radiation can change the physical properties of many materials. Strong radiation fields could lead to damage of waste matrices, brittleness of the metal containers, and disruption of any crystalline structure in the seals. The low level of activity of the waste in the WIPP is unlikely to generate a strong radiation field. According to the inventory data presented in Leigh, Trone, and Fox (2005), the overall activity for all TRU radionuclides has decreased from 3.44×10^6 Ci reported in the CCA, to 2.48×10^6 Ci in the CRA-2004, to 2.32×10^6 Ci in the CRA-2009. This decrease will not change the original screening argument. Furthermore, PA calculations assume instantaneous container failure and waste dissolution according to the source-term model (see the CCA, Chapter 6.0, Section 6.4.3.4, Section 6.4.3.5, and Section 6.4.3.6). Therefore, radiological effects on the properties of the waste, container, shaft seals, and panel closures have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3 Geological and Mechanical FEPs

SCR-6.3.1 Excavation-Induced Changes

SCR-6.3.1.1 FEP Numbers: W18 and W19
FEP Titles: *Disturbed Rock Zone* (W18)
Excavation-Induced Change in Stress (W19)

SCR-6.3.1.1.1 Screening Decision: UP

Excavation-induced host rock fracturing through formation of a *Disturbed Rock Zone* and *Changes in Stress* are accounted for in PA calculations.

SCR-6.3.1.1.2 Summary of New Information

No new information has been identified relating to the screening of these two FEPs.

SCR-6.3.1.1.3 Screening Argument

Construction of the repository has caused local excavation-induced changes in stress in the surrounding rock as discussed in the CCA, Chapter 3.0, Section 3.3.1.5. Excavation-induced changes in stress has led to failure of intact rock around the opening, creating a DRZ of fractures. On completion of the WIPP excavation, the extent of the induced stress field perturbation will be sufficient to have caused dilation and fracturing in the anhydrite layers "a" and "b," MB 139, and, possibly, MB 138. The creation of the DRZ around the excavation and the disturbance of the anhydrite layers and MBs will alter the permeability and effective porosity of the rock around the repository, providing enhanced pathways for flow of gas and brine between the waste-filled rooms and the nearby interbeds. This excavation-induced, host-rock fracturing is accounted for in PA calculations (the CCA, Chapter 6.0, Section 6.4.5.3).

The DRZ around repository shafts and panel closures could provide pathways for flow from the repository to hydraulically conductive units above the repository horizon. The effectiveness of long-term shaft seals and panel closures are dependent upon providing sufficient backstress for salt creep to heal the DRZ around them, so that connected flow paths out of the repository horizon will cease to exist. These factors are considered in the current designs.

SCR-6.3.1.2 FEP Numbers: W20 and W21
FEP Titles: *Salt Creep* (W20)
Change in the Stress Field (W21)

SCR-6.3.1.2.1 Screening Decision: UP

Salt Creep in the Salado and any resultant *Changes in the Stress Field* are accounted for in PA calculations.

SCR-6.3.1.2.2 Summary of New Information

No new information has been identified relating to these two FEPs.

SCR-6.3.1.2.3 Screening Argument

Salt creep will lead to changes in the stress field, compaction of the waste and containers, and consolidation of the long-term components of the sealing system. It will also tend to close fractures in the DRZ, leading to reductions in porosity and permeability, increases in pore fluid pressure, and reductions in fluid flow rates in the repository. Salt creep in the Salado is

accounted for in PA calculations (the CCA, Chapter 6.0, Section 6.4.3.1). The long-term repository seal system relies on the consolidation of the crushed-salt seal material and healing of the DRZ around the shaft seals and panel closures to achieve a low permeability under stresses induced by salt creep. Shaft seal and panel closure performance is discussed further in Section SCR-6.3.5.1 (FEPs W36, W37, W113, and W114).

SCR-6.3.1.3 FEP Number: W22
FEP Title: *Roof Falls*

SCR-6.3.1.3.1 Screening Decision: UP

The potential effects of *Roof Ralls* on flow paths are accounted for in PA calculations.

SCR-6.3.1.3.2 Summary of New Information

No new information has been identified relating to this FEP.

SCR-6.3.1.3.3 Screening Argument

Instability of the DRZ could lead to localized roof falls in the first few hundred years. If instability of the DRZ causes roof falls, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep. In the long term, the effects of roof falls in the repository are likely to be minor because salt creep will reduce the void space and the potential for roof falls as well as promote healing of any roof material that has fallen into the rooms. However, because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in PA assumes that a higher permeability zone remains for the long term. Thus the potential effects of roof falls on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

SCR-6.3.1.4 FEP Numbers: W23 and W24
FEP Titles: *Subsidence* (W23)
Large Scale Rock Fracturing (W24)

SCR-6.3.1.4.1 Screening Decision(s): SO-C (W23)
SO-P (W24)

Fracturing within units overlying the Salado and surface displacement caused by *Subsidence* associated with repository closure have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The potential for excavation- or repository-induced *Subsidence* to create *Large Scale Rock Fracturing* and fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of the low probability of occurrence over 10,000 years.

SCR-6.3.1.4.2 Summary of New Information

Continuous survey data, reported annually, reaffirm that subsidence is minimal and near the accuracy of the survey itself (see annual COMPs reports in Appendix DATA-2009).

SCR-6.3.1.4.3 Screening Argument

Instability of the DRZ could lead to localized roof falls in the first few hundred years. If instability of the DRZ causes roof falls, development of the DRZ may be sufficient to disrupt the anhydrite layers above the repository, which may create a zone of rock containing anhydrite extending from the interbeds toward a waste-filled room. Fracture development is most likely to be induced as the rock stress and strain distributions evolve because of creep and the local lithologies. In the long term, the effects of roof falls in the repository are likely to be minor because salt creep will reduce the void space and the potential for roof falls as well as promote healing of any roof material that has fallen into the rooms. Because of uncertainty in the process by which the disposal room DRZ heals, the flow model used in PA assumed that a higher-permeability zone remained for the long term. The CCA PAVT modified the DRZ permeability to a sampled range. Thus the potential effects of roof falls on flow paths are accounted for in PA calculations through appropriate ranges of the parameters describing the DRZ.

The amount of subsidence that can occur as a result of salt creep closure or roof collapse in the WIPP excavation depends primarily on the volume of excavated rock, the initial and compressed porosities of the various emplaced materials (waste, backfill, panel and drift closures, and seals), the amount of inward creep of the repository walls, and the gas and fluid pressures within the repository. The DOE (Westinghouse 1994) has analyzed potential excavation-induced subsidence with the primary objective of determining the geomechanical advantage of backfilling the WIPP excavation. The DOE (Westinghouse 1994, pp. 3-4 through 3-23) used mass conservation calculations, the influence function method, the National Coal Board empirical method, and the two-dimensional, finite-difference-code, Fast Lagrangian Analysis of Continua (FLAC) to estimate subsidence for conditions ranging from no backfill to emplacement of a highly compacted crushed-salt backfill. The DOE (Westinghouse 1994, pp. 2-17 to 2-23) also investigated subsidence at potash mines located near the WIPP site to gain insight into the expected subsidence conditions at the WIPP and to calibrate the subsidence calculation methods.

Subsidence over potash mines will be much greater than subsidence over the WIPP because of the significant differences in stratigraphic position, depth, extraction ratio, and layout. The WIPP site is located stratigraphically lower than the lowest potash mine, which is near the base of the McNutt. At the WIPP site, the base of the McNutt is about 150 m (490 ft) above the repository horizon. The WIPP rock extraction ratio in the waste disposal region will be about 22%, as compared to 65% for the lowest extraction ratios within potash mines investigated by the DOE (Westinghouse 1994, p. 2-17).

The DOE (Westinghouse 1994, p. 2-22) reported the maximum total subsidence at potash mines to be about 1.5 m (5 ft). This level of subsidence has been observed to have caused surface fractures. However, the DOE (Westinghouse 1994, p. 2-23) found no evidence that subsidence over potash mines had caused fracturing sufficient to connect the mining horizon to water-bearing units or the land surface. The level of disturbance caused by subsidence above the WIPP

repository will be less than that associated with potash mining and thus, by analogy, will not create fluid flow paths between the repository and the overlying units.

The various subsidence calculation methods used by the DOE (Westinghouse 1994, pp. 3-4 to 3-23) provided similar and consistent results, which support the premise that subsidence over the WIPP will be less than subsidence over potash mines. Estimates of maximum subsidence at the land surface for the cases of no backfill and highly compacted backfill are 0.62 m (2 ft) and 0.52 m (1.7 ft), respectively. The mass conservation method gave the upper bound estimate of subsidence in each case. The surface topography in the WIPP area varies by more than 3 m (10 ft), so the expected amount of repository-induced subsidence will not create a basin, and will not affect surface hydrology significantly. The DOE (Westinghouse 1994, Table 3-13) also estimated subsidence at the depth of the Culebra using the FLAC model for the case of an empty repository (containing no waste or backfill). The FLAC analysis assumed the Salado to be halite and the Culebra to have anhydrite material parameters.

Maximum subsidence at the Culebra was estimated to be 0.56 m (1.8 ft). The vertical strain was concentrated in the Salado above the repository. Vertical strain was less than 0.01% in units overlying the Salado and was close to zero in the Culebra (Westinghouse 1994, Figure 3-40). The maximum horizontal displacement in the Culebra was estimated to be 0.02 m (0.08 ft), with a maximum tensile horizontal strain of 0.007%. The DOE (Westinghouse 1994, 4-1 to 4-2) concluded that the induced strains in the Culebra will be uniformly distributed because no large-scale faults or discontinuities are present in the vicinity of the WIPP. Furthermore, strains of this magnitude would not be expected to cause extensive fracturing.

At the WIPP site, the Culebra transmissivity varies spatially over approximately five orders of magnitude (see Appendix TFIELD-2009, Figure TFIELD-64). Where transmissive horizontal fractures exist, hydraulic conductivity in the Culebra is dominated by flow through the fractures. An induced tensile vertical strain may result in an increase in fracture aperture and corresponding increases in hydraulic conductivity. The magnitude of increase in hydraulic conductivity can be estimated by approximating the hydrological behavior of the Culebra with a simple conceptual model of fluid flow through a series of parallel fractures with uniform properties. A conservative estimate of the change in hydraulic conductivity can be made by assuming that all the vertical strain is translated to fracture opening (and none to rock expansion). This method for evaluating changes in hydraulic conductivity is similar to that used by the EPA in estimating the effects of subsidence caused by potash mining (Peake 1996, U.S. Environmental Protection Agency 1996c).

The equivalent porous medium hydraulic conductivity, K (m/s), of a system of parallel fractures can be calculated assuming the cubic law for fluid flow (Witherspoon et al. 1980):

$$K = \frac{w^3 \rho g N}{12 \mu D} \qquad \text{(SCR.10)}$$

where w is the fracture aperture, ρ is the fluid density (taken to be 1,000 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2 (32 ft) per second squared), μ is the fluid viscosity (taken as 0.001 pascal seconds), D is the effective Culebra thickness (7.7 m (26.3 ft)), and N is the number of fractures. For 10 fractures with a fracture aperture, w, of 6×10^{-5} m (2×10^{-4} ft), the

Culebra hydraulic conductivity, K, is approximately 7 m per year (2×10^{-7} m (6.5×10^{-7} ft) per second). The values of the parameters used in this calculation are within the range of those expected for the Culebra at the WIPP site (Appendix TFIELD-2009).

The amount of opening of each fracture as a result of subsidence-induced tensile vertical strain, ε, (assuming rigid rock), is $D\varepsilon/N$ meters. Thus, for a vertical strain of 0.0001, the fracture aperture, w, becomes approximately 1.4×10^{-4} m. The Culebra hydraulic conductivity, K, then increases to approximately 85 m (279 ft) per year (2.7×10^{-6} m (8.9×10^{-6} ft) per second). Thus, on the basis of a conservative estimate of vertical strain, the hydraulic conductivity of the Culebra may increase by an order of magnitude. In PA calculations, multiple realizations of the Culebra T fields are generated as a means of accounting for spatial variability and uncertainty (Appendix TFIELD-2009). A change in hydraulic conductivity of one order of magnitude through vertical strain is within the range of uncertainty incorporated in the Culebra T fields through these multiple realizations. Thus changes in the horizontal component of Culebra hydraulic conductivity resulting from repository-induced subsidence have been eliminated from PA calculations on the basis of low consequence.

A similar calculation can be performed to estimate the change in vertical hydraulic conductivity in the Culebra as a result of a horizontal strain of 0.00007 m/m (Westinghouse 1994, p. 3-20). Assuming this strain to be distributed over about 1,000 fractures (neglecting rock expansion), with zero initial aperture, in a lateral extent of the Culebra of about 800 m (2,625 ft) (Westinghouse 1994, Figure 3-39), then the subsidence-induced fracture aperture is approximately 6×10^{-5} m (1.9×10^{-4} ft). Using the values for ρ, g, and μ, above, the vertical hydraulic conductivity of the Culebra can then be calculated, through an equation similar to above, to be 7 m (23 ft) per year (2×10^{-7} m (6.5×10^{-7} ft) per second). Thus vertical hydraulic conductivity in the Culebra may be created as a result of repository-induced subsidence, although this is expected to be insignificant.

In summary, as a result of observations of subsidence associated with potash mines in the vicinity of the WIPP, the potential for subsidence to create fluid flow paths between the repository and units overlying the Salado has been eliminated from PA calculations on the basis of low probability. The effects of repository-induced subsidence on hydraulic conductivity in the Culebra have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.2 Effects of Fluid Pressure Changes

SCR-6.3.2.1 FEP Numbers: W25 and W26
FEP Titles: *Disruption Due to Gas Effects* (W25)
Pressurization (W26)

SCR-6.3.2.1.1 Screening Decision: UP

The mechanical effects of gas generation through *Pressurization* and *Disruption Due to Gas Effects* flow are accounted for in PA calculations.

SCR-6.3.2.1.2 Summary of New Information

No new information has been identified relating to these FEPs.

SCR-6.3.2.1.3 Screening Argument

The mechanical effects of gas generation, including the slowing creep closure of the repository because of gas pressurization and the fracturing of interbeds in the Salado through disruption due to gas effects are accounted for in PA calculations (the CCA, Chapter 6.0, Section 6.4.5.2 and Section 6.4.3.1).

SCR-6.3.3 Effects of Explosions

SCR-6.3.3.1 FEP Number: W27
FEP Title: *Gas Explosions*

SCR-6.3.3.1.1 Screening Decision: UP

The potential effects of *Gas Explosions* are accounted for in PA calculations.

SCR-6.3.3.1.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-6.3.3.1.3 Screening Argument

Explosive gas mixtures could collect in the head space above the waste in a closed panel. The most explosive gas mixture potentially generated will be a mixture of hydrogen, methane (CH_4), and oxygen, which will convert to CO_2 and water on ignition. This means that there is little likelihood of a gas explosion in the long term because the rooms and panels are expected to become anoxic and oxygen depleted. Compaction through salt creep will also greatly reduce any void space in which the gas can accumulate. Analysis (see the CRA-2004, Appendix BARRIERS, Attachment PCS) indicates that the most explosive mixture of hydrogen, CH_4, and oxygen will be present in the void space approximately 20 years after panel-closure emplacement. This possibility of an explosion prior to the occurrence of anoxic conditions is considered in the design of the operational panel closure. The effect of such an explosion on the DRZ is expected to be no more severe than a roof fall, which is accounted for in the PA calculations (FEP W22).

SCR-6.3.3.2 FEP Number: W28
FEP Title: *Nuclear Explosions*

SCR-6.3.3.2.1 Screening Decision: SO-P

Nuclear Explosions have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.3.3.2.2 Summary of New Information

This FEP has been updated to include the most recent inventory information as presented in Leigh, Trone, and Fox (2005).

SCR-6.3.3.2.3 Screening Argument

Nuclear explosions have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years. For a nuclear explosion to occur, a critical mass of Pu would have to undergo rapid compression to a high density. Even if a critical mass of Pu could form in the system, there is no mechanism for rapid compression. Inventory information used for the CCA, the CRA-2004, and the CRA-2009 are presented in Leigh, Trone, and Fox (2005). The updated inventory information for the CRA-2009 shows a reduction of TRU radionuclides from previous estimates. Thus current criticality screening arguments are conservatively bounded by the previous CCA screening arguments (Rechard et al. 1996, 2000, and 2001).

SCR-6.3.4 Thermal Effects

SCR-6.3.4.1 FEP Numbers: W29, W30, W31, W72, and W73
FEP Titles: *Thermal Effects on Material Properties* (W29)
Thermally-Induced Stress Changes (W30)
Differing Thermal Expansion of Repository Components (W31)
Exothermic Reactions (W72)
Concrete Hydration (W73)

SCR-6.3.4.1.1 Screening Decision: SO-C

The effects of *Thermally-Induced Stress*, *Differing Thermal Expansion of Repository Components*, and *Thermal Effects on Material Properties* in the repository have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.

The thermal effects of *Exothermic Reactions*, including *Concrete Hydration*, have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.4.1.2 Summary of New Information

This FEP has been updated to include the most recent inventory information as presented in Leigh, Trone, and Fox (2005). Thermal calculations have been updated with the updated quantities of reactants and provided below.

SCR-6.3.4.1.3 Screening Argument

Thermally induced stress could result in pathways for groundwater flow in the DRZ, in the anhydrite layers and MBs, and through seals, or it could enhance existing pathways. Conversely, elevated temperatures will accelerate the rate of salt creep and mitigate fracture development.

Thermal expansion could also result in uplift of the rock and ground surface overlying the repository, and thermal buoyancy forces could lift the waste upward in the salt rock.

The distributions of thermal stress and strain changes depend on the induced temperature field and the differing thermal expansion of components of the repository, which depends on the components' elastic properties. Thermal effects on material properties (such as permeability and porosity) could potentially affect the behavior of the repository.

Exothermic reactions in the WIPP repository include MgO hydration, MgO carbonation, aluminum (Al) corrosion, and cement hydration (Bennett et al. 1996). Wang (1996) has shown that the temperature rise by an individual reaction is proportional to $\sqrt{VM}$, where V is the maximum rate of brine inflow into a waste panel for a reaction limited by brine inflow (or a specified maximum reaction rate for a reaction limited by its own kinetics) and M is the quantity of the reactant. MgO hydration, cement hydration, and Al corrosion are assumed to be limited by brine inflow because they all consume water and have high reaction rates. The amounts of reactants are tabulated in Table SCR-4.

Table SCR-4. Changes in Inventory Quantities from the CCA to the CRA-2009

Inventory	CCA	CRA-2004	CRA-2009
MgO (tons)	85,600[a]	72,760 (because of the elimination of mini-sacks)[a]	59,385[e]
Cellulosics (tons)	5,940[b]	8,120[c]	8,907[f]
Plastics (tons)	3,740[b]	8,120[c]	10,180[f]
Rubber (tons)	1,100[b]	1,960[c]	1,885[f]
Aluminum alloys (tons)	1,980[b]	1,960[c]	2,030[f]
Cement (tons)	8,540[b]	9,971[d]	13,888[g]

[a] U.S. Department of Energy (2000a)

[b] U.S. Department of Energy (1996b). Only CH-TRU wastes are considered. Total volume of CH-TRU wastes is 1.1×10^5 m^3. This is not scaled to WIPP disposal volume.

[c] CRA-2004 Appendix DATA, Attachment F. Only CH-TRU wastes are considered. Total volume of CH-TRU waste is 1.4×10^5 m^3. This is not scaled to WIPP disposal volume.

[d] This estimate is derived from data in Leigh (2003) includes both reacted and unreacted cement. (1.2×10^7 kg $\times$ 1.4×10^5/168485/1000 kg/ton = 9971 tons cement).

[e] This estimate is derived by assuming that Panel 1 has an MgO excess factor of 1.95, three panel equivalents have a 1.67 excess factor, and the remaining 6 panel equivalents have a 1.2 excess factor, resulting in a 1.416 projected excess factor for a full repository. The projected excess factor is then multiplied by the equivalent cellulose value of 28,098 × (40.3/27) (the MgO molar ratio).

[f] This value is derived using material densities reported in Leigh et al., (2005a) and total CH-TRU waste volume (1.45×10^5 m^3 reported in Leigh, Trone, and Fox (2005)).

[g] This value is derived from data in Leigh (2003) and Leigh, Trone, and Fox (2005). ((1.2×10^7 kg) × 39/29 × (1.45×10^5)/168485/1000 kg/ton = 13,888 tons cement).

Similarly, MgO carbonation, which consumes CO_2, is limited by CO_2 generation from microbial degradation. Given a biodegradation rate constant, the total CO_2 generated per year is proportional to the total quantity of biodegradable materials in the repository. Using the computational methods in Wang and Brush (1996a and 1996b), the inventory of biodegradable materials has been changed from 23,884 (8,120 + 1.7 × 8,120 + 1,960) tons for the CRA-2004[1]

[1] The 1.7 molar conversion rate for plastic is based on analyses presented in Wang and Brush (1996a and 1996b).

to 28,098 (8,907 + 1.7 × 10,180 + 1,885) tons of equivalent cellulosics for the CRA-2009.[1] This increase in biodegradable materials corresponds to a proportional increase in CO_2 generation. For MgO carbonation and microbial degradation, the calculated temperature rises have been updated for the changes in both microbial gas generation and waste inventory and are presented in Table SCR-5.

Temperature rises (^oC) by exothermic reactions are revised as follows:

CCA conditions following a drilling event show that Al corrosion could, at most, result in a short-lived (two years) temperature increase of about 6 °C (10.8 °F) above ambient room temperature (about 27 °C (80 °F)) (Bennett et al. 1996). A temperature rise of 6 °C (10.8 °F) represented the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Revised maximum temperature rises by exothermic reactions for CRA-2009 are still less than 10 ºC (18 °F) (as shown in Table SCR-5). Such small temperature changes cannot affect material properties. Thus thermal effects on material properties in the repository have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Table SCR-5. CCA and CRA Exothermic Temperature Rises

Reactant	CCA[a]	CRA-2004[a]	CRA-2009[a]
MgO hydration	< 4.5	< 4.7	< 4.2
MgO carbonation	< 0.6	< 0.7	< 0.6
Microbial degradation	< 0.8	< 1.4	< 1.5
Aluminum corrosion	< 6.0	< 6.8	< 6.9
Cement hydration	< 2.0	< 2.5	< 3.0

[a] All values are in degrees Celsius.

All potential sources of heat and elevated temperature have been evaluated and found not to produce high enough temperature changes to affect the repository's performance. Sources of heat within the repository include radioactive decay and exothermic chemical reactions such as backfill hydration and metal corrosion. The rates of these exothermic reactions are limited by the availability of brine in the repository. Concrete hydration in the seals is a significant source of heat, but it is relatively short-lived (Loken 1994 and Loken and Chen 1994). Energy released by the hydration of the seal concrete could raise the temperature of the concrete to approximately 53 °C (127 °F), and that of the surrounding salt to approximately 38 °C (100 °F), one week after seal emplacement. Elevated temperatures will persist for a short period of time, perhaps a few years or a few decades. The thermal stresses from these temperatures and the temperatures in the concrete itself have been calculated to be below the design compressive strength for the concrete. Thus thermal stresses should not degrade the long-term performance of the seals. In general, the various sources of heat do not appear to be great enough to jeopardize the performance of the disposal system.

SCR-6.3.5 Mechanical Effects on Material Properties

SCR-6.3.5.1 FEP Numbers: W32, W36, W37, W39, W113, and W114
FEP Titles: *Consolidation of Waste* (W32)
Consolidation of Shaft Seals (W36)
Mechanical Degradation of Shaft Seals (W37)
Underground Boreholes (W39)
Consolidation of Panel Closures (W113)
Mechanical Degradation of Panel Closures (W114)

SCR-6.3.5.1.1 Screening Decision: UP

Consolidation of Waste is accounted for in PA calculations. *Consolidation of Shaft Seals* and *Panel Closures* and *Mechanical Degradation of Shaft Seals* and *Panel Closures* are accounted for in PA calculations. Flow through isolated, unsealed *Underground Boreholes* is accounted for in PA calculations.

SCR-6.3.5.1.2 Summary of New Information

The titles of W36 and W37 have been modified to specifically apply to shaft seals. New FEPs W113, *Consolidation of Panel Closures*, and W114, *Mechanical Degradation of Panel Closures*, have been added to comprehensively address these repository components. These changes were made as a result of the FEPs analysis conducted for the Panel Closure Redesign planned change request (Kirkes 2006).

SCR-6.3.5.1.3 Screening Argument

Consolidation of waste is accounted for in PA calculations in the modeling of creep closure of the disposal room (Appendix PA-2009, Section PA-4.2.3).

Consolidation of shaft seals, consolidation of panel closures, mechanical degradation of shaft seals, and mechanical degradation of panel closures are accounted for in PA calculations through the permeability ranges assumed for the seal and closure systems (Appendix PA-2009, Section PA-4.2.7 and Section PA-4.2.8).

The site investigation program has also involved the drilling of boreholes from within the excavated part of the repository. Following their use for monitoring or other purposes, these underground boreholes will be sealed where practical, and salt creep will also serve to consolidate the seals and to close the boreholes. Any boreholes that remain unsealed will connect the repository to anhydrite interbeds within the Salado, and thus provide potential pathways for radionuclide transport. PA calculations account for fluid flow to and from the interbeds by assuming that the DRZ has a permanently enhanced permeability that allows flow of repository brines into specific anhydrite layers and interbeds. This treatment is also considered to account for the effects of any unsealed boreholes.

SCR-6.3.5.2 FEP Number: W33
FEP Title: *Movement of Containers*

SCR-6.3.5.2.1 Screening Decision: SO-C

Movement of Containers has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5.2.2 Summary of New Information

The FEP description has been updated to reflect new waste inventory data.

SCR-6.3.5.2.3 Screening Argument

Movement of waste containers placed in salt may occur as a result of two buoyancy mechanisms (Dawson and Tillerson 1978): (1) the density contrast between the waste container and the surrounding salt, and (2) the temperature contrast between a salt volume that includes a heat source and the surrounding unheated salt. When the density of the waste container is greater than the density of the surrounding salt, the container sinks relative to the salt, whereas when the salt density is greater than the container density, the container rises relative to the salt. Similarly, when a discrete volume of salt within a large salt mass is heated, the heat raises the temperature of the discrete volume above that of the surrounding salt, thereby inducing density contrasts and buoyant forces that initiate upward flow of the heated salt volume. In a repository setting, the source of the heat may be radioactive decay of the waste itself or exothermic reactions of the backfill materials and waste constituents, e.g., MgO hydration, MgO carbonation, Al corrosion, cement hydration, and calcium oxide hydration.

For the CCA, the density of the compacted waste and the grain density of the halite in the Salado were assumed to be 2,000 kg/m^3 and 2,163 kg/m^3, respectively. Because this density contrast is small, the movement of containers relative to the salt was considered minimal, particularly when drag forces on the waste containers were also considered. In addition, vertical movement initiated in response to thermally induced density changes for high-level waste containers of a similar density to those at the WIPP were calculated to be approximately 0.35 m (1.1 ft) (Dawson and Tillerson 1978, p. 22). This calculated movement was considered conservative, given that containers at the WIPP will generate much less heat and will, therefore, move less. As a result, container movement was eliminated from PA calculations on the basis of low consequences to the performance of the disposal system.

The calculations performed for the DOE (U.S. Department of Energy 1996a) were based on estimates of the waste inventory. However, with the initiation of waste disposal, actual waste inventory is tracked and future waste stream inventories have been refined. Based on an evaluation of these data, two factors may affect the conclusions reached in DOE (U.S. Department of Energy 1996a) concerning container movement.

The first factor is changes in density of the waste form. According to CRA-2009 inventory data (Leigh, Trone, and Fox 2005), the waste density has changed only slightly since that anticipated for the CCA (see Leigh et al. 2005a, Table 9). Some future waste streams may, however, be

more highly compacted, perhaps having a density roughly three times greater than that assumed in the CCA, while others may be less dense. In calculations of container movement, Dawson and Tillerson (1978, p. 22) varied container density by nearly a factor of 3 (from 2,000 kg/m^3 (125 lb/ft^3) to 5,800 kg/m^3 (362 lb/ft^3)) and found that an individual dense container could move vertically as much as about 28 m (92 ft). Given the geologic environment of the WIPP, a container would likely encounter a dense stiff unit (such as an anhydrite stringer) that would arrest further movement far short of this upper bound; however, because of the massive thickness of the Salado salt, even a movement of 28 m (92 ft) would have little impact on performance.

The second inventory factor that could affect container movement is the composition of the waste (and chemical buffer) relative to its heat production. Radioactive decay, nuclear criticality, and exothermic reactions are three possible sources of heat in the WIPP repository. According to Leigh, Trone, and Fox (2005), the TRU radionuclide inventory has decreased from 3.44×10^6 Ci reported in the CCA, to 2.48×10^6 Ci in the CRA-2004, to 2.32×10^6 Ci in the CRA-2009. Such a small change will not result in a significant deviation from the possible temperature rise predicted in the CCA. Additionally, and as shown in Section SCR-6.3.4.1 (FEPs W72 and W73), temperature rises from exothermic reactions are quite small (see Table SCR-5). Note that the revised maximum temperature increases caused by exothermic reactions are still less than 10 °C (18 °F).

Based on the small differences between the temperature and density assumed in the CCA and those determined using new inventory data (Leigh, Trone, and Fox 2005), the conclusion about the importance of container movement reported in the CCA will not be affected, even when more highly compacted future waste streams are considered. The effects of the revised maximum temperature rise and higher-density future waste streams on container movement are competing factors (high-density waste will sink, whereas the higher-temperature waste-salt volume will rise) that may result in even less movement. Therefore, movement of waste containers has been eliminated from PA calculations on the basis of low consequence.

SCR-6.3.5.3 FEP Number: W34
FEP Title: *Container Integrity*

SCR-6.3.5.3.1 Screening Decision: SO-C Beneficial

Container Integrity has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.3.5.3.2 Summary of New Information

No new information has been identified relating to this FEP.

SCR-6.3.5.3.3 Screening Argument

Container integrity is required only for waste transportation. Past PA calculations show that a significant fraction of steel and other Fe-base materials will remain undegraded over 10,000 years (see, for example, Helton et al. 1998). In addition, it is assumed in both CCA and CRA-2004 calculations that there is no microbial degradation of plastic container materials in

75% of PA realizations (Wang and Brush 1996). All these undegraded container materials will (1) prevent the contact between brine and radionuclides; and (2) decrease the rate and extent of radionuclide transport because of high tortuosity along the flow pathways and, as a result, increase opportunities for metallic iron and corrosion products to beneficially reduce radionuclides to lower oxidation states. Therefore, container integrity can be eliminated on the basis of its beneficial effect on retarding radionuclide transport. PA assumes instantaneous container failure and waste dissolution according to the source-term model.

SCR-6.3.5.4 FEP Number: W35
FEP Title: *Mechanical Effects of Backfill*

SCR-6.3.5.4.1 Screening Decision: SO-C

The *Mechanical Effects of Backfill* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.3.5.4.2 Summary of New Information

In February 2008, the EPA approved a reduction in the minimum amount of MgO to be placed in the repository (Reyes 2008). This reduction is described fully in Appendix MgO-2009. While this reduction is important to WIPP operations, it has no bearing on PA calculations and the screening decisions and arguments for FEPs that are related to backfill, buffers, and barriers.

SCR-6.3.5.4.3 Screening Argument

The chemical conditioners or backfill added to the disposal room will act to resist creep closure. However, calculations have shown that because of the high porosity and low stiffness of the waste and the high waste to potential backfill volume, inclusion of backfill does not significantly decrease the total subsidence in the waste emplacement area or disposal room (Westinghouse 1994). In 2001, the DOE eliminated MgO mini-sacks from the repository, reducing the total inventory from 85,600 short tons to 74,000 short tons, which reduced the potential backfill volume (U.S. Environmental Protection Agency 2001). More recently, the required amount of MgO has been further reduced (see Appendix MgO-2009 and Reyes [2008]). Therefore, the mechanical effects of backfill have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.4 Subsurface Hydrological and Fluid Dynamic FEPs

SCR-6.4.1 Repository-Induced Flow

SCR-6.4.1.1 **FEP Numbers:** W40 and W41
FEP Titles: *Brine Inflow* (W40)
Wicking (W41)

SCR-6.4.1.1.1 Screening Decision: UP

Two-phase brine and gas flow and capillary rise (wicking) in the repository and the Salado are accounted for in PA calculations.

SCR-6.4.1.1.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-6.4.1.1.3 Screening Argument

Brine inflow to the repository may occur through the DRZ, impure halite, anhydrite layers, or clay layers. Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Two-phase flow of brine and gas in the repository and the Salado is accounted for in PA calculations (Appendix PA-2009, Section PA-4.2).

Capillary rise (or wicking) is a potential mechanism for liquid migration through unsaturated zones in the repository. Capillary rise in the waste material could affect gas generation rates, which are dependent on water availability. Potential releases caused by drilling intrusion are also influenced by brine saturations and therefore by wicking. Capillary rise is therefore accounted for in PA calculations (Appendix PA-2009, Section PA-4.2).

SCR-6.4.2 Effects of Gas Generation

SCR-6.4.2.1 FEP Number: W42
FEP Title: *Fluid Flow Due to Gas Production*

SCR-6.4.2.1.1 Screening Decision: UP

Fluid Flow Due to Gas Production in the repository and the Salado is accounted for in PA calculations.

SCR-6.4.2.1.2 Summary of New Information

No new information has been identified related to this FEP.

SCR-6.4.2.1.3 Screening Argument

Pressurization of the repository through gas generation could limit the amount of brine that flows into the rooms and drifts. Gas may flow from the repository through the DRZ, impure halite, anhydrite layers, or clay layers. The amount of water available for reactions and microbial activity will impact the amounts and types of gases produced (W44 through W55, Section SCR-6.5.1.1, Section SCR-6.5.1.2, Section SCR-6.5.1.3, Section SCR-6.5.1.4, Section SCR-6.5.1.5, Section SCR-6.5.1.6, Section SCR-6.5.1.7, Section SCR-6.5.1.8, and Section SCR-6.5.1.9). Gas generation rates, and therefore repository pressure, may change as the water content of the repository changes. Pressure changes and fluid flow due to gas production in the repository and the Salado are accounted for in PA calculations through modeling the two-phase flow (Appendix PA-2009, Section PA-4.2).

SCR-6.4.3 Thermal Effects

SCR-6.4.3.1 FEP Number: W43
FEP Title: *Convection*

SCR-6.4.3.1.1 Screening Decision: SO-C

Convection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.4.3.1.2 Summary of New Information

No new information has been identified relative to the screening of this FEP.

SCR-6.4.3.1.3 Screening Argument

Temperature differentials in the repository could initiate convection. The resulting thermally induced brine flow or thermally-induced, two-phase flow could influence contaminant transport. Thermal gradients in the disposal rooms could potentially drive the movement of water vapor. For example, temperature increases around waste located at the edges of the rooms could cause evaporation of water entering from the DRZ. This water vapor could condense on cooler waste containers in the rooms and could contribute to brine formation, corrosion, and gas generation.

The characteristic velocity, *Vi*, for convective flow of fluid component *I* in an unsaturated porous medium is given by (from Hicks 1996)

$$V_i \approx -\frac{k_i}{\mu_i}\left(\alpha_i \rho_{i0} g \Delta T\right) \qquad \text{(SCR.11)}$$

where α_i (per degree Kelvin) is the coefficient of expansion of the i^{th} component, k_i is the intrinsic permeability (m^2), μ_i is the fluid viscosity (pascal second), ρ_{i0} (kg/m^3) is the fluid density at a reference point, g is the acceleration due to gravity, and ΔT is the change in temperature. This velocity may be evaluated for the brine and gas phases expected in the waste disposal region.

For a temperature increase of 10 °C (18 °F), the characteristic velocity for convective flow of brine in the DRZ around the concrete shaft seals is approximately 7×10^{-4} m (2.3×10^{-3} ft) per year (2×10^{-11} m (6.6×10^{-11} ft) per second), and the characteristic velocity for convective flow of gas in the DRZ is approximately 1×10^{-3} m (3.2×10^{-3} ft) per year (3×10^{-11} m (9.8×10^{-11} ft) per second) (Hicks 1996). For a temperature increase of 25 °C (45 °F), the characteristic velocity for convective flow of brine in the concrete seals is approximately 2×10^{-7} m (6.5×10^{-7} ft) per year (6×10^{-15} m (1.9×10^{-14} ft) per second), and the characteristic velocity for convective flow of gas in the concrete seals is approximately 3×10^{-7} m (9.8×10^{-7} ft) per year (8×10^{-15} m (2.6×10^{-4} ft) per second) (Hicks 1996). These values of Darcy velocity are much smaller than the expected values associated with brine inflow to the disposal rooms of fluid flow resulting from gas generation. In addition, the buoyancy forces generated by smaller temperature contrasts in the DRZ, resulting from backfill, concrete hydration, and radioactive decay will be short-lived and insignificant compared to the other driving forces for fluid flow. The short-term concrete seals will be designed to function as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). Thus temperature increases associated with concrete hydration will not result in significant buoyancy-driven fluid flow through the concrete seal system. In summary, temperature changes in the disposal system will not cause significant thermal convection. Furthermore, the induced temperature gradients will be insufficient to generate water vapor and drive significant moisture migration.

Temperature effects on fluid viscosity would be most significant in the DRZ surrounding the hydrating concrete seals (where temperatures of approximately 38 °C (100 °F) are expected). The viscosity of pure water decreases by about 19% over a temperature range of between 27 °C (80 °F) and 38 °C (100 °F) (Batchelor 1973, p. 596). Although at a temperature of 27 °C (80 °F), the viscosity of Salado brine is about twice that of pure water (Rechard et al. 1990, a-19), the magnitude of the variation in brine viscosity between 27 °C (80 °F) and 38 °C (100 °F) will be similar to the magnitude of the variation in viscosity of pure water. The viscosity of air over this temperature range varies by less than 7% (Batchelor 1973, p. 594) and the viscosity of gas in the waste disposal region over this temperature range is also likely to vary by less than 7%. The Darcy fluid flow velocity for a porous medium is inversely proportional to the fluid viscosity. Thus increases in brine and gas flow rates may occur as a result of viscosity variations in the vicinity of the concrete seals. However, these viscosity variations will persist only for a short period in which temperatures are elevated, and, thus, the expected variations in brine and gas viscosity in the waste disposal region will not significantly affect the long-term performance of the disposal system.

For the CCA conditions following a drilling event, Al corrosion could, at most, result in a short-lived (two years) temperature increase of about 6 °C (10.8 °F). A temperature rise of 6 °C (10.8 °F) represented the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously. Revised maximum temperature rises by exothermic reactions for CRA-2009 are still less than 10 °C (18 °F) (as shown in Table SCR-5). Such small temperature changes cannot affect material properties.

In summary, temperature changes in the disposal system will not cause significant thermally induced two-phase flow. Thermal convection has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5 Geochemical and Chemical FEPs

SCR-6.5.1 Gas Generation

SCR-6.5.1.1 FEP Numbers: W44, W45, and W48
FEP Titles: *Degradation of Organic Material* (W44)
Effects of Temperature on Microbial Gas Generation (W45)
Effects of Biofilms on Microbial Gas Generation (W48)

SCR-6.5.1.1.1 Screening Decision: UP

Microbial gas generation from *Degradation of Organic Material* is accounted for in PA calculations, and the *Effects of Temperature on Microbial Gas Generation* and the *Effects of Biofilm Formation on Microbial Gas Generation* are incorporated in the gas generation rates used.

SCR-6.5.1.1.2 Summary of New Information

These FEPs have been updated to be consistent with the latest inventory information.

SCR-6.5.1.1.3 Screening Argument

Microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials, will produce mainly CO_2, but also nitrogen oxide, nitrogen, hydrogen sulfide, hydrogen, and CH_4. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from degradation of organic material is accounted for in PA calculations.

The following subsections discuss the effects of temperature, pressure, radiation, and biofilms on gas production rates via their control of microbial gas generation processes.

SCR-6.5.1.1.3.1 Effects of Temperature on Microbial Gas Generation
Calculations and experimental studies of induced temperature distributions within the repository have been undertaken and are described in FEPs W29, W30, and W31 (Section SCR-6.3.4.1). Numerical analysis suggests that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH-TRU and RH-TRU waste is likely to be less than 3 °C (5.4 °F) (FEP W13).

Temperature increases resulting from exothermic reactions are discussed in FEPs W72 and W73 (Section SCR-6.3.4.1). Potentially the most significant exothermic reactions are concrete hydration, backfill hydration, and aluminum corrosion. Hydration of the seal concrete could

raise the temperature of the concrete to approximately 53 °C (127 °F) and that of the surrounding salt to approximately 38 °C (100 °F) one week after seal emplacement (W73).

As discussed in FEPs W72 and W73 (Section SCR-6.3.4.1), the maximum temperature rise in the disposal panels as a consequence of backfill hydration will be less than 4.2 °C (7.6 °F), resulting from brine inflow following a drilling intrusion into a waste disposal panel. Note that AICs will prevent drilling within the controlled area for 100 years after disposal. By this time, any heat generation by radioactive decay and concrete seal hydration will have decreased substantially, and the temperatures in the disposal panels will have decreased to close to initial values.

Under similar conditions following a drilling event, Al corrosion could, at most, result in a short-lived (two years) temperature rise of about 6.9 °C (12.4 °F) (see W72). These calculated maximum heat generation rates resulting from Al corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus the temperature rise of 10 °C (18 °F) represents the maximum that could occur as a result of any combination of exothermic reactions occurring simultaneously.

Relatively few data exist on the effects of temperature on microbial gas generation under expected WIPP conditions. Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experiments. Increases in temperature from ambient up to 40 °C (104 °F) or 50 °C (122 °F) were reported to increase gas production, mainly via the degradation of cellulosic waste under either aerobic or anaerobic conditions (Molecke 1979, p. 7). Above 70 °C (158 °F), however, gas generation rates were generally observed to decrease. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates, representing likely states within the repository. Gas generation rates were presented as ranges with upper and lower bounds as estimates of uncertainty (Molecke 1979, p. 7). Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). These experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. These experiments were carried out at a reference temperature of 30 °C (86 °F) based on the average temperature expected in the repository. Gas generation rates used in the PA calculations are described in Appendix PA-2009, Section PA-4.2.5. The effects of temperature on microbial gas generation are implicitly incorporated in the gas generation rates used.

SCR-6.5.1.1.3.2 Effects of Biofilms on Microbial Gas Generation

The location of microbial activity within the repository is likely to be controlled by the availability of substrates and nutrients. Biofilms may develop on surfaces where nutrients are concentrated. They consist of one or more layers of cells with extracellular polymeric material, and serve to maintain an optimum environment for growth. Within such a biofilm ecosystem, nutrient retention and recycling maximize microbe numbers on the surface (see, for example, Stroes-Gascoyne and West 1994, pp. 9–10).

Biofilms can form on almost any moist surface, but their development is likely to be restricted in porous materials. Even so, their development is possible at locations throughout the disposal system. The effects of biofilms on microbial gas generation may affect disposal system performance through control of microbial population size and their effects on radionuclide transport.

Molecke (1979, p. 4) summarized microbial gas generation rates observed during a range of experimental studies. The experiments were conducted over a range of temperatures and chemical conditions and for different substrates representing likely states within the repository. However, the effect of biofilm formation in these experiments was uncertain. Molecke (1979, p. 7), presented gas generation rates as ranges, with upper and lower bounds as estimates of uncertainty. Later experiments reported by Francis and Gillow (1994) support the gas generation rate data reported by Molecke (1979). Their experiments investigated microbial gas generation under a wide range of possible conditions in the repository. These conditions included the presence of microbial inoculum, humid or inundated conditions, cellulosic substrates, additional nutrients, electron acceptors, bentonite, and initially oxic or anoxic conditions. Under the more favorable conditions for microbial growth established during the experiments, the development of populations of halophilic microbes and associated biofilms was evidenced by observation of an extracellular, carotenoid pigment, bacterioruberin, in the culture bottles (Francis and Gillow 1994, p. 59). Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Appendix PA-2009, Section PA-4.2.5. The effects of biofilms on microbial gas generation rates are implicitly incorporated in the gas generation rates.

Biofilms may also influence contaminant transport rates through their capacity to retain and thus retard both the microbes themselves and radionuclides. This effect is not accounted for in PA calculations, but is considered potentially beneficial to calculated disposal system performance. Microbial transport is discussed in Section SCR-6.6.3.1.

SCR-6.5.1.2 FEP Number: W46
FEP Title: *Effects of Pressure on Microbial Gas Generation*

SCR-6.5.1.2.1 Screening Decision: SO-C

The *Effects of Pressure on Microbial Gas Generation* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.1.2.3 Screening Argument

Directly relevant to WIPP conditions, the gas generation experiments with actual waste components at Argonne National Laboratory provide no indication of any enhancement of pressured nitrogen atmosphere (2,150 pounds per square inch absolute [psia]) on microbial gas generation (Felicione et al. 2001). In addition, microbial breakdown of cellulosic material, and possibly plastics and other synthetic materials in the repository, will produce mainly CO_2 and

CH_4 with minor amounts of nitrogen oxide, nitrogen, and hydrogen sulfide. The accumulation of these gaseous species will contribute the total pressure in the repository. Increases in the partial pressures of these reaction products could potentially limit gas generation reactions. However, such an effect is not taken into account in WIPP PA calculations. The rate of microbial gas production will depend upon the nature of the microbial populations established, the prevailing conditions, and the substrates present. Microbial gas generation from degradation of organic material is accounted for in PA calculations.

Chemical reactions may occur depending on, among other things, the concentrations of available reactants, the presence of catalysts and the accumulation of reaction products, the biological activity, and the prevailing conditions (for example, temperature and pressure). Reactions that involve the production or consumption of gases are often particularly influenced by pressure because of the high molar volume of gases. The effect of high total pressures on chemical reactions is generally to reduce or limit further gas generation.

Few data exist from which the effects of pressure on microbial gas generation reactions that may occur in the WIPP can be assessed and quantified. Studies of microbial activity in deep-sea environments (for example, Kato et al. 1994, p. 94) suggest that microbial gas generation reactions are less likely to be limited by increasing pressures in the disposal rooms than are inorganic gas generation reactions (for example, corrosion). Consequently, the effects of pressure on microbial gas generation have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.3 FEP Number: W47
FEP Title: *Effects of Radiation on Microbial Gas Generation*

SCR-6.5.1.3.1 Screening Decision: SO-C

The *Effects of Radiation on Microbial Gas Generation* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.3.2 Summary of New Information

The FEP screening argument has been updated to reflect the radionuclide inventory used for CRA-2009 calculations, although the screening decision has not changed.

SCR-6.5.1.3.3 Screening Argument

Radiation may slow down microbial gas generation rates, but such an effect is not taken into account in WIPP PA calculations. According to the inventory data presented in Leigh, Trone, and Fox (2005), the overall activity for all TRU radionuclides has decreased from 3.44×10^6 Ci reported in the CCA, to 2.48×10^6 Ci in the CRA-2004, to 2.32×10^6 Ci in the CRA-2009. This decrease will not affect the original screening argument.

Experiments investigating microbial gas generation rates suggest that the effects of alpha radiation from TRU waste is not likely to have significant effects on microbial activity (Barnhart et al. 1980; Francis 1985). Consequently, the effects of radiation on microbial gas generation

have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.4 FEP Numbers: W49 and W51
FEP Titles: *Gasses from Metal Corrosion*
Chemical Effects of Corrosion

SCR-6.5.1.4.1 Screening Decision: UP

Gas generation from metal corrosion is accounted for in PA calculations, and the effects of chemical changes from metal corrosion are incorporated in the gas generation rates used.

SCR-6.5.1.4.2 Summary of New Information

No new information has been identified related to these FEPs.

SCR-6.5.1.4.3 Screening Argument

Oxic corrosion of waste drums and metallic waste will occur at early times following closure of the repository and will deplete its oxygen content. Anoxic corrosion will follow the oxic phase and will produce hydrogen while consuming water. Gases from metal corrosion are accounted for in PA calculations.

The predominant chemical effect of corrosion reactions on the environment of disposal rooms will be to lower the oxidation state of the brines and maintain reducing conditions.

Molecke (1979, p. 4) summarized gas generation rates that were observed during a range of experiments. The experiments were conducted over a range of temperatures and chemical conditions representing likely states within the repository. Later experiments reported by Telander and Westerman (1993) support the gas generation rate data reported by Molecke (1979). Their experiments investigated gas generation from corrosion under a wide range of possible conditions in the repository. The studies included corrosion of low-carbon steel waste packaging materials in synthetic brines, representative of intergranular Salado brines at the repository horizon, under anoxic (reducing) conditions.

Gas generation rates used in the PA calculations have been derived from available experimental data and are described in Appendix PA-2009, Section PA-4.2.5. The effects of chemical changes from metal corrosion are, therefore, accounted for in PA calculations.

SCR-6.5.1.5 FEP Number: W50
FEP Title: *Galvanic Coupling (within the repository)*

SCR-6.5.1.5.1 Screening Decision: SO-C

The effects of *Galvanic Coupling* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.5.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.1.5.3 Screening Argument

Galvanic coupling (i.e. establishing an electrical current through chemical processes) could lead to the propagation of electric potential gradients between metals in the waste form, canisters, and other metals external to the waste form, potentially influencing corrosion processes, gas generation rates, and chemical migration.

Metallic ore bodies external to the repository are nonexistent (see the CCA, Appendix GCR) and therefore galvanic coupling between the waste and metals external to the repository would not occur. However, a variety of metals will be present within the repository as waste metals and containers, creating a potential for formation of galvanic cells over short distances. As an example, the presence of copper could influence rates of hydrogen gas production resulting from the corrosion of iron. The interactions between metals depend upon their physical disposition and the prevailing solution conditions, including pH and salinity. Good physical and electrical contact between the metals is critical to the establishment of galvanic cells.

Consequently, given the preponderance of iron over other metals within the repository and the likely passivation of many nonferrous materials, the influence of these electrochemical interactions on corrosion, and therefore on gas generation, is expected to be minimal. Therefore, the effects of galvanic coupling have been eliminated from PA calculations on the basis of low consequence.

SCR-6.5.1.6 FEP Number: W52
FEP Title: *Radiolysis of Brine*

SCR-6.5.1.6.1 Screening Decision: SO-C

Gas generation from *Radiolysis of Brine* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.6.2 Summary of New Information

No new information has been identified relative to this FEP.

SCR-6.5.1.6.3 Screening Argument

Radiolysis of brine in the WIPP disposal rooms, and of water in the waste, will lead to the production of gases and may significantly affect the oxygen content of the rooms. This, in turn, will affect the prevailing chemical conditions and potentially the concentrations of radionuclides that may be mobilized in the brines.

The overall reaction for the radiolysis of water in the waste and brine is

$$H_2O \rightarrow H_2 + \tfrac{1}{2} O_2. \qquad \text{(SCR.12)}$$

However, the production of intermediate oxygen-bearing species that may subsequently undergo reduction will lead to reduced oxygen gas yields. The remainder of this section is concerned with the physical effects of gas generation by radiolysis of brine.

Reed et al. (1993) studied radiolytic gas generation during experiments lasting between 155 and 182 days. These experiments involved both synthetic brines similar to those sampled from the Salado at the WIPP repository horizon, and brines occurring in reservoirs in the Castile, as well as real brines sampled from the Salado in the repository workings. The brines were spiked with ^{239}Pu(VI) at concentrations between 6.9×10^{-9} and 3.4×10^{-4} molal. During these relatively short-term experiments, hydrogen gas was observed as the product of radiolysis. Oxygen gas was not observed; this was attributed to the formation of intermediate oxygen-bearing species. However, given sufficient exposure to alpha-emission, oxygen production may reach 50% that of hydrogen.

An estimate of the potential rate of gas generation caused by the radiolysis of brine, R_{RAD}, can be made by making the following assumptions:

- Gas production occurs following the reaction above, so that 1.5 moles of gas are generated for each mole of water consumed
- Gas production occurs as a result of the alpha decay of ^{239}Pu
- ^{239}Pu concentrations in the disposal room brines are controlled by solubility equilibria
- All of the dissolved Pu is ^{239}Pu

R_{RAD} is then given by

$$R_{RAD} = \frac{Y_g C_{Pu} SA_{Pu} \overline{E}_\alpha V_B}{N_D N_A} \qquad \text{(SCR.13)}$$

$$R_{RAD} = \frac{\left(\frac{1.5 \text{ molecule gas}}{\text{molecule } H_2O}\right)\left(3.15\times10^{7}\ \frac{\text{s}}{\text{yr}}\right)\left(3\times10^{-4}\ \frac{\text{mol}}{\text{L}}\right)\left(5.42\times10^{11}\ \frac{\text{Bq}}{\text{mol}}\right)\left(5.15\times10^{6}\ \frac{\text{eV}}{\text{dis}}\right)\left(\frac{1.5\ H_2O}{100\text{ eV}}\right)\left(4.36\times10^{8}\text{ L}\right)}{\left(8\times10^{5}\text{ drums}\right)\left(6.022\times10^{23}\ \frac{\text{molecules}}{\text{mole}}\right)}$$

$$= 0.533 \text{ mol/drum/yr} \qquad \text{(SCR.14)}$$

Y_g = radiolytic gas yield, in number of moles of gas produced per number of water molecules consumed
C_{Pu} = maximum dissolved concentration of plutonium (molar)
SA_{Pu} = specific activity of ^{239}Pu (5.42×10^{11} becquerels (Bq) per mole)
$\overline{E}_\alpha$ = average energy of α-particles emitted during ^{239}Pu decay (5.15×10^{6} eV)
G = number of water molecules split per 100 eV of energy transferred from alpha-particles
V_B = volume of brine in the repository (L)

N_D = number of CH-TRU drums in the repository (~8×10^5)
N_A = Avogadro constant (6.022×10^{23} molecules per mole)

The value of *G* used in this calculation has been set at 0.015, the upper limit of the range of values observed (0.011 to 0.015) during experimental studies of the effects of radiation on WIPP brines (Reed et al. 1993). A maximum estimate of the volume of brine that could potentially be present in the disposal region has been made from its excavated volume of 436,000 m^3 (520,266 cubic yards [yd^3]). This estimate, in particular, is considered to be highly conservative because it makes no allowance for creep closure of the excavation, or for the volume of waste and backfill that will be emplaced, and takes no account of factors that may limit brine inflow. These parameter values lead to an estimate of the potential rate of gas production caused by the radiolysis of brine of 0.6 moles per drum per year or less.

Assuming ideal gas behavior and repository conditions of 30 °C (86 °F) and 14.8 MPa (lithostatic pressure), this is equivalent to approximately 6.8×10^4 L (1.8×10^4 gal) per year.

Potential gas production rates from other processes that will occur in the repository are significantly greater than this. For example, under water-saturated conditions, microbial degradation of cellulosic waste has the potential to yield between 1.3×10^6 and 3.8×10^7 L (3.4×10^5 and 1.0×10^7 gal) per year; anoxic corrosion of steels has the potential to yield up to 6.3×10^5 L (1.6×10^5 gal) per year.

In addition to the assessment of the potential rate of gas generation by radiolysis of brine given above, a study of the likely consequences on disposal system performance has been undertaken by Vaughn et al. (1995). A model was implemented in BRAGFLO to estimate radiolytic gas generation in the disposal region according to the equation above.

A set of BRAGFLO simulations was performed to assess the magnitude of the influence of the radiolysis of brine on contaminant migration to the accessible environment. The calculations considered radiolysis of water by 15 isotopes of Th, Pu, U, and Am. Conditional CCDFs of normalized contaminated brine releases to the Culebra via a human intrusion borehole and the shaft system, as well as releases to the subsurface boundary of the accessible environment via the Salado interbeds, were constructed and compared to the corresponding baseline CCDFs calculated excluding radiolysis. The comparisons indicated that radiolysis of brine does not significantly affect releases to the Culebra or the subsurface boundary of the accessible environment under disturbed or undisturbed conditions (Vaughn et al. 1995). Although the analysis of Vaughn et al. (1995) used data that are different than those used in the PA calculations, estimates of total gas volumes in the repository are similar to those considered in the analysis performed by Vaughn et al. (1995).

Therefore, gas generation by radiolysis of brine has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.7 FEP Number: W53
FEP Title: *Radiolysis of Cellulose*

SCR-6.5.1.7.1 Screening Decision: SO-C

Gas generation from *Radiolysis of Cellulose* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.7.2 Summary of New Information

This FEP has been updated with new inventory data related to cellulose content.

SCR-6.5.1.7.3 Screening Argument

Molecke (1979) compared experimental data on gas production rates caused by radiolysis of cellulose and other waste materials with gas generation rates by other processes, including bacterial (microbial) waste degradation. The comparative gas generation rates reported by Molecke (1979, p. 4) are given in terms of most probable ranges, using units of moles per year per drum, for drums of 0.21 m^3 (0.27 yd^3) in volume. A most probable range of 0.005 to 0.011 moles per year per drum is reported for gas generation caused by radiolysis of cellulosic material (Molecke 1979, p. 4). As a comparison, a most probable range of 0.0 to 5.5 moles per year per drum is reported for gas generation by bacterial degradation of waste.

The data reported by Molecke (1979) are consistent with more recent gas generation investigations made under the WIPP program, and indicate that radiolysis of cellulosic materials will generate significantly less gas than other gas generation processes. Gas generation from radiolysis of cellulosics therefore can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Radiolytic gas generation is controlled by the radioactivity of wastes and the waste properties. According to the new inventory presented in Leigh, Trone, and Fox (2005), the overall activity for all TRU radionuclides has decreased from 3.44×10^6 Ci reported in the CCA, to 2.48×10^6 Ci in the CRA-2004, to 2.32×10^6 Ci in the CRA-2009. Such decreasing activity levels imply that the radiolytic effects will be decreased from those presented in the CCA.

Radiolytic gas generation is also limited by transportation requirements, which state that the hydrogen generated in the innermost layer of confinement must be no more than 5% over 60 days (U.S. Department of Energy 2000b). Thus the maximum rate allowed for transportation is 0.201 m^3/drum × 5% × 1,000 L/m^3/60 days × 365 days/yr = 61 L/drum/yr, smaller than the maximum microbial gas generation rate. Note that this estimate is very conservative and the actual rates are even smaller. It is a general consensus within the international research community that the effect of radiolytic gas generation on the long-term performance of a low/intermediate level waste repository is negligible (Rodwell et al. 1999).

SCR-6.5.1.8 FEP Number: W54
FEP Title: *Helium Gas Production*

SCR-6.5.1.8.1 Screening Decision: SO-C

Gas generation from helium production has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.8.2 Summary of New Information

The updated information for the WIPP disposal inventory indicates that the expected WIPP-scale radionuclide activity (2.32 million Ci of TRU isotopes) (Leigh, Trone, and Fox 2005) is less than previously estimated in TWBIR Rev 3 (U.S. Department of Energy 1996b). Thus the helium gas production argument for CRA-2009 is conservatively bounded by the CCA screening argument. The FEP screening argument and screening decision remain unchanged except for editorial changes.

SCR-6.5.1.8.3 Screening Argument

Helium gas production will occur by the reduction of α-particles (helium nuclei) emitted from the waste. The maximum amount of helium that could be produced can be calculated from the number of α-particles generated during radioactive decay. The α-particles are converted to helium gas by the following reaction:

$$^{4}He^{2+} + 2e^{-} \rightarrow He(g) \qquad \text{(SCR.15)}$$

For the screening argument used in the CCA, the inventory *(I)* that may be emplaced in the repository is approximately 4.07 million Ci or 1.5×10^{17} Bq (see the CCA, Appendix BIR). Assuming that the inventory continues to yield α-particles at this rate throughout the 10,000-yr regulatory period, the maximum rate of helium gas produced (R_{He}) may be calculated from

$$R_{He} = \frac{I\left(\frac{1\ He\ atom}{\alpha - decay}\right)}{N_A} \qquad \text{(SCR.16)}$$

R_{He} is the rate of helium gas production in the repository (mole per second).

I is the waste inventory, 1.5×10^{17} Bq, assuming that 1 Bq is equal to 1 α-decay per second, and N_A is Avogadro's constant (6.022×10^{23} atoms per mole). These assumptions regarding the inventory lead to maximum estimates for helium production because some of the radionuclides will decay by beta and gamma emission.

R_{He} is approximately 5.5×10^{-7} moles per second based on an α-emitting inventory of 4.07 million Ci (much greater than current inventory estimates) (Leigh, Trone, and Fox 2005). Assuming ideal gas behavior and repository conditions of 30 °C (86 °F) and 14.8 MPa or 146 atmospheres (lithostatic pressure) yields approximately 1.3 L (0.34 gal) per year.

The effects of helium gas production have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.9 FEP Number: W55
FEP Title: *Radioactive Gases*

SCR-6.5.1.9.1 Screening Decision: SO-C

The formation and transport of *Radioactive Gases* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.1.9.2 Summary of New Information

This FEP has been updated with references to the latest inventory information.

SCR-6.5.1.9.3 Screening Argument

Based on the composition of the anticipated waste inventory, as described in the CRA-2004, Appendix DATA, Attachment F, the radioactive gases that will be generated in the repository are radon (Rn) and ^{14}C-labeled CO_2 and CH_4.

Leigh, Trone, and Fox (2005) indicates that a small amount of carbon-14 (2.41 Ci) will be disposed in the WIPP. This amount is insignificant in comparison with the section 191.13 cumulative release limit for ^{14}C.

Notwithstanding this comparison, consideration of transport of radioactive gases could potentially be necessary in respect of the section 191.15 individual protection requirements. ^{14}C may partition into CO_2 and CH_4 formed during microbial degradation of cellulosic and other organic wastes (for example, rubbers and plastics). However, total fugacities of CO_2 in the repository are expected to be very low because of the action of the MgO backfill, which will lead to incorporation of CO_2 in solid magnesite. Similarly, interaction of CO_2 with cementitious wastes will limit CO_2 fugacities by the formation of solid calcium carbonate. Thus, because of the formation of solid carbonate phases in the repository, significant transport of ^{14}C as carbon dioxide-14 has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

Potentially significant volumes of CH_4 may be produced during the microbial degradation of cellulosic waste. However, volumes of methane-14 will be small given the low total inventory of carbon-14 and the tendency of carbon-14 to be incorporated into solid carbonate phases in the repository. Therefore, although transport of carbon-14 could occur as methane-14, this effect has been eliminated from the current PA calculations on the basis of low consequence to the performance of the disposal system.

Rn gas will contain proportions of the alpha emitters ^{219}Rn, ^{220}Rn, and ^{222}Rn. All of these have short half-lives, but ^{222}Rn is potentially the most important because it is produced from the abundant waste isotope, ^{238}Pu, and because it has the longest half-life of the radon isotopes ($\approx$ 4 days). ^{222}Ra will exhibit secular equilibrium with its parent ^{226}Rn, which has a half-life of 1600

years. Consequently, ^{222}Rn will be produced throughout the 10,000-yr regulatory time period. Conservative analysis of the potential ^{222}Rn inventory suggests activities of less than 716 Ci at 10,000 years (Bennett 1996).

Direct comparison of the estimated level of ^{222}Rn activity with the release limits specified in section 191.13 cannot be made because the release limits do not cover radionuclides with half-lives less than 20 years. For this reason, production of Rn gas can be eliminated from the PA calculations on regulatory grounds. Notwithstanding this regulatory argument, the small potential Rn inventory means that the formation and transport of Rn gas can also be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2 Speciation

SCR-6.5.2.1 FEP Number: W56
FEP Title: *Speciation*

SCR-6.5.2.1.1 Screening Decision: UP – Disposal Room
UP – Culebra
SO-C – Beneficial – Shaft Seals

Chemical *Speciation* is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms and the degree of chemical retardation estimated during contaminant transport. The effects of cementitious seals on chemical *Speciation* have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.2.1.2 Summary of New Information

No new information has been identified related to the screening of this FEP.

SCR-6.5.2.1.3 Screening Argument

Chemical speciation refers to the form in which elements occur under a particular set of chemical or environmental conditions. Conditions affecting chemical speciation include the temperature, pressure, and salinity (ionic strength) of the water in question. The importance of chemical speciation lies in its control of the geochemical reactions likely to occur and the consequences for actinide mobility.

SCR-6.5.2.1.3.1 Disposal Room

The concentrations of radionuclides that dissolve in any brines present in the disposal rooms after repository closure will depend on the stability of the chemical species that form under the prevailing conditions (for example, temperature, pressure, and ionic strength). The method used to derive radionuclide solubilities in the disposal rooms (see Appendix SOTERM-2009, Section SOTERM-4.0) considers the expected conditions. The MgO backfill will buffer pH values in the disposal room to between 9 and 10. Thus chemical *Speciation* is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.1.3.2 Repository Seals

Certain repository materials have the potential to interact with groundwater and significantly alter the chemical speciation of any radionuclides present. In particular, extensive use of cementitious materials in the seals may have the capacity to buffer groundwaters to extremely high pH (for example, Bennett et al. 1992, pp. 315–25). At high pH values, the speciation and adsorption behavior of many radionuclides is such that their dissolved concentrations are reduced in comparison with near-neutral waters. This effect reduces the migration of radionuclides in dissolved form. The effects of cementitious seals on groundwater chemistry have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.2.1.3.3 Culebra

Chemical speciation will affect actinide retardation in the Culebra. The dependence of An retardation on speciation in the Culebra is accounted for in PA calculations by sampling over ranges of K_ds. The ranges of K_ds are based on the range of groundwater compositions and speciation in the Culebra, including consideration of nonradionuclide solutes. The methodology used to simulate sorption in the Culebra is described in Appendix PA-2009, Section PA-4.9.

SCR-6.5.2.2 FEP Number: W57
FEP Title: *Kinetics of Speciation*

SCR-6.5.2.2.1 Screening Decision: SO-C

The effects of reaction kinetics in chemical speciation reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.2.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.2.2.3 Screening Argument

Chemical speciation of actinides describes the composition and relative distribution of dissolved species, such as the hydrated metal ion, or complexes, whether with organic or inorganic ligands. Conditions affecting chemical speciation include temperature, ionic strength, ligand concentration, and pH of the solution. Some ligands, such as hydroxide, may act to decrease An solubility, while others, such as citrate, frequently have the opposite influence, often increasing An solubility.

SCR-6.5.2.2.4 Disposal Room Equilibrium Conditions

The concentrations of radionuclides that can be dissolved in brines within the disposal rooms will depend on the thermodynamic stabilities and solubilities of the respective metal complexes. The Fracture-Matrix Transport (FMT) calculations and database input used to determine the brine solubilities of radionuclides takes into account the expected conditions, including temperature, ionic strength, pH, and ligand concentration. The chemical speciation at

equilibrium is accounted for in PA calculations in the estimates of radionuclide solubility in the disposal rooms.

SCR-6.5.2.2.5 Kinetics of Complex Formation

The waste that is emplaced within the WIPP contains radionuclides, including actinides or An-bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition and by the kinetics of dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and ethylene diamine tetra-acetate (EDTA) are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-yr regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions. As a result, the rate of approach to an equilibrium distribution of solution species takes place much more rapidly than dissolution, making the dissolution reaction the rate-limiting step. The effects of reaction kinetics in aqueous systems are discussed by Lasaga et al. (1994), who suggest that in contrast to many heterogeneous reactions, homogeneous aqueous geochemical speciation reactions involving relatively small inorganic species occur rapidly and are accurately described by thermodynamic equilibrium models that neglect explicit consideration of reaction kinetics.

For that reason, the rate at which solution species approach equilibrium distribution is of no consequence to repository performance. Kinetics of chemical speciation may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.3 Precipitation and Dissolution

SCR-6.5.3.1 FEP Numbers: W58, W59, and W60
FEP Titles: *Dissolution of Waste* (W58)
Precipitation of Secondary Minerals (W59)
Kinetics of Precipitation and Dissolution (W60)

SCR-6.5.3.1.1 Screening Decision: UP – W58
SO-C Beneficial – W59
SO-C – W60

Waste dissolution and the release of radionuclides in the disposal rooms are accounted for in PA calculations. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effect of reaction kinetics in controlling the rate of waste dissolution within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.5.3.1.3 Screening Argument

Dissolution of waste and precipitation of secondary minerals control the concentrations of radionuclides in brines and can influence rates of contaminant transport. Waste dissolution is accounted for in PA calculations. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

At low temperatures, precipitation and dissolution reactions are caused by changes in fluid chemistry that result in chemical undersaturation or oversaturation (Bruno and Sandino 1987). Precipitation can be divided into two stages: nucleation and crystal growth. Following nucleation, growth rates depend on the rates of surface processes and the transport of materials to the growth site. Mineral dissolution often depends on whether a surface reaction or transport of material away from the reaction site acts as the rate-controlling process. The former case may cause selective dissolution along crystallographically controlled features, whereas the latter may induce rapid bulk dissolution (Berner 1981). Thus a range of kinetic behaviors will be exhibited by different mineral precipitation and dissolution reactions in geochemical systems.

SCR-6.5.3.1.3.1 Disposal Room

The waste that is emplaced within the WIPP contains radionuclides, including actinides or An-bearing materials in solid phases, e.g. metal oxides, salts, coprecipitated solids, and contaminated objects. In the event of contact with brine, the solution phase concentration of dissolved radionuclides is controlled both by the solution composition and the kinetics of dissolution of the solid phases, effectively approaching equilibrium from undersaturation. Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonated and hydroxide, and with organic ligands such as acetate, citrate, oxalate, and EDTA are kinetically very fast, reaching equilibrium in less than 1 s, which is infinitesimally small on the time scale of the 10,000-yr regulatory period. The rate at which thermodynamic equilibrium is approached between solution composition and the solubility-controlling solid phases will be limited by rate of dissolution of the solid materials in the waste. As a result, until equilibrium is reached, the solution concentration of the actinides will be lower than the concentration predicted based upon equilibrium of the solution phase components with the solubility-limiting solid phases. The WIPP An source term model, which describes interactions of the waste and brine, is described in detail in the CCA, Chapter 6.0, Section 6.4.3.5. The assumption of instantaneous equilibrium in waste dissolution reactions is a conservative approach, yielding maximum concentration estimates for radionuclides in the disposal rooms because a time-weighted average resulting from a kinetically accurate estimate of solution compositions would have lower concentrations at early times. Waste dissolution at the thermodynamic equilibrium solubility limit is accounted for in PA calculations. However, the kinetics of dissolution within the disposal rooms has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.3.1.3.2 Geological Units

During groundwater flow, radionuclide precipitation processes that occur will lead to reduced contaminant transport. No credit is given in PA calculations to the potentially beneficial occurrence of precipitation of secondary minerals. The formation of radionuclide-bearing precipitates from groundwaters and brines and the associated retardation of contaminants have been eliminated from PA calculations on the basis of beneficial consequence to disposal system performance. As a result, kinetics of precipitation has also been eliminated from PA calculations because no credit is taken for precipitation reactions.

SCR-6.5.4 Sorption

SCR-6.5.4.1 FEP Numbers: W61, W62, and W63
FEP Titles: *Actinide Sorption* (W61)
Kinetics of Sorption (W62)
Changes in Sorptive Surfaces (W63)

SCR-6.5.4.1.1 Screening Decision: UP – (W61, W62) In the Culebra and Dewey Lake
SO-C – Beneficial – (W61, W62) In the Disposal Room, Shaft Seals, Panel Closures, Other Geologic Units
UP – (W63**)**

Sorption within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Sorption within the Culebra and the Dewey Lake is accounted for in PA calculations. Sorption processes within other geological units of the disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system. Mobile adsorbents (for example, microbes and humic acids), and the sorption of radionuclides at their surfaces, are accounted for in PA calculations in the estimates of the concentrations of actinides that may be carried. The potential effects of reaction kinetics in adsorption processes and of *Changes in Sorptive Surfaces* are accounted for in PA calculations.

SCR-6.5.4.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.5.4.1.3 Screening Argument

Sorption may be defined as the accumulation of matter at the interface between a solid and an aqueous solution. Within PA calculations, including those made for the WIPP, the use of isotherm representations of An sorption prevails because of their computational simplicity in comparison with other models (Serne 1992, pp. 238−39).

The mechanisms that control the kinetics of sorption processes are, in general, poorly understood. Often, sorption of inorganic ions on mineral surfaces is a two-step process consisting of a short period (typically minutes) of diffusion-controlled, rapid uptake, followed by slower processes (typically weeks to months) including surface rearrangement, aggregation and precipitation, and solid solution formation (Davis and Kent 1990, p. 202). Available data concerning rates of sorption reactions involving the important radionuclides indicate that, in general, a range of kinetic behavior is to be expected.

The relevance to the WIPP of sorption reaction kinetics lies in their effects on chemical transport. Sorption of waste contaminants to static surfaces of the disposal system, such as seals and host rocks, acts to retard chemical transport. Sorption of waste contaminants to potentially mobile surfaces, such as colloids, however, may act to enhance chemical transport, particularly if the kinetics of contaminant desorption are slow or the process is irreversible (nonequilibrium).

The following subsections discuss sorption in the disposal rooms, shaft seals, panel closures, the Culebra, and other geological units of the WIPP disposal system. Sorption on colloids, microbes, and particulate material is also discussed.

SCR-6.5.4.1.3.1 Disposal Room

The concentrations of radionuclides that dissolve in waters entering the disposal room will be controlled by a combination of sorption and dissolution reactions. However, because sorption processes are surface phenomena, the amount of material likely to be involved in sorption mass transfer processes will be small relative to that involved in the bulk dissolution of waste. WIPP PA calculations therefore assume that dissolution reactions control radionuclide concentrations. Sorption on waste, containers, and backfill within the disposal rooms, which would serve to reduce radionuclide concentrations, has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4 Shaft Seals and Panel Closures

The CCA, Chapter 3.0 and Appendix SEAL describe the seals that are to be placed at various locations in the access shafts and waste panel access tunnels. The materials to be used include crushed salt, bentonite clay, and cementitious grouts. Of these, the latter two in particular possess significant sorption capacities. No credit is given for the influence of sorption processes that may occur in seal materials and their likely beneficial effects on radionuclide migration rates. The effects of sorption processes in shaft seals and panel closures have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.1 Culebra

Sorption within the Culebra is accounted for in PA calculations as discussed in the CCA, Chapter 6.0, Section 6.4.6.2. The model used comprises an equilibrium, sorption isotherm approximation, employing constructed CDFs of K_ds applicable to dolomite in the Culebra. The potential effects of reaction kinetics in adsorption processes are encompassed in the ranges of K_ds used. The geochemical speciation of the Culebra groundwaters and the effects of changes in sorptive surfaces are implicitly accounted for in PA calculations for the WIPP in the ranges of K_ds used.

SCR-6.5.4.1.4.2 Other Geological Units

During groundwater flow, any radionuclide sorption processes that occur between dissolved or colloidal actinides and rock surfaces will lead to reduced rates of contaminant transport. The sorptive capacity of the Dewey Lake is sufficiently large to prevent any radionuclides that enter it from being released to the accessible environment over 10,000 years (Wallace et al. 1995). Thus sorption within the Dewey Lake is accounted for in PA calculations, as discussed in the CCA, Chapter 6.0, Section 6.4.6.6. No credit is given to the potentially beneficial occurrence of sorption in other geological units outside the Culebra. Sorption processes within other geological units of the disposal system have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.5.4.1.4.3 Sorption on Colloids, Microbes, and Particulate Material

The interactions of sorption processes with colloidal, microbial, or particulate transport are complex. Neglecting sorption of contaminants on immobile surfaces in the repository shafts and Salado (for example, the clays of the Salado interbeds) is a conservative approach because it leads to overestimated transport rates. However, neglecting sorption on potentially mobile adsorbents (for example, microbes and humic acids) cannot be shown to be conservative with respect to potential releases, because mobile adsorbents may act to transport radionuclides sorbed to them. Consequently, the concentrations of actinides that may be carried by mobile adsorbents are accounted for in PA calculations (see the CCA, Chapter 6.0, Section 6.4.3.6).

SCR-6.5.5 Reduction-Oxidation Chemistry

SCR-6.5.5.1 FEP Numbers: W64 and W66

FEP Titles: *Effects of Metal Corrosion*
Reduction-Oxidation Kinetics

SCR-6.5.5.1.1 Screening Decision: UP

The effects of reduction-oxidation reactions related to metal corrosion on reduction-oxidation conditions are accounted for in PA calculations. Reduction-oxidation reaction kinetics are accounted for in PA calculations.

SCR-6.5.5.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.5.5.1.3 Screening Argument

SCR-6.5.5.1.3.1 Reduction-Oxidation Kinetics

In general, investigation of the reduction-oxidation couples present in aqueous geochemical systems suggests that most reduction-oxidation reactions are not in thermodynamic equilibrium (Wolery 1992, p. 27). The lack of data characterizing the rates of reactions among trace element reduction-oxidation couples leads to uncertainty in elemental speciation. This uncertainty in reduction-oxidation kinetics is accounted for in PA calculations in the dissolved An source term model (see Appendix SOTERM-2009, Section SOTERM-4.0), which estimates the probabilities that particular actinides occur in certain oxidation states.

SCR-6.5.5.1.3.2 Corrosion

Other than gas generation, which is discussed in FEPs W44 through W55, the main effect of metal corrosion will be to influence the chemical conditions that prevail within the repository. Ferrous metals will be the most abundant metals in the WIPP, and these will corrode on contact with any brines entering the repository. Initially, corrosion will occur under oxic conditions owing to the atmospheric oxygen present in the repository at the time of closure. However, consumption of the available oxygen by corrosion reactions will rapidly lead to anoxic (reducing) conditions. These changes and controls on conditions within the repository will affect the chemical speciation of the brines and may affect the oxidation states of the actinides present. Changes to the oxidation states of the actinides will lead to changes in the concentrations that may be mobilized during brine flow. The oxidation states of the actinides are accounted for in PA calculations by the use of parameters that describe probabilities that the actinides exist in particular oxidation states and, as a result, the likely An concentrations. Therefore, the effects of metal corrosion are accounted for in PA calculations.

SCR-6.5.5.2 FEP Number: W65
FEP Title: *Reduction-Oxidation Fronts*

SCR-6.5.5.2.1 Screening Decision: SO-P

The migration of *Reduction-Oxidation Fronts* through the repository has been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.5.5.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.5.2.3 Screening Argument

The development of reduction-oxidation fronts in the disposal system may affect the chemistry and migration of radionuclides. Reduction-oxidation fronts separate regions that may be characterized, in broad terms, as having different oxidation potentials. On either side of a reduction-oxidation front, the behavior of reduction-oxidation-sensitive elements may be controlled by different geochemical reactions. Elements that exhibit the greatest range of oxidation states (for example, U, Np, and Pu) will be the most affected by reduction-oxidation front development and migration. The migration of reduction-oxidation fronts may occur as a result of diffusion processes, or in response to groundwater flow, but will be restricted by the occurrence of heterogeneous buffering reactions (for example, mineral dissolution and precipitation reactions). Indeed, these buffering reactions cause the typically sharp, distinct nature of reduction-oxidation fronts.

Of greater significance is the possibility that the flow of fluids having different oxidation potentials from those established within the repository might lead to the development and migration of a large-scale reduction-oxidation front. Reduction-oxidation fronts have been observed in natural systems to be the loci for both the mobilization and concentration of radionuclides, such as U. For example, during investigations at two U deposits at Poços de Caldas, Brazil, U was observed by Waber (1991) to be concentrated along reduction-oxidation

fronts at the onset of reducing conditions by its precipitation as U oxide. In contrast, studies of the Alligator Rivers U deposit in Australia by Snelling (1992) indicated that the movement of the relatively oxidized weathered zone downwards through the primary ore body as the deposit was eroded and gradually exhumed led to the formation of secondary uranyl-silicate minerals and the mobilization of U in its more soluble U(VI) form in near-surface waters. The geochemical evidence from these sites suggests that the reduction-oxidation fronts had migrated only slowly, at most on the order of a few tens of meters per million years. These rates of migration were controlled by a range of factors, including the rates of erosion, infiltration of oxidizing waters, geochemical reactions, and diffusion processes.

The migration of large-scale reduction-oxidation front through the repository as a result of regional fluid flow is considered unlikely over the regulatory period on the basis of comparison with the slow rates of reduction-oxidation front migration suggested by natural system studies. This comparison is considered conservative because the relatively impermeable nature of the Salado suggests that reduction-oxidation front migration rates at the WIPP are likely to be slower than those observed in the more permeable lithologies of the natural systems studied. Large-scale reduction-oxidation fronts have therefore been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 yrs.

SCR-6.5.5.3 FEP Number: W67
FEP Title: *Localized Reducing Zones*

SCR-6.5.5.3.1 Screening Decision: SO-C

The formation of *Localized Reducing Zones* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.5.5.3.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.5.3.3 Screening Argument

The dominant reduction reactions in the repository include steel corrosion and microbial degradation. The following bounding calculation shows that molecular diffusion alone will be sufficient to mix brine chemistry over a distance of meters and therefore the formation of localized reducing zones in the repository is of low consequence.

The diffusion of a chemical species in a porous medium can be described by Fick's equation (e.g., Richardson and McSween 1989, p.132):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial X}\left(D_{eff} \frac{\partial C}{\partial X} \right) \qquad \text{(SCR.17)}$$

where C is the concentration of the diffusing chemical species, t is the time, X is the distance, and D_{eff} is the effective diffusivity of the chemical species in a given porous medium. D_{eff} is related to the porosity (ϕ) of the medium by (e.g., Oelkers 1996):

$$D_{eff} = \phi^2 D \quad \text{(SCR.18)}$$

where D is the diffusivity of the species in pure solution. The D values for most aqueous species at room temperatures fall into a narrow range, and 10^{-5} cm^2 (1.5×10^{-6} in.^{2}) per s is a good approximation (e.g., Richardson and McSween 1989, p.138). From the WIPP PA calculations (Bean et al. 1996, p.7-29; WIPP Performance Assessment, 1993, Equation B-8), the porosity in the WIPP waste panels after room closure is calculated to be 0.4 to 0.7. From Equation (SCR.19), the effective diffusivity D_{eff} in the waste is estimated to be $2 - 5 \times 10^{-6}$ cm^2 (7×10^{-7} in.^{2}) per second (= $6 - 16 \times 10^{-3}$ m^2/year).

Given a time scale of T, the typical diffusion penetration distance (L) can be determined by scaling:

$$L = \sqrt{D_{eff} T} \quad \text{(SCR.19)}$$

Using Equation (SCR.20), the diffusion penetration distance in the WIPP can be calculated as a function of diffusion time, as shown in Figure SCR-1.

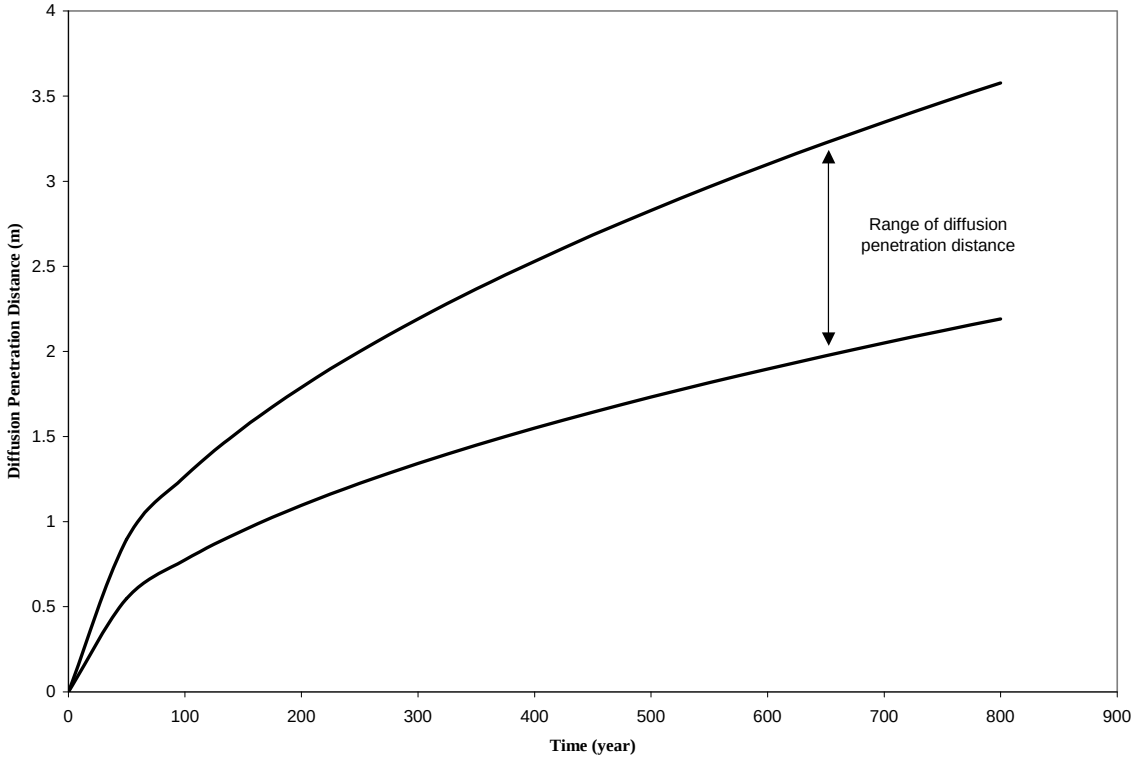

Figure SCR-1. Diffusion Penetration Distance in the WIPP as a Function of Diffusion Time

Direct brine release requires the repository gas pressure to be at least 8 MPa (Stoelzel et al. 1996). The CRA-2009 calculations show that it will take at least 100 years for the repository pressure to reach this critical value by gas generation processes (see Nemer and Clayton 2008,

Figure 6-24). Over this time scale, according to Equation (SCR.20) and Figure SCR-1, molecular diffusion alone can mix brine composition effectively at least over a distance of ~ 1 m (3.3 ft).

The above calculation assumes diffusion only through liquid water. This assumption is applicable to steel corrosion, the humid rate of which is zero. Note that microbial reactions can also consume or release gaseous species. The diffusion of a gaseous species is much faster than an aqueous one. Thus molecular diffusion can homogenize microbial reactions even at a much larger scale.

The height of waste stacks in the repository after room closure (h) can be calculated by:

$$h = \frac{h_0\left(1-\varphi_0\right)}{1-\varphi} \qquad \text{(SCR.20)}$$

where h_0 and ϕ_0 are the initial height of waste stacks and the initial porosity of wastes, which are assumed to be 4 m and 0.88, respectively, in the WIPP PA. For $\phi = 0.4 – 0.7$, h is estimated to be 0.8 to 1.4 m. This means that molecular diffusion alone can homogenize redox reaction in the vertical dimension of the repository. Therefore, the formation of localized reducing zones is unlikely. The general repository environment will become reducing shortly after room closure because of metal corrosion and microbial reactions. Therefore, localized reducing zone*s* can be eliminated from PA calculations on the basis of low consequence to the disposal system.

SCR-6.5.6 Organic Complexation

SCR-6.5.6.11 **FEP Numbers:** W68, W69, and W71
FEP Titles: *Organic Complexation* (W68)
Organic Ligands (W69)
Kinetics of Organic Complexation (W71)

SCR-6.5.6.1.1 Screening Decision: UP – W68 and W69
SO-C – W71

The effects of anthropogenic *Organic Complexation* reactions, including the effects of *Organic Ligands*, humic, and fulvic acids, have been incorporated in the PA calculations. The kinetics of organic ligand complexation is screened out because the rate at which organic ligands are complexed to actinide is so fast that it has no consequence to repository performance.

SCR-6.5.6.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.5.6.1.3 Screening Argument

From a PA standpoint, the most important actinides are Th, U, Np, Pu, and Am. Dissolved Th, U, Np, Pu, and Am will essentially speciate entirely as Th(IV), U(IV) or U(VI), Np(IV) or Np(V), Pu(III) or Pu(IV), and Am(III) under the strongly reducing conditions expected as a

result of the presence of Fe(II) and microbes (see the CRA-2004, Appendix PA, Attachment SOTERM, Section SOTERM-2.2.5).

Some organic ligands can increase the actinide solubilities. An estimate of the complexing agents in the TRU solidified waste forms scheduled for disposal in the WIPP is presented in the CRA-2004, Appendix DATA, Attachment F, Table DATA-F-33. Acetate, citrate, oxalate, and EDTA were determined to be the only water-soluble and actinide-complexing organic ligands present in significant quantities in the TWBIR. These ligands and their complexation with actinides (Th(IV), U(VI), Np(V), and Am(III)) in a variety of ionic strength media were studied at Florida State University (FSU) (Choppin et al. 2001). The FSU studies showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved An concentrations. Lactate behavior was also studied at FSU because it appeared in the preliminary inventory of nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990); lactate did not appear in the CRA-2004 inventory, nor does it appear in the inventory used for the CRA-2009.

The solubility of the actinides is calculated using FMT, a computer code for calculating actinide concentration limits based on thermodynamic parameters. The parameters for FMT are derived both from experimental investigations specifically designed to provide parameter values for this model and from the published literature.

Although the FSU experimental work on organic ligands complexation showed that acetate, citrate, oxalate, and EDTA are capable of significantly enhancing dissolved An concentrations, SNL did not include the results in the FMT calculations for the CCA PA because (1) the thermodynamic database for organic complexation of actinides was not considered adequate at the time, and (2) side-calculations using thermodynamic data for low-ionic-strength NaCl solutions showed that transition metals (in particular iron, nickel, chromium, vanadium, and manganese present in waste drum steel) would compete effectively with the actinides for the binding sites on the organic ligands, thus preventing significant complexation of actinides.

The CRA-2009 calculations include the effects of organic ligands (acetate, citrate, EDTA, and oxalate) on actinide solubilities in the FMT calculations (Brush and Xiong 2003). The FMT database includes all of the results of experimental studies (Choppin et al. 2001) required to predict the complexation of dissolved An(III), An(IV), and An(V) species by acetate, citrate, EDTA, and oxalate (Giambalvo 2002a, 2002b).

Solution complexation reactions of most metal ions with common inorganic ligands, such as carbonate and hydroxide, and with organic ligands, such as acetate, citrate, oxalate, and EDTA, are kinetically very fast, reaching equilibrium in fractions of a second, an inconsequentially short time increment on the scale of the 10,000-yr regulatory period. Reactions of these types are generally so fast that special techniques must be adopted to measure the reaction rates; as a practical matter, the reaction rate is limited by the mixing rate when metal solutions are combined with ligand solutions.

For that reason, the rate at which organic ligands are complexed to actinide is of no consequence to repository performance. Kinetics of organic complexation may be eliminated from PA calculations on the basis of no consequence.

SCR-6.5.6.2 FEP Number: W70
FEP Title: *Humic and Fulvic Acids*

SCR-6.5.6.2.1 Screening Decision: UP

The presence of *Humic Acids* and *Fulvic Acids* is incorporated in PA calculations.

SCR-6.5.6.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.6.2.3 Screening Argument

The occurrence of humic acids and fulvic acids is incorporated in PA calculations in the models for radionuclide transport by humic colloids (see Appendix PA-2009, Section PA-4.3.2).

SCR-6.5.7 Chemical Effects on Material Properties

SCR-6.5.7.1 FEP Numbers: W74, W76, and W115
FEP Titles: *Chemical Degradation of Shaft Seals* (W74)
Microbial Growth on Concrete (W76)
Chemical Degradation of Panel Closures (W115)

SCR-6.5.7.1.1 Screening Decision: UP

The effects of *Chemical Degradation of Shaft Seals*, *Chemical Degradation of Panel Closures*, and *Microbial Growth on Concrete* are accounted for in PA calculations.

SCR-6.5.7.1.2 Summary of New Information

Changes to the titles of these FEPs are a result of the FEPs analysis conducted for the Panel Closure Redesign planned change request (Kirkes 2006).

SCR-6.5.7.1.3 Screening Argument

The concrete used in the seal systems and panel closure systems will degrade as a result of chemical reaction with the infiltrating groundwater. Degradation could lead to an increase in permeability of the seal system. The main uncertainties with regard to cement degradation rates at the WIPP are the effects of groundwater chemistry, the exact nature of the cementitious phases present, and the rates of brine infiltration. The PA calculations take a conservative approach to these uncertainties by assuming a large increase in permeability of the concrete seals only a few hundred years after closure. These permeability values are based on seal design considerations and consider the potential effects of degradation processes. Therefore, the effects of chemical degradation of seals and chemical degradation of panel closures are accounted for in PA calculations through the CDFs used for seal material permeabilities.

Concrete can be inhabited by alkalophilic bacteria, which could produce acids, thereby accelerating the seal degradation process. Nitrification processes, which will produce nitric acid, tend to be aerobic, and will be further limited at the WIPP by the low availability of ammonium in the brines (Pedersen and Karlsson 1995, p. 75). Because of the limitations on growth caused by the chemical conditions, it is likely that the effects of microbial growth on concrete will be small. The effects of such microbial activity on seal properties are, therefore, implicitly accounted for in PA calculations through the CDFs used for seal material permeabilities.

SCR-6.5.7.2 FEP Number: W75
FEP Title: *Chemical Degradation of Backfill*

SCR-6.5.7.2.1 Screening Decision: SO-C

The effects on material properties of the *Chemical Degradation of Backfill* have been eliminated from PA calculations on the basis of low consequence.

SCR-6.5.7.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.5.7.2.3 Screening Argument

Degradation of the chemical conditioners or backfill added to the disposal room is a prerequisite of their function in buffering the chemical environment of the disposal room. However, the chemical reactions (Snider 2001) and dissolution involved will change the physical properties of the material. Because the mechanical and hydraulic characteristics of the backfill have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system, the effects of the chemical degradation of backfill on material properties have been eliminated from PA calculations on the same basis.

SCR-6.6 Contaminant Transport Mode FEPs

SCR-6.6.1 Solute and Colloid Transport

SCR-6.6.1.1 FEP Number: W77
FEP Title: *Solute Transport*

SCR-6.6.1.1.1 Screening Decision: UP

Transport of dissolved radionuclides is accounted for in PA calculations.

SCR-6.6.1.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.6.1.1.3 Screening Argument

Solute transport may occur by advection, dispersion, and diffusion down chemical potential gradients, and is accounted for in PA calculations (see Appendix PA-2009, Section PA-2.1.4.4).

SCR-6.6.1.2 FEP Numbers: W78, W79, W80, and W81

FEP Titles: *Colloidal Transport* (W78)
Colloidal Formation and Stability (W79)
Colloidal Filtration (W80)
Colloidal Sorption (W81)

SCR-6.6.1.2.1 Screening Decision: UP

Formation of colloids, transport of colloidal radionuclides, and colloid retardation through filtration and sorption are accounted for in PA calculations.

SCR-6.6.1.2.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.6.1.2.3 Screening Argument

Colloids typically have sizes of between 1 nm and 1 μm and may form stable dispersions in groundwaters. Colloid formation and stability depends on their composition and the prevailing chemical conditions (for example, salinity). Depending on their size, colloid transport may occur at different rates than those of fully dissolved species. They may be physically excluded from fine porous media, and their migration may be accelerated through fractured media in channels where velocities are greatest. However, they can also interact with the host rocks during transport and become retarded. These interactions may be of a chemical or physical nature and include electrostatic effects leading to colloid sorption, and sieving leading to colloid filtration and pore blocking. Colloidal formation and stability is accounted for in PA calculations through estimates of colloid numbers in the disposal room based on the prevailing chemical conditions (Appendix SOTERM-2009, Section SOTERM-3.8). Colloidal sorption, colloidal filtration, and colloidal transport in the Culebra are accounted for in PA calculations (Appendix SOTERM-2009, Section SOTERM-3.8).

SCR-6.6.2 Particle Transport

SCR-6.6.2.1 FEP Numbers: W82, W83, W84, W85, and W86
FEP Titles: *Suspension of Particles* (W82)
Rinse (W83)
Cuttings (W84)
Cavings (W85)
Spallings (W86)

SCR-6.6.2.1.1 Screening Decision: DP – W82, W84, W85, W86
SO-C – W83

The formation of particulates through *Rinse* and subsequent transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system. The transport of radionuclides as particulates (cuttings, cavings, and spallings) during penetration of the repository by a borehole, is accounted for in PA calculations.

SCR-6.6.2.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.6.2.1.3 Screening Argument

Suspensions of particles that have sizes larger than colloids are unstable because the particles undergo gravitational settling. It is unlikely that brine flow will be rapid enough within the WIPP disposal rooms to generate particulate suspensions through rinse and transport under undisturbed conditions. Mobilization of suspensions would effect a local and minor redistribution of radionuclides within the room and would not result in increased radionuclide transport from the repository. The formation of particulates through rinse and transport of radionuclides in groundwater and brine has been eliminated from PA calculations for undisturbed conditions on the basis of low consequence to the performance of the disposal system.

Inadvertent human intrusion into the repository by a borehole could result in transport of waste material to the ground surface through drilling-induced flow and blowouts (FEPs H21 and H23, Section SCR-5.2.1.1 and Section SCR-5.2.1.3). This waste could include material intersected by the drill bit (cuttings), material eroded from the borehole wall by circulating drilling fluid (cavings), and material that enters the borehole as the repository depressurizes (spallings). Transport of radionuclides by these materials and in brine is accounted for in PA calculations and is discussed in Appendix PA-2009, Section PA-4.5.

SCR-6.6.3 Microbial Transport

SCR-6.6.3.1 FEP Number: W87
FEP Title: *Microbial Transport*

SCR-6.6.3.1.1 Screening Decision: UP

Transport of radionuclides bound to microbes is accounted for in PA calculations.

SCR-6.6.3.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.6.3.1.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system. Because of their colloidal size, microbes, and any radionuclides bound to them, may be transported at different rates than radionuclides in solution. Microbial transport of radionuclides is accounted for in PA calculations (Appendix SOTERM-2009, Section SOTERM-5.0).

SCR-6.6.3.2 FEP Number: W88
FEP Title: *Biofilms*

SCR-6.6.3.2.1 Screening Decision: SO-C Beneficial

The effects of *Biofilms* on microbial transport have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.6.3.2.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.6.3.2.3 Screening Argument

Microbes will be introduced into the disposal rooms during the operational phase of the repository and will also occur naturally in geological units throughout the disposal system.

Biofilms may influence microbial and radionuclide transport rates through their capacity to retain, and therefore retard, both the microbes themselves and radionuclides. The formation of biofilms in deep subsurface environments such as in the WIPP is controversial. Since the microbial degradation experiments at Brookhaven National Laboratory (BNL) bracket expected repository conditions, the potential effect of biofilms formation on microbial degradation and transport, if any, has been captured in the PA parameters derived from those experiments (Francis and Gillow 1994; Francis et. al 1997; Francis and Gillow 2000; Gillow and Francis 2001a; Gillow and Francis 2001b; Gillow and Francis 2002a; Gillow and Francis 2002b). As a matter of fact, no apparent formation of stable biofilms was observed in the BNL experiments.

The formation of biofilms tends to reduce cell suspension and mobility. This effect has been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.6.4 Gas Transport

SCR-6.6.4.1 FEP Number: W89
FEP Title: *Transport of Radioactive Gases*

SCR-6.6.4.1.1 Screening Decision: SO-C

The *Transport of Radioactive Gases* has been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.6.4.1.2 Summary of New Information

This FEP discussion has been updated to include recent inventory information.

SCR-6.6.4.1.3 Screening Argument

The production and potential transport of radioactive gases are eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. Transportable radioactive gases are comprised mainly of isotopes of Rn and ^{14}C. Rn gases are eliminated from PA because their inventory is small (<7 Ci; (Leigh, Trone, and Fox 2005)) and their half-lives are short (<4 days), resulting in insignificant potential for release from the repository.

SCR-6.7 Contaminant Transport Processes

SCR-6.7.1 Advection

SCR-6.7.1.1 FEP Number: W90
FEP Title: *Advection*

SCR-6.7.1.1.1 Screening Decision: UP

Advection of contaminants is accounted for in PA calculations.

SCR-6.7.1.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.7.1.1.3 Screening Argument

Advection (that is, the transport of dissolved and solid material by flowing fluid) is accounted for in PA calculations (Appendix PA-2009, Section PA-4.3.5).

SCR-6.7.2 Diffusion

SCR-6.7.2.1 FEP Numbers: W91 and W92
FEP Titles: *Diffusion* (W91)
Matrix Diffusion (W92)

SCR-6.7.2.1.1 Screening Decision: UP

Diffusion of contaminants and retardation by *Matrix Diffusion* are accounted for in PA calculations.

SCR-6.7.2.1.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.7.2.1.3 Screening Argument

Diffusion (that is, the movement of molecules or particles both parallel to and transverse to the direction of advection in response to Brownian forces) and, more specifically matrix diffusion, whereby movement is transverse to the direction of advection within a fracture and into the surrounding rock matrix, are accounted for in PA calculations (Appendix PA-2009, Section PA-4.9).

SCR-6.7.3 Thermochemical Transport Phenomena

SCR-6.7.3.1 FEP Number: W93
FEP Title: *Soret Effect*

SCR-6.7.3.1.1 Screening Decision: SO-C

The effects of thermochemical transport phenomena (the *Soret Effect*) have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.3.1.2 Summary of New Information

This FEP has been updated with new thermal heat rise values for Al corrosion, based on the latest inventory data.

SCR-6.7.3.1.3 Screening Argument

According to Fick's law, the diffusion flux of a solute is proportional to the solute concentration gradient. In the presence of a temperature gradient there will also be a solute flux proportional to the temperature gradient (the Soret Effect). Thus the total solute flux, J, in a liquid phase may be expressed as

$$J = -D\bar{V}C - ND\bar{V}T \qquad \text{(SCR.21)}$$

where C is the solute concentration, T is the temperature of the liquid, D is the solute diffusion coefficient, and

$$N = S_T C(1-C) \tag{SCR.22}$$

in which S_T is the Soret coefficient. The mass conservation equation for solute diffusion in a liquid is then

$$\frac{\partial C}{\partial t} = \nabla \cdot (D\nabla C + ND\nabla T) \tag{SCR.23}$$

When temperature gradients exist in solutions with both light and heavy solute molecules, the heavier molecules tend to concentrate in the colder regions of the solution. Typically, large temperature gradients are required for Soret diffusion to be significant compared to Fickian diffusion.

Radioactive decay, nuclear criticality, and exothermic reactions are three possible sources of heat in the WIPP repository. The U.S. Department of Energy (1980) estimated that radioactive decay of CH-TRU waste will result in a maximum temperature rise at the center of the repository of 1.6 °C (2.9 °F) at 80 years after waste emplacement. Sanchez and Trellue (1996) have shown that the total thermal load of RH-TRU waste will not significantly affect the average temperature increase in the repository. Temperature increases of about 3 °C (5.4 °F) may occur at the locations of RH-TRU containers with maximum thermal power (60 W). Such temperature increases are likely to be short-lived on the time scale of the 10,000-yr regulatory period because of the rapid decay of heat-producing nuclides in RH-TRU waste, such as ^{137}Cs (cesium), ^{90}Sr (strontium), ^{241}Pu, and ^{147}Pm (promethium), whose half-lives are approximately 30, 29, 14, and 3 years, respectively. Soret diffusion generated by such temperature gradients will be negligible compared to other radionuclide transport mechanisms.

Temperature increases resulting from exothermic reactions are discussed in Section SCR-6.3.4.1. Potentially the most significant exothermic reactions are concrete hydration, backfill hydration, and aluminum corrosion. Hydration of the seal concrete could raise the temperature of the concrete to approximately 50 °C (122 °F) and that of the surrounding salt to approximately 38 °C (100 °F) one week after seal emplacement.

However, the concrete seals will act as barriers to fluid flow for at least 100 years after emplacement, and seal permeability will be minimized (Wakeley et al. 1995). As a result, short-term temperature increases associated with concrete hydration will not result in significant Soret diffusion through the seal system.

The maximum temperature rise in the disposal panels will be less than 5 °C (9 °F) as a consequence of MgO hydration. Note that AICs will prevent drilling within the controlled area for 100 years after disposal. Heat generation by radioactive decay and concrete seal hydration will have decreased substantially after 100 years, and the temperatures in the disposal panels will have decreased nearly to the temperature of the undisturbed host rock.

If the repository were to be inundated following a drilling intrusion, Al corrosion could, at most, result in a short-lived (two years) temperature increase of about 6.9 °C (12.4 °F). These calculated maximum heat generation rates resulting from Al corrosion and backfill hydration could not occur simultaneously because they are limited by brine availability; each calculation assumes that all available brine is consumed by the reaction of concern. Thus the temperature rise of 6.9 °C (12.4 °F) represents the maximum that could occur as a result of a combination of exothermic reactions occurring simultaneously. Temperature increases of this magnitude will not result in significant Soret diffusion within the disposal system.

The limited magnitude and spatial scale of temperature gradients in the disposal system indicate that Soret diffusion will be insignificant, allowing the effects of thermochemical transport (soret effect) to be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4 Electrochemical Transport Phenomena

SCR-6.7.4.1 FEP Number: W94
FEP Title: *Electrochemical Effects*

SCR-6.7.4.1.1 Screening Decision: SO-C

The effects of electrochemical transport phenomena caused by electrochemical reactions have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4.1.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.4.1.3 Screening Argument

The variety of waste metals and metal packaging in the repository may allow galvanic cells spanning short distances to be established. The interactions among the metals depend upon their physical characteristics and the chemical conditions in the repository. For example, good physical and electrical contact, which is critical to the establishment of galvanic cells, may be impeded by electrically nonconductive waste materials. Additionally, in order to establish a galvanic cell, it is necessary that the metals have different values for standard reduction potentials. For example, a galvanic cell is not expected to be formed by contact of two segments of metals with identical compositions. As a result, galvanic cells can only be established by contact of dissimilar metals, as might happen because of contact between a waste drum and the contents, or between contents within a waste package. The localized nature of electrochemical transport is restricted to the size scale over which galvanic cells can develop, i.e., on the order of size of waste packages. Since the possible range of transport is restricted by the physical extent of galvanic activity, electrochemical effects cannot act as long-range transport mechanisms for radionuclides and therefore are of no consequence to the performance of the repository.

SCR-6.7.4.2 FEP Number: W95
FEP Title: *Galvanic Coupling* (outside the repository)

SCR-6.7.4.2.1 Screening Decision: SO-P

The effects of *Galvanic Coupling* between the waste and metals external to the repository on transport have been eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.7.4.2.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.4.2.3 Screening Argument

With regard to the WIPP, galvanic coupling refers to the establishment of galvanic cells between metals in the waste form, canisters, and other metals external to the waste form.

Long-range electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of electric potential gradients may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of electric potentials is usually less than about 100 millivolts (mV) and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976). Metals external to the waste form can include natural metallic ore bodies in the host rock. However, metallic ore bodies and metallic sulfide ores do not exist in the region of the repository (the CCA, Appendix GCR). As a result, galvanic coupling between the waste and metallic materials outside the repository cannot occur. Therefore, galvanic coupling is eliminated from PA calculations on the basis of low probability of occurrence over 10,000 years.

SCR-6.7.4.3 FEP Number: W96
FEP Title: *Electrophoresis*

SCR-6.7.4.3.1 Screening Decision: SO-C

The effects of electrochemical transport phenomena caused by *Electrophoresis* have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.4.3.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.4.3.3 Screening Argument

Long range (in terms of distance) electric potential gradients may exist in the subsurface as a result of groundwater flow and electrochemical reactions. The development of potentials may be associated with the weathering of sulfide ore bodies, variations in rock properties at geological contacts, bioelectric activity associated with organic matter, natural corrosion reactions, and temperature gradients in groundwater. With the exception of mineralization potentials associated with metal sulfide ores, the magnitude of such potentials is usually less than about 100 mV and the potentials tend to average to zero over distances of several thousand feet (Telford et al. 1976, p. 458). Short range potential gradients caused by the corrosion of metals within the waste may be set up over distances that are restricted to the size scale of the waste packages.

A variety of metals will be present within the repository as waste metals and metal packaging, which may allow electrochemical cells to be established over short distances. The types of interactions that will occur depend on the metals involved, their physical characteristics, and the prevailing solution conditions. Electrochemical cells that may be established will be small relative to the size of the repository, limiting the extent to which migration of contaminants by electrophoresis can occur. The electric field gradients will be of small magnitude and confined to regions of electrochemical activity in the area immediately surrounding the waste material. As a result, electrophoretic effects on migration behavior caused by both long and short range potential gradients have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5 Physiochemical Transport Phenomena

SCR-6.7.5.1 FEP Number: W97
FEP Title: *Chemical Gradients*

SCR-6.7.5.1.1 Screening Decision: SO-C

The effects of enhanced diffusion across *Chemical Gradients* have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5.1.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.5.1.3 Screening Argument

Chemical gradients within the disposal system, whether induced naturally or resulting from repository material and waste emplacement, may influence the transport of contaminants. Gradients will exist at interfaces between different repository materials and between repository and geological materials. Distinct chemical regimes will be established within concrete seals and adjoining host rocks. Similarly, chemical gradients will exist between the waste and the surrounding rocks of the Salado. Other chemical gradients may exist because of the juxtaposition of relatively dilute groundwaters and brines or between groundwaters with

different compositions. Natural gradients currently exist between different groundwaters in the Culebra.

Enhanced diffusion is a possible consequence of chemical gradients that occur at material boundaries. However, the distances over which enhanced diffusion could occur will be small in comparison to the size of the disposal system. Processes that may be induced by chemical gradients at material boundaries include the formation or destabilization of colloids. For example, cementitious materials that will be emplaced in the WIPP as part of the waste and the seals contain colloidal-sized materials, such as calcium-silicate-hydrate gels, and alkaline pore fluids. Chemical gradients will exist between the pore fluids in the cementitious materials and the less alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral fragment type. Colloidal compositions may include calcium and magnesium oxides, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Experimental investigations of the stability of inorganic, mineral fragment colloidal dispersions have been carried out as part of the WIPP colloid-facilitated actinide transport program (Papenguth and Behl 1996). Results of the investigations indicate that the salinities of the WIPP brines are sufficient to cause destabilization of mineral fragment colloidal dispersions. Therefore, concentrations of colloidal suspensions originating from concrete within the repository are expected to be extremely low, and are considered in PA calculations for completeness.

SCR-6.7.5.2 FEP Number: W98
FEP Title: *Osmotic Processes*

SCR-6.7.5.2.1 Screening Decision: SO-C

The effects of *Osmotic Processes* have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.7.5.2.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.5.2.3 Screening Argument

Osmotic processes, i.e., diffusion of water through a semipermeable or differentially permeable membrane in response to a concentration gradient, may occur at interfaces between waters of different salinities. Osmotic processes can occur if waters of different salinities and/or compositions exist on either side of a particular lithology such as clay, or a lithological boundary that behaves as a semipermeable membrane. At the WIPP, clay layers within the Salado may act as semipermeable membranes across which osmotic processes may occur.

In the absence of a semipermeable membrane, water will move from the more dilute water into the more saline water. However, the migration of dissolved contaminants across an interface may be restricted depending upon the nature of the membrane. A hydrological gradient across a semipermeable membrane may either enhance or oppose water movement by osmosis depending on the direction and magnitude of the gradient. Dissolved contaminants that cannot pass through

a semipermeable membrane may be moved towards the membrane and concentrated along the interface when advection dominates over osmosis and reverse osmosis occurs. Thus both osmosis and reverse osmosis can restrict the migration of dissolved contaminants and possibly lead to concentration along interfaces between different water bodies. The effects of osmotic processes have been eliminated from PA calculations on the basis of beneficial consequence to the performance of the disposal system.

SCR-6.7.5.3 FEP Number: W99
FEP Title: *Alpha Recoil*

SCR-6.7.5.3.1 Screening Decision: SO-C

The effects of *Alpha Recoil* processes on radionuclide transport have been eliminated from PA calculations on the basis of low consequence to performance of the disposal system.

SCR-6.7.5.3.2 Summary of New Information

No new information relating to this FEP has been identified.

SCR-6.7.5.3.3 Screening Argument

Alpha particles are emitted with sufficiently high energies that daughter nuclides recoil appreciably to conserve system momentum. For example, ^{238}U decays to ^{234}Th with emission of a 4.1 megaelectron volt (MeV) alpha particle. The law of conservation of momentum requires that the daughter nuclide, ^{234}Th, recoils in the opposite direction with an energy of approximately 0.07 MeV. The energy is great enough to break chemical bonds or cause ^{234}Th to move a short distance through a crystal lattice. If the ^{234}Th is close enough to the surface of the crystal, it will be ejected into the surroundings. ^{234}Th decays to ^{234}Pa which decays to ^{234}U with respective half-lives of 24.1 days and 1.17 minutes. The recoil and decay processes can lead to the apparent preferential dissolution or leaching of ^{234}U relative to ^{238}U from crystal structures and amorphous or adsorbed phases. Preferential leaching may be enhanced because of radiation damage to the host phase resulting from earlier radioactive decay events. Consequently, ^{234}U sometimes exhibits enhanced transport behavior relative to ^{238}U.

The influence of alpha recoil processes on radionuclide transport through natural geologic media is dependent on many site-specific factors, such as mineralogy, geometry, and microstructure of the rocks, as well as geometrical constraints on the type of groundwater flow, e.g., porous or fracture flow. Studies of natural radionuclide-bearing groundwater systems often fail to discern a measurable effect of alpha-recoil processes on radionuclide transport above the background uncertainty introduced by the spatial heterogeneity of the geological system. Consequently, the effects of the alpha recoil processes that occur on radionuclide transport are thought to be minor. These effects have therefore been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5.4 FEP Number: W100
FEP Title: *Enhanced Diffusion*

SCR-6.7.5.4.1 Screening Decision: SO-C

Enhanced diffusion is a possible consequence of chemical gradients that occur at material boundaries. However, the distances over which enhanced diffusion could occur will be small in comparison to the size of the disposal system. Therefore, the effects of *Enhanced Diffusion* across chemical gradients at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.

SCR-6.7.5.4.2 Summary of New Information

No new information has been identified for this FEP.

SCR-6.7.5.4.3 Screening Argument

Enhanced diffusion only occurs where there are higher than average chemical gradients. The spatial extent of chemical gradients should be quite limited and as enhanced diffusion occurs, it will tend to reduce the chemical gradient. Thus the driving force for the enhanced diffusion will be reduced and eventually eliminated as the system approaches steady state or equilibrium conditions. Because of the limited spatial extent of enhanced diffusion, its effect on radionuclide transport should be small.

Processes that may be induced by chemical gradients at material boundaries include the formation or destabilization of colloids. For example, cementitious materials, emplaced in the WIPP as part of the waste and the seals, contain colloidal-sized phases such as calcium-silicate-hydrate gels and alkaline pore fluids. Chemical gradients will exist between the pore fluids in the cementitious materials and the less-alkaline surroundings. Chemical interactions at these interfaces may lead to the generation of colloids of the inorganic, mineral-fragment type. Colloidal compositions may include calcium and MgO, calcium hydroxide, calcium-aluminum silicates, calcium-silicate-hydrate gels, and silica. Concentrations of colloidal suspensions originating from concrete within the repository are considered in PA calculations even though expected to be extremely low.

Distinct interfaces between waters of different salinities and different densities may limit mixing of the water bodies and affect flow and contaminant transport. Such effects have been eliminated from PA calculations on the basis of low consequence to the performance of the disposal system.

The effects of enhanced diffusion across chemical gradients at material boundaries have been eliminated from PAs on the basis of low consequence to the performance of the disposal system.

SCR-6.8 Ecological FEPs

SCR-6.8.1 Plant, Animal, and Soil Uptake

SCR-6.8.1.1 FEP Numbers: W101, W102, and W103
FEP Titles: *Plant Uptake* (W101)
Animal Uptake (W102)
Accumulation in Soils (W103)

SCR-6.8.1.1.1 Screening Decision: SO-R for section 191.13 – W101, W102
SO-C Beneficial for section 191.13 – W103
SO-C for section 191.15 – W101, W102, W103

Plant Uptake, *Animal Uptake*, and *Accumulation in Soils* have been eliminated from compliance assessment calculations for section 191.15 on the basis of low consequence. *Plant Uptake* and *Animal Uptake* in the accessible environment have been eliminated from PA calculations for section 191.13 on regulatory grounds. *Accumulation in Soils* within the controlled area has been eliminated from PA calculations for section 191.13 on the basis of beneficial consequences.

SCR-6.8.1.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.8.1.1.3 Screening Argument

The results of the calculations presented in Section 34, "Results of Performance Assessment," show that releases to the accessible environment under undisturbed conditions are restricted to lateral releases through the DRZ at repository depth. Thus, for evaluating compliance with the EPA's individual protection requirements in section 191.15, FEPs that relate to plant uptake, animal uptake, and accumulation in soils have been eliminated from compliance assessment calculations on the basis of low consequence.

PAs for evaluating compliance with the EPA's cumulative release requirements in section 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to plant uptake and animal uptake in the accessible environment have been eliminated from PA calculations on regulatory grounds. Accumulation in soils that may occur within the controlled area would reduce releases to the accessible environment and can, therefore, be eliminated from PA calculations on the basis of beneficial consequence.

SCR-6.8.2 Human Uptake

SCR-6.8.2.1 FEP Numbers: W104, W105, W106, W107, and W108
FEP Titles: *Ingestion* (W104)
Inhalation (W105)
Irradiation (W106)
Dermal Sorption (W107)
Injection (W108)

SCR-6.8.2.1.1 Screening Decision: SO-R
SO-C for section 191.15

Ingestion, *Inhalation*, *Irradiation*, *Dermal Sorption*, and *Injection* have been eliminated from compliance assessment calculations for section 191.15 and Part 191 Subpart C on the basis of low consequence. FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations for section 191.13 on regulatory grounds.

SCR-6.8.2.1.2 Summary of New Information

No new information has been identified for these FEPs.

SCR-6.8.2.1.3 Screening Argument

As described in Section 54, "Scope of Compliance Assessments," releases to the accessible environment under undisturbed conditions are restricted to lateral migration through anhydrite interbeds within the Salado. Because of the bounding approach taken for evaluating compliance with the EPA's individual protection requirements in section 191.15 and the groundwater protection requirements in Part 191 Subpart C (see Section 54), FEPs that relate to human uptake by ingestion, inhalation, irradiation, dermal sorption, and injection have been eliminated from compliance assessment calculations on the basis of low consequence.

PAs for evaluating compliance with the EPA's cumulative release requirements in section 191.13 need not consider radionuclide migration in the accessible environment. Therefore, FEPs that relate to human uptake in the accessible environment have been eliminated from PA calculations on regulatory grounds.

SCR-7.0 References

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Application
for the
Waste Isolation Pilot Plant

Appendix SOTERM-2009
Actinide Chemistry Source Term

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix SOTERM-2009
Actinide Chemistry Source Term

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Acronyms and Abbreviations

%	percent
α	alpha particle
a_c	activity of a chemical species
µm	micrometer, micron
ACP	LANL-CO Actinide Chemistry Project
am	amorphous
AP	Analysis Plan
aq	aqueous
ASTP	Actinide Source Term Program
atm	atmosphere
β	(apparent) stability constant, or beta particle
Bq	becquerel
BRAGFLO	Brine and Gas Flow code
CAPHUM	maximum (cap) concentration of actinide associated with mobile humic colloids
CAPMIC	maximum concentrations of actinides that could be associated with microbes
CCA	Compliance Certification Application
Ci	Curie
cm^{-1}	per centimeter
CN	coordination number
coll	colloid
conc	concentration
CONCINT	concentration of actinide associated with mobile actinide intrinsic colloids
CONCMIN	concentration of actinide associated with mobile mineral fragment colloids
CPR	cellulosic, plastic, and rubber
C_{Pu}	maximum concentration of all combined isotopes of Pu
cr	crystalline phase
CRA	Compliance Recertification Application
DBR	direct brine release
D-H	Debye-Hückel theory
DOE	U.S. Department of Energy
DRZ	disturbed rock zone

EDTA	ethylenediaminetetraacetic acid
EPA	U.S. Environmental Protection Agency
EQ3/6	software package for geochemical modeling of aqueous systems
eV	electron volt
EXAFS	Extended X-Ray Absorption Fine Structure
f_{CO_2}	fugacity of carbon dioxide
FMT	Fracture-Matrix Transport
ft	feet
γ	gamma radiation or activity coefficient
g	gaseous, or gram
g/mL	gram per milliliter
GBq	giga becquerel
GWB	Generic Weep Brine, a synthetic brine representative of fluids in Salado brine reservoirs
h	hours
I	ionic strength
K	degree Kelvin or stability constant
kg	kilogram
K_{sp}	solubility product
L	liter
LANL	Los Alamos National Laboratory
LET	Linear Energy Transfer
log	logarithm
$\log_{10}$	logarithm base 10
m	meter, molal
M	mole per liter
m^2	square meter
m^3	cubic meter
mg/L	milligram per liter
mL	milliliter
mM	millimole per liter
mol	mole
molec	molecule

MPa	megapascal
N	degree of polymerization number
N_A	Avogadro's number
NIST	National Institute of Standards and Technology
nm	nanometer
NUTS	Nuclide Transport System code
orgs	organics
OXSTAT	oxidation state parameter
PA	Performance Assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
pC_{H+} or pcH	Negative logarithm of H^+ concentration in moles per liter
pCO_2	Partial pressure of carbon dioxide
pH	negative logarithm of H^+ activity
pH_{obs}	negative logarithm of H^+ activity measured
PHUMCIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Castile brine
PHUMOXn	Proportionality constant for humic colloids and actinides in the +n oxidation state
PHUMSIM	Proportionality constant for concentration of actinides associated with mobile humic colloids, in Salado brine
pK_a	negative logarithm of the dissociation constant of an acid
pm	picometer
pmH	negative logarithm of H^+ concentration in molal
P_{O2}	partial pressure of molecular oxygen
PROPMIC	proportionality constant describing the amount of actinide element bound to mobile microbes
RH	relative humidity
s	solid or second
SECOTP2D	computer program that simulates single or multiple component radionuclide transport in fractures or granular aquifers
SEM	scanning electron microscope
SNL	Sandia National Laboratories
SOTERM	WIPP Actinide Source Term
SPC	Salado Primary Constituents

$t_{½}$	half-life
TDS	total dissolved solid
TRU	transuranic
TWBIR	Transuranic Waste Baseline Inventory Report
V	volt, or vanadium
w	with
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System
XANES	X-Ray Absorption Near Edge Structure
XRD	X-Ray Diffraction
yr	year

Elements and Chemical Compounds

Am	Americium
Am(III)	Americium in the +3 oxidation state
Am(IV)	Americium in the +4 oxidation state
Am(V)	Americium in the +5 oxidation state
Am(VI)	Americium in the +6 oxidation state
Am^{2+}	Americium cation - Aqueous form of the americium in the +2 oxidation state that only exists as a transient
Am^{3+}	Americium cation - Aqueous form of the americium in the +3 oxidation state
Am^{4+}	Americium cation - Aqueous form of the americium in the +4 oxidation state
$Am(CO_3)_n^{(3-2n)}$	Americium (III) carbonate complex with n=1, 2, or 3
$AmCO_3OH$	Americium (III) carbonato hydroxide
AmO_2^+	Americium oxo-cation – Aqueous form of the americium in the +5 oxidation state
AmO_2^{2+}	Americium oxo-cation – Aqueous form of the americium in the +6 oxidation state
AmO_2OH	Americium (V) oxide hydroxide
$AmOH^{2+}$	Americium (III) hydroxide cation – (1:1) complex
$Am(OH)_2^+$	Americium (III) hydroxide cation – (1:2) complex
$Am(OH)_3$	Americium hydroxide
$AmPO_4$	Americium (III) phosphate
$Am(SO_4)_n^{(3-2n)}$	Americium (III) sulfate complex with n = 1 or 2
$[An]_p$	Concentration of an adsorbed actinide element (mol/particle)
An	Actinide
An(III)	General actinide in the +3 oxidation state
An(IV)	General actinide in the +4 oxidation state
An(V)	General actinide in the +5 oxidation state
An(VI)	General actinide in the +6 oxidation state
An^{3+}	Aqueous form of the actinide in the +3 oxidation state
An^{4+}	Aqueous form of the actinide in the +4 oxidation state
An^{n+}	Aqueous form of the actinide in the +n oxidation state
$An_2(CO_3)_3$	Actinide (III) carbonate – (2:3) complex

$An_2(CO_3)_2^{2+}$	Actinide (III) carbonate iaon – (2:2) complex
$AnB_4O_7^{+}$	Actinide (III) tetraborate ion – (1:1) complex
$AnCl^{2+}$	Actinide (III) chloride ion – (1:1) complex
$An(CO_3)^{+}$	Actinide (III) carbonate ion – (1:1) complex
$An(CO_3)_2^{-}$	Actinide (III) carbonate ion – (1:2) complex
$An(CO_3)_3^{3-}$	Actinide (III) carbonate ion – (1:3) complex
$AnCO_3OH$	Actinide (III) carbonate hydroxide
$AnL^{(n+m)}$	Complex of an actinide with a charge n and an organic ligand L with a charge m
$An(V)O_2^{+}$ or AnO_2^{+}	Aqueous form of the actinide in the +5 oxidation state
$An(VI)O_2^{2+}$ or AnO_2^{2+}	Aqueous form of the actinide in the +6 oxidation state
$AnOH^{2+}$	Actinide (III) hydroxide cation – (1:1) complex
$An(OH)_3$	Hydroxide of the actinide (III)
$AnPO_4$	Actinide (III) phosphate
$AnSO_4^{+}$	Actinide (III) sulfate ion – (1:1) complex
$B_3O_3(OH)_4^{-}$	Hydroxy polynuclear form of boric acid
$B_4O_7^{2-}$	Tetraborate anion
$B(OH)_x^{3-x}$	Hydroxyborate ions
Ba^{2+}	Barium cation
Br^{-}	Bromide anion
[C]	Concentration of species *C* in solution
$[C_\theta]$	Concentration of a chosen standard state
C	Carbon or concentration
$C_6H_{10}O_5$	Cellulose
CH_4	Methane
$CH_3CO_2^{-}$	Acetate anion
$(CH_2CO_2)_2C(OH)(CO_2)^{3-}$	Citrate anion
$(CH_2CO_2)_2N(CH_2)_2N(CH_2CO_2)_2^{4-}$	Ethylenediaminetetraacetate (EDTA) anion
$C_2O_4^{2-}$	Oxalate anion
Ca^{2+}	Calcium cation
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
$CaMg(CO_3)_2$	Dolomite, calcium magnesium carbonate

CaO	Calcium oxide
$Ca_4[Pu(OH)_8]^{4+}$	Calcium plutonium (IV) hydroxide cation complex
$CaSO_4$	Anhydrite, calcium sulfate
$CaSO_4 \cdot 2H_2O$	Gypsum, hydrated calcium sulfate
$Ca_4[Th(OH)_8]^{4+}$	Calcium thorium (IV) hydroxide cation complex
CeO_2	Cerium dioxide
Cl	Chlorine
Cl^-	Chloride ion
Cl_2	Chlorine
Cl_2^-	Chlorine free radical
Cl_3^-	Chlorine anion
$ClBr^-$	Chloride bromide radical
ClO^-	Hypochlorite anion
ClO_2^-	Chlorite anion
ClO_3^-	Chlorate anion
ClO_4^-	Perchlorate anion
Cm	Curium
Cm(III)	Curium in the +3 oxidation state
Cm(IV)	Curium in the +4 oxidation state
Cm^{3+}	Curium cation – Aqueous form of the curium at the +3 oxidation state
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate anion
Cr	Chromium
Cs	Cesium
Cu	Copper
F^-	Fluoride
Fe	Iron
Fe(0)	Zero-valent iron
$FeCl_4^{2-}$	Iron (II) tetrachloride anion
$FeCO_3$	Iron (II) carbonate, ferrous carbonate
Fe_3O_4	Magnetite, iron (II,III) oxide
Fe^{2+}	Aqueous form of the iron in the +2 oxidation state, ferrous anion

Fe^{3+}	Aqueous form of the iron in the +3 oxidation state, ferric anion
Fe(II)	Iron in the +2 oxidation state
Fe(III)	Iron in the +3 oxidation state
$Fe(OH)_3$	Ferric hydroxide
$Fe(OH)_2 \cdot (x-2)H_2O$	Hydrated ferrous hydroxide
FeOOH	Goethite, iron oxide hydroxide
FeS	Iron (II) sulfide
H	Hydrogen
H^+	Hydrogen cation
H_2	Hydrogen
HA	Humic acid
HAal-LBr	Aliphatic humic acid isolated from sediments collected from Lake Bradford, Florida, prepared by Florida State University
HAar-Gor	Aromatic humic acid isolated from groundwaters near Gorleben, Germany, obtained from Professor J.-I. Kim, Institut für Radiochemie, München
$HClO_4$	Perchloric acid
hmag.	Hydromagnesite
HPO_4^{2-}	Hydrogenphosphate anion
HCO_3^-	Bicarbonate anion, hydrogen carbonate anion
H_2O	Water
H_2O_2	Hydrogen peroxide
HOBr	Hypobromous acid
HOCl	Hypochlorous acid
$H_2PO_4^-$	Dihydrogen phosphate anion
H_2S	Hydrogen sulfide
K	Potassium
K^+	Potassium cation
$K_2MgCa_2(SO_4)_4 \cdot 2H_2O$	Polyhalite
$KNpO_2CO_3 \cdot 2H_2O$	Hydrated potassium neptunium (V) carbonate – (1:1:1) complex
$K_3NpO_2(CO_3)_2 \cdot 0.5H_2O$	Hydrated potassium neptunium (V) carbonate – (3:1:2) complex
K_2SO_4	Potassium sulfate
$K_2U_2O_7$	Potassium diuranate

mag.	Magnesite
Mg	Magnesium
Mg^{2+}	Magnesium cation
$MgCl_2$	Magnesium chloride
$Mg_3(OH)_5Cl{\cdot}4H_2O$	Magnesium chloride hydroxide hydrate
$MgCO_3$	Magnesite, magnesium carbonate
$Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$	Hydromagnesite
$Mg_2(OH)_3Cl{\cdot}4H_2O$	Magnesium chloride hydroxide hydrate, magnesium oxychloride
MgO	Periclase, magnesium oxide
$Mg(OH)_2$	Brucite, magnesium hydroxide
Mn	Manganese
N_2	Nitrogen
Na	Sodium
Na^+	Sodium cation
Na_2SO_4	Sodium sulfate
$Na_2S_2O_4$	Sodium hydrosulfite
$NaAm(CO_3)_2$	Sodium americium (III) carbonate
NaCl	Halite, sodium chloride
$NaNpO_2CO_3{\cdot}3.5H_2O$	Hydrated sodium neptunium (V) carbonate – (1:1:1) complex
$Na_3NpO_2(CO_3)_2$	Sodium neptunium (V) carbonate – (3:1:2) complex
NaOH	Sodium hydroxide
$NaUO_2O(OH)\ H_2O$	Clarkeite, sodium uranate
$Na_2U_2O_7{\cdot}xH_2O$	Sodium diuranate hydrate
Nd	Neodymium
Nd(III)	Neodymium in the +3 oxidation state
$Nd(OH)_3$	Neodymium (III) hydroxide
Ni	Nickel
Ni^{2+}	Nickel (II) cation
Np	Neptunium
Np(IV)	Neptunium in the +4 oxidation state
Np(V)	Neptunium in the +5 oxidation state
Np(VI)	Neptunium in the +6 oxidation state

Np^{4+}	Neptunium cation – Aqueous form of the neptunium at the +4 oxidation state
NpO_2^+ or $Np(V)O_2^+$	Neptunyl cation – Aqueous form of the neptunium at the +5 oxidation state
NpO_2^{2+} or $Np(VI)O_2^{2+}$	Neptunyl cation – Aqueous form of the neptunium at the +6 oxidation state
$NpO_2CO_3^-$	Neptunium (V) carbonate ion – (1:1) complex
$NpO_2(CO_3)_2^{3-}$	Neptunium (V) carbonate ion – (1:2) complex
$NpO_2(CO_3)_3^{5-}$	Neptunium (V) carbonate ion – (1:3) complex
NpO_2OH	Neptunium (V) hydroxide
$NpO_2(OH)_2^-$	Neptunium (V) hydroxide ion – (1:2) complex
NO_3^-	Nitrate anion
N_S	Adsorption site density (sites/nm^2)
O	Oxygen
O_2	Molecular oxygen
OBr^-	Hypobromite anion
OCl^-	Hypochlorite anion
OH^-	Hydroxide anion
$OH\cdot$	Hydroxyl radical
Pb	Lead
Pb(0)	Zero-valent lead
Pb(II)	Lead in the +2 oxidation state
Pb^{2+}	Lead cation – Aqueous form of the lead at the +2 oxidation state
Pb^{4+}	Lead cation – Aqueous form of the lead at the +4 oxidation state
$PbCl_2$	Lead (II) chloride
$PbCO_3$	Lead (II) carbonate
$[Pb_6O(OH)_6]^{4+}$	Lead (II) polyoxyhydroxide cation
PbO	Lead (II) oxide
PO_4^{3-}	Phosphate anion
$(PbOH)_2CO_3$	Lead (II) hydroxide carbonate
PbS	Lead (II) sulfide
$PbSO_4$	Lead (II) sulfate
Pu	Plutonium

Pu(III)	Plutonium in the +3 oxidation state
Pu(IV)	Plutonium in the +4 oxidation state
Pu(V)	Plutonium in the +5 oxidation state
Pu(VI)	Plutonium in the +6 oxidation state
Pu(VII)	Plutonium in the +7 oxidation state
Pu^{3+}	Plutonium cation – Aqueous form of the plutonium at the +3 oxidation state
Pu^{4+}	Plutonium cation – Aqueous form of the plutonium at the +4 oxidation state
$Pu(CO_3)^{+}$	Plutonium (III) carbonate ion – (1:1) complex
$Pu(CO_3)_2^{-}$	Plutonium (III) carbonate ion – (1:2) complex
$Pu(CO_3)_3^{3-}$	Plutonium (III) carbonate ion – (1:3) complex
PuF_2^{2+}	Plutonium (IV) fluoride cation
PuO_2	Plutonium (IV) dioxide
PuO_{2+x}	Oxidized plutonium (IV) dioxide
PuO_2CO_3	Plutonium (VI) carbonate
$PuO_2CO_3^{-}$	Plutonium (V) carbonate ion – (1:1) complex
$PuO_2(CO_3)_2^{3-}$	Plutonium (V) carbonate ion – (1:2) complex
$PuO_2(CO_3)_2^{2-}$	Plutonium (VI) carbonate ion – (1:2) complex
$PuO_2(CO_3)_3^{4-}$	Plutonium (VI) carbonate ion – (1:3) complex
PuO_2F^{+}	Plutonium (VI) oxofluoride cation
PuO_2^{+} or $Pu(V)O_2^{+}$	Plutonyl cation – Aqueous form of the plutonium at the +5 oxidation state
PuO_2^{2+} or $Pu(VI)O_2^{2+}$	Plutonyl cation – Aqueous form of the plutonium at the +6 oxidation state
$PuO_3 \cdot xH_2O$	Plutonium (VI) trioxide-hydrate
$PuOH^{3+}$	Plutonium (IV) hydroxide cation – (1:1) complex
$Pu(OH)_2^{2+}$	Plutonium (IV) hydroxide cation – (1:2) complex
$Pu(OH)_3^{+}$	Plutonium (IV) hydroxide cation – (1:3) complex
$Pu(OH)_4$	Plutonium (IV) hydroxide
$[Pu(H_2O)_m]^{n+}$	Hydrolysis complex of plutonium
$[Pu(O)Pu(O)Pu(O)...]_n$	Plutonium polymer
Ra	Radium
S^{2-}	Sulfide anion

SO_4^{2-}	Sulfate anion
Sr	Strontium
Tc(IV)	Technetium in the +4 oxidation state
Th	Thorium
Th(IV)	Thorium in the +4 oxidation state
Th^{3+}	Thorium cation – Aqueous form of the thorium at the +3 oxidation state
Th^{4+}	Thorium cation – Aqueous form of the thorium at the +4 oxidation state
$Th(CO_3)_5^{6-}$	Thorium (IV) pentacarbonyl ion complex
ThO_2	Thorium dioxide
$Th(OH)_4$	Thorium hydroxide
$Th(OH)(CO_3)_4^{5-}$	Thorium (IV) hydroxide carbonate ion – (1:1:4) complex
$Th(OH)_2(CO_3)_2^{2-}$	Thorium (IV) hydroxide carbonate ion – (1:2:2) complex
$Th(OH)_3CO_3^-$	Thorium (IV) hydroxide carbonate ion – (1:3:1) complex
$Th(OH)_2SO_4$	Thorium (IV) hydroxide sulfate ion – (1:2:1) complex
$Th(SO_4)_3^{2-}$	Thorium (IV) sulfate ion – (1:3) complex
$Th(SO_4)_2$	Thorium (IV) sulfate
U	Uranium
U(III)	Uranium in the +3 oxidation state
U(IV)	Uranium in the +4 oxidation state
U(V)	Uranium in the +5 oxidation state
U(VI)	Uranium in the +6 oxidation state
U^{3+}	Uranium cation – Aqueous form of the uranium at the +3 oxidation state
U^{4+}	Uranium cation – Aqueous form of the uranium at the +4 oxidation state
U_3O_7	Triuranium heptaoxide
U_4O_9	Tetrauranium nonaoxide
UO_2	Uraninite, uranium (IV) dioxide
UO_2^{2+} or $U(VI)O_2^{2+}$	Uranyl cation – Aqueous form of the uranium at the +6 oxidation state
UO_2CO_3	Rutherfordine, uranium (VI) carbonate
$UO_2(CO_3)_2^{2-}$	Uranium (VI) carbonate ion – (1:2) complex
$UO_2(CO_3)_3^{4-}$	Uranium (VI) carbonate ion – (1:3) complex or triscarbonato complex
$(UO_2)_3(CO_3)_6^{6-}$	Uranium (VI) carbonate ion – (3:6) complex
$(UO_2)_2(CO_3)(OH)_3^-$	Uranium (VI) carbonate hydroxide ion – (2:1:3) complex
$(UO_2)_{11}(CO_3)_6(OH)_{12}^{2-}$	Uranium (VI) carbonate hydroxide ion – (11:6:12) complex

UO_2OH^+	Uranium (VI) hydroxide ion – (1:1) complex
$(UO_2)_3(OH)_5^+$	Uranium (VI) hydroxide ion – (3:5) complex
$UO_2(OH)_3^-$	Uranium (VI) hydroxide ion – (1:3) complex
$UO_2(OH)_4^{2-}$	Uranium (VI) hydroxide ion – (1:4) complex
$U(OH)_3^+$	Uranium (IV) hydroxide ion – (1:3) complex
$U(OH)_4$	Uranium (IV) hydroxide
$UO_2.xH_2O$	Hydrous uranium (IV) dioxide
$(UO_2)(OH)_2 \cdot xH_2O$ or $UO_3 \cdot xH_2O$	Schoepite, hydrated uranium trioxide
V	Vanadium
ZrO_2	Zirconium dioxide

SOTERM-1.0 Introduction

Appendix SOTERM-2009 (Actinide Chemistry Source Term) is a summary of the U. S. Department of Energy's (DOE's) understanding of the Waste Isolation Pilot Plant (WIPP) chemical conditions, assumptions, and processes; the underlying actinide chemistry; and the resulting dissolved actinide concentrations that were calculated based on this repository chemistry. This appendix supplements Appendix PA-2009 in the 2009 Compliance Recertification Application (CRA-2009). The calculational results summarized here are based on the 2004 Performance Assessment (PA) Baseline Calculations (PABC) (Leigh et al. 2005), and hence on the various assumptions about chemical conditions in the repository that were included in the formulation of that baseline. WIPP-related geochemical experimental results obtained within and outside of the WIPP project since these calculations were performed are also summarized.

Actinide release from the WIPP is a critical performance measure for the WIPP as a transuranic (TRU) repository. There are a number of potential pathways for actinide release considered by the WIPP PA, and these are discussed in detail in Appendix PA-2009. Quantifying the impact of these releases contributes directly to assessing compliance with 40 CFR Part 191 (U.S. Environmental Protection Agency 1993).

In the undisturbed scenario for PA, actinide releases up the shafts or laterally through the marker beds are physically insignificant in all realizations and have no impact on compliance (Appendix PA-2009, Section PA-7.2). The self-sealing of the salt and the reducing anoxic environment in the repository provide the primary mechanisms for geologic isolation of the TRU waste in the undisturbed scenario. For the disturbed scenarios, actinide releases can occur primarily as a result of inadvertent human intrusions (i.e., boreholes drilled into or through the repository). For example, direct brine release (DBR) to the accessible environment may occur during a drilling intrusion, or actinides may be transported up a borehole to the Culebra Formation and then move laterally through the Culebra to the land withdrawal boundary (LWB). The potential for human intrusions makes it important to assess the range of possible repository conditions and associated dissolved actinide concentrations associated with the disturbed scenarios.

This appendix focuses on the actinide source term used to calculate actinide release from the WIPP for the DBR release and transport through the Salado and Culebra Formations. This actinide source term is the sum of the soluble and colloidal species in brine. Direct release of actinide particulates to the surface resulting from cuttings, cavings, and spallings is not considered part of the actinide source term because these particulate releases do not depend on the mobilized actinide concentrations in brine.

The relative importance of radioelements that significantly contribute to the actinide source term, and consequently impact the long-term performance of the WIPP, as established in the 2004 Compliance Recertification Application (CRA-2004) (U.S. Department of Energy 2004), Appendix SOTERM, and the CRA-2004 PABC is:

$$\text{Pu} \approx \text{Am} \gg \text{U} > \text{Th} \gg \text{Np, Cm, and fission products.} \qquad \text{(SOTERM.1)}$$

The TRU components for this list of radionuclides are the α-emitting isotopes of plutonium (Pu), americium (Am), neptunium (Np), and curium (Cm) with half-lives greater than 20 years. These TRU actinides make up the waste unit factor used to calculate the normalized release from the WIPP in U.S. Environmental Protection Agency (EPA) units, as required by Part 191. In SOTERM, the chemistry of thorium (Th) and uranium (U) is also discussed, since these actinides are present in the WIPP waste and their chemistry is analogous to the TRU components.

This appendix has the following overall organization:

- An overview of key near-field conditions and biogeochemical processes is presented in Section SOTERM-2.0.
- An updated literature review and summary of WIPP-relevant results for the key actinides is given in Section SOTERM-3.0.
- A summary of the WIPP actinide PA approach and assumptions, along with the calculated actinide solution concentrations, are provided in Section SOTERM-4.0.
- The PA implementation of the dissolved and colloidal components of the source term is described in Section SOTERM-5.0.

Each of these sections identifies important changes and/or new information since the CRA-2004 and the CRA-2004 PABC (Leigh et al. 2005).

SOTERM-2.0 Expected WIPP Repository Conditions, Chemistry, and Processes

The preemplacement and postemplacement near-field processes and conditions that could affect actinide concentrations in the WIPP are discussed in this section. An up-front summary of the current WIPP chemistry model assumptions is given in Table SOTERM-1, with a more detailed discussion of each assumption presented in the following sections. Emphasis is placed on how these processes and conditions in the repository could affect the concentrations of dissolved and colloidal actinide species in brine.

SOTERM-2.1 Ambient Geochemical Conditions

The ambient geochemical conditions are discussed in detail in the CRA-2004, Chapter 6.0. The Salado, which is the repository horizon, is predominantly pure halite (NaCl), with interbeds (marker beds) consisting mainly of anhydrite ($CaSO_4$). The nearly pure halite contains accessory evaporite minerals such as anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$), polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$), magnesite ($MgCO_3$), and clays. Small quantities of intergranular (grain-boundary) brines and intragranular brines (fluid inclusions) are associated with the salt at the repository horizon. These brines are highly concentrated solutions (ionic strength up to 8 moles per liter [M]) of predominantly sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), chloride (Cl^-), and sulfate (SO_4^{2-}), with smaller amounts of calcium (Ca^{2+}), carbonate (CO_3^{2-}), and borate ($B(OH)_4^-$ and/or $B_4O_7^{2-}$). These brines have been in contact with the Salado evaporite minerals since their deposition (estimated to be 250 million years) and are saturated with respect to these minerals.

Underlying the Salado Formation is the Castile, composed of alternating units of interlaminated carbonate, anhydrite, and nearly pure halite. The Castile in the vicinity of the WIPP site is known to contain localized brine reservoirs with sufficient pressure to force brine to the surface if penetrated by a borehole. Castile brines are predominantly saturated NaCl solutions containing Ca^{2+} and SO_4^{2-}, as well as small concentrations of other elements, and are about eight times more concentrated than seawater. Overlying the Salado in the vicinity of the WIPP site is the Culebra of the Rustler Formation, a fractured dolomite ($CaMg(CO_3)_2$) layer. It is significant because it is expected to be the most transmissive geologic pathway to the accessible environment. Culebra brines are generally more dilute than the Salado and Castile brines, and are predominantly NaCl with K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, and CO_3^{2-}. More detailed information on the distribution of Culebra brine salinity in the WIPP site and vicinity can be found in Appendix HYDRO-2009.

SOTERM-2.2 Repository Conditions

Repository conditions that could potentially affect actinide solubility are briefly summarized in this section. These include: repository pressure, repository temperature, water content and relative humidity, the minimum free volume for actinide release (effective porosity), and the extent of the disturbed rock zone (DRZ).

Table SOTERM-1. Summary of Current WIPP Chemistry Model Assumptions (Leigh et al. 2005)

Repository Condition or Parameter	CRA-2004/CRA-2004 PABC Assumptions	SOTERM-2009 Section Containing References
Ambient Geochemistry	Predominantly halite of the Salado Formation, with anhydrite interbeds and inclusions.	SOTERM-2.1
Temperature	Ambient temperature is 28 °C (82 °F). An increase of up to 3 °C (5.4 °F) is possible as a result of the emplacement of TRU waste.	SOTERM-2.2.2
Humidity	~70 percent (%) relative humidity (RH) at the repository temperature.	SOTERM-2.2.3
Water Content	Host rock is groundwater-saturated with inclusions in the salt that range from 0.057% to 3% by mass. Repository is unsaturated for up to 1000 years (yr) depending on pressure and intrusion scenarios.	SOTERM-2.2.3
Pressure	A lithostatic pressure of about 15 megapascals (MPa) (148 atmospheres [atm]) at repository depth; a hydrostatic pressure of about 8 MPa (79.0 atm) at the bottom of an intrusion borehole at repository depth.	SOTERM-2.2.1
Gas Phase	Initially air/oxic at repository closure, but rapidly transitions to an anoxic atmosphere dominated by hydrogen with smaller amounts of methane and nitrogen. Trace amounts of carbon dioxide, hydrogen sulfide, and other microbially produced gases may be present.	SOTERM-2.2.3 SOTERM-2.4.1
DRZ	Upper bound of 12 meter (m) above the repository and 2 m below the repository horizon.	SOTERM-2.2.5
Minimum Brine Volume for DBR	The calculated minimum volume of brine from any source needed for DBR release is 10011 cubic meters (m^3).	SOTERM-2.2.4
WIPP Brine	High-ionic-strength brine bracketed by Generic Weep Brine (GWB) and ERDA-6 brine formulations	SOTERM-2.3.1
pH	pH of about 9 and controlled by MgO, borate, and carbonate.	SOTERM-2.3.2
MgO	Engineered barrier for the WIPP that will sequester carbon dioxide (CO_2) and control increases and decreases in pH by the precipitation of brucite, hydromagnesite, and magnesite.	SOTERM-2.3.3
Microbial Effects	Gas generation, primarily carbon dioxide and hydrogen sulfide, resulting from the biodegradation of cellulosic, plastic, and rubber (CPR) materials and creation of reducing conditions, including bioreduction of actinide elements from higher oxidation states.	SOTERM-2.4.1
Corrosion	Container steel and metals in WIPP waste will react to remove oxygen and produce hydrogen.	SOTERM-2.3.4
Radiolysis	Localized oxidizing effects possible near high-activity actinides, but overall radiolytic processes are overwhelmed by the in-room chemistry.	SOTERM-2.4.2

SOTERM-2.2.1 Repository Pressure

The preexcavation lithostatic pressure (Stein 2005, CRA-2004 PABC, Section 4.1.1) in the WIPP at repository depth is about 15 MPa (148 atm). This pressure can be reestablished after repository closure due to salt creep and gas generation, but there are a number of PA vectors that predict pressure may not be fully restored even by the end of the 10,000-yr period of WIPP performance, and final pressures may range from 6 to 15 MPa (in the undisturbed scenario) and from 0.1 to 15 MPa (in the disturbed scenarios) considered in the CRA-2004 PABC. In this context, the pressure in the repository after closure cannot significantly exceed the far-field confining stress of about 15 MPa.

DBR can occur when the pressure in the repository at the time of a drilling intrusion exceeds 8 MPa and a sufficient amount of brine has already flowed into the repository (see related discussions in Section SOTERM-2.2.4 and Stein 2005). Eight MPa is the pressure exerted by a column of brine-saturated drilling fluid at the depth of the repository (Stoelzel and OBrien 1996). For repository pressures less than 8 MPa, no DBRs are assumed to occur because the fluid pressure in the repository cannot eject the drilling fluid from the borehole. There is also no DBR release until the brine volume exceeds the minimum brine volume (see Section SOTERM-2.2.4) needed to fill the effective porosity present in the compacted TRU waste.

When discussing the possible range of brine pressure to the source term, it is important to assess the possibility that the pressures experienced in the WIPP could impact actinide solubilities. In this context, the maximum pressure possible (~15 MPa) is well below pressures needed to affect the solution chemistry, and is not expected to have a significant effect on actinide solubilities or processes that lead to the association of actinides with colloidal particles. For these reasons, the effect of pressure on actinide solubility is not considered in the WIPP PA.

SOTERM-2.2.2 Repository Temperature

The ambient preemplacement temperature at the WIPP repository horizon was established to be 28 ºC (82 ºF) (Munson et al., 1987). The emplacement of TRU waste in the WIPP is expected to increase the ambient temperature by only a few degrees Celsius at most (Sanchez and Trellue 1996, Wang and Brush 1996a). For the purposes of PA, the temperature of the WIPP underground repository is assumed to be constant with time at 300 Kelvin (K) (27 ºC [80 ºF]) (Appendix PA-2009).

Actinide solubilities were calculated in WIPP PA using thermodynamic and laboratory data measured at 25 ºC [77 ºF]. The expected effect of the slightly elevated temperature in the WIPP on actinide concentrations is relatively small, especially when compared to other uncertainties inherent in the measurement and calculation of the actinide solubilities and colloidal concentrations. For this reason, the very small effect of temperature on actinide solubility was not considered in WIPP PA calculations.

SOTERM-2.2.3 Water Content and Relative Humidity

A key argument for the WIPP as a TRU waste repository is that the self-sealing of the salt will limit the availability and transport of water into and through the repository, and correspondingly

minimize the potential release of TRU from the repository. In all the undisturbed repository scenarios considered by PA, no actinide release from the WIPP is predicted (Leigh et al. 2005). There is, however, groundwater in the WIPP, even in undisturbed scenarios, that is potentially available to interact with the TRU waste. The salt surrounding waste is groundwater-saturated with both intergranular and intragranular water. The amount of water present as inclusions in the salt was used as a random variable in PA calculations (Leigh et al. 2005) with a range of 0.057 to 3 mass % based on what was measured in preexcavation salt (Skokan et al. 1987 and Powers et al. 1978). This brine can seep into the repository horizon and fill the excavated areas (TRU waste). Brine saturation of the repository is estimated to occur in less than 1000 years after repository closure.

The presence of some brine in the WIPP prior to brine saturation leads to an environment that will contain an atmosphere of up to about 70% RH, defined by the vapor pressure of saturated brine at the repository temperature. This water vapor pressure will be present, at least in part, until brine saturation occurs as a result of some human intrusions or brine seepage into the excavated area.

The presence of a humid environment in the WIPP prior to brine saturation may have a transitory effect on actinide solubilities. These transitory/temporary phases are not considered in WIPP PA because they will be rapidly overwhelmed by the in-room chemistry and higher reactivity of the waste components should brine inundation or saturation occur.

SOTERM-2.2.4 Minimum Repository Brine Volume

The minimum brine volume is the volume of brine needed for a DBR to occur during an intrusion scenario. There have been two calculational efforts to estimate this volume in the compacted TRU waste for the WIPP. Prior to the 1996 Compliance Certification Application (CCA) (U.S. Department of Energy 1996), Larson (1996) estimated this volume, calculated at 2000 years after repository closure with an assumption of no gas generation, to be 343 m^3 per room and a minimum brine saturation of 0.75 for 116 equivalent rooms. This led to a repository-scale volume of 29,841 m^3. Under these assumptions, this was the minimum brine volume needed for DBR.

Since this initial calculation, new information has led to a reassessment of this minimum volume (Stein 2005). The most important changes in this new calculation were: (1) it was based on the structural results used in the most current PA, (2) the time of the calculation was extended from 2000 to 10,000 years after repository closure, (3) a corrected waste-filled repository volume was used, and (4) the calculation was made to be more in line with the DBR conceptual model that requires a hydrostatic pressure of about 8 MPa. These changes led to a calculated per-room volume of 301.5 m^3, a reduction in the minimum brine saturation value to 0.276, and 120.3 equivalent rooms. This led to an overall repository-scale volume of 10,011 m^3.

The minimum repository brine volume has two important potential impacts on calculating actinide concentrations in the WIPP. The first is that the predicted inventory of some actinides, when fully dissolved in this brine volume, lead to concentrations that are below their predicted solubility, most importantly Np and Cm. In this context, they are assumed to be fully dissolved in the brine and may have an insignificant impact on the calculated actinide release in WIPP PA

based on inventory arguments alone. The second impact is on the predicted concentration of key organic and inorganic complexants that coexist with the TRU species in WIPP waste. The maximum concentrations of acetate, citrate, and ethylenediaminetetraacetic acid (EDTA) (see Section SOTERM-2.3.6) are defined by their fully dissolved concentration in the minimum brine volume.

SOTERM-2.2.5 DRZ

More detailed discussions of the DRZ can be found in Appendix PA-2009. The DRZ is a zone immediately surrounding the excavated repository that has been altered by the construction of the repository. In the Brine and Gas Flow (BRAGFLO) code, the Upper DRZ has a height of about 12 m (39 feet [ft]) and the Lower DRZ has a depth of about 2.2 m (7.2 ft) (Leigh et al. 2005, Figure 4-1). The creation of this DRZ disturbs the anhydrite layers and marker beds and alters the permeability and effective porosity of the rock around the excavated areas, providing enhanced pathways for the flow of gas and brine between the waste-filled rooms and the nearby interbeds.

The DRZ is important to the calculation of dissolved actinide concentrations because it potentially makes the minerals in the interbeds "available" for reaction with the TRU and emplaced waste components. The most important of these minerals is the calcium sulfate (anhydrite) that could function as a source of sulfate for processes in the repository subsequent to brine inundation. Currently, sulfate is assumed to be available from the DRZ into the waste area, which prolongs microbial sulfate reduction processes in the WIPP.

SOTERM-2.3 Repository Chemistry

Brine present in the WIPP will react with emplaced TRU waste, waste components, and engineered barrier materials to establish the brine chemistry that will define actinide solubilities and colloid formation. In this context, the composition of the brine in the repository horizon will be defined by a combination of factors, including the initial composition of the in-flow brine; reactions that control pH; and the extent to which this brine is altered by equilibration with the waste components, emplaced container materials, and the waste-derived organic chelating agents that can dissolve in the brine. An overview of this repository chemistry is given in this section.

SOTERM-2.3.1 WIPP Brine

The composition of brine in and around the WIPP site prior to waste emplacement was established by sampling the groundwater and intergranular inclusions in the Salado and Castile (Popielak et al. 1983, Snider 2003a). Synthetic brines that simulate these compositions were developed and have been used for WIPP laboratory studies. The two simulated brines that best represent these repository-relevant, end-member brines are: (1) GWB, which simulates intergranular (grain-boundary) brines from the Salado at or near the stratigraphic horizon of the repository (Snider 2003a); and (2) ERDA-6, which simulates brine from the ERDA-6 well, typical of fluids in Castile brine reservoirs (Popielak et al. 1983). The concentrations of key inorganic species in these two brines, along with some brine properties, are listed in Table SOTERM-2.

Table SOTERM-2. Compositions of GWB and ERDA-6 Prior To and After Equilibration with MgO (Brush et al. 2006)

Ion or Property[a]	GWB[b] Before Reaction with MgO, Halite, and Anhydrite	GWB After Reaction with MgO, Halite, and Anhydrite[c]	ERDA-6[d] Before Reaction with MgO, Halite, and Anhydrite	ERDA-6 After Reaction with MgO, Halite, and Anhydrite[c]
$B(OH)_x^{3-x}$ (see Footnote e)	158 mM	166 mM	63 mM	62.4 mM
Na^+	3.53 M	4.35 M	4.87 M	5.24 M
Mg^{2+}	1.02 M	0.578 M	19 mM	157 mM
K^+	0.467 M	0.490 M	97 mM	96.1 mM
Ca^{2+}	14 mM	8.95 mM	12 mM	10.7 mM
SO_4^{2-}	177 mM	228 mM	170 mM	179 mM
Cl^-	5.86 M	5.38 M	4.8 M	5.24 M
Br^-	26.6 mM	27.8 mM	11 mM	10.9 mM
Total Inorganic C (as HCO_3^-)	Not reported	0.35 mM	16 mM	0.428 mM
pH	Not reported	8.69	6.17	8.94
Relative Density	1.2	1.23	1.22	1.22
Ionic Strength (m)	7.56	7.66	6.05	6.80

[a] Ions listed represent the total of all species with this ion.

[b] From Snider (2003a)

[c] From Brush et al. (2006)

[d] From Popielak et al. (1983)

[e] Boron species will be present in brine as boric acid, hydroxy polynuclear forms ($B_3O_3(OH)_4^-$, and/or borate forms (e.g., $B_4O_7^{2-}$)

At the time of the CCA, Brine A (Molecke 1983) and Salado Primary Constituents (SPC) Brine, a version of Brine A from which trace elements had been removed, were used to simulate Salado brines for laboratory and modeling studies. Since the CCA, however, GWB has been shown to be more representative of intergranular Salado brines than either Brine A or SPC Brine (Brush and Xiong 2003a, Snider 2003a). This brine formulation is currently used to represent Salado brines in PA. In particular, the magnesium concentration of GWB (1.0 M) simulates the average concentration of this element in Salado brines more closely than Brine A (1.44 M).

The reaction with MgO, based on the modeling calculations performed, leads to some potentially significant changes in the composition of the brine (see Table SOTERM-2). The most important of these changes for GWB brine is the lowering of the magnesium concentration from 1.02 to 0.578 M, a decrease in calcium concentration from 14 to 8.95 mM, and a pH of 8.69. For ERDA-6, there is a significant increase in the magnesium concentration from 19 to 157 mM, a decrease in total inorganic carbon from 16 to 0.428 mM, and an increase of the pH to 8.94 from 6.17. The pH associated with these MgO-reacted brines established the range of expected pH values in the WIPP for the calculation of actinide solubilities, and the composition of these reacted brines were used in PA to calculate actinide solubility in brine (Brush 2005).

Salado brine will enter the repository after closure, and can be supplemented by Castile brine in some human intrusion scenarios. It is also possible that groundwater from the Rustler and Dewey Lake Formation could flow down the borehole into the repository, mix with the waste, and then be forced back up a borehole. The majority of WIPP-specific solubility studies since the CRA-2004 were performed using GWB or ERDA-6 brines, since these brines bracket the expected range in brine composition. Including brine mixing in PA has been considered and rejected because using the end member brines (i.e., GWB or ERDA-6 brines) brackets the median values and uncertainties for the solubility calculations.

In addition to using these end-member brines in PA, other simplifying assumptions were also made:

1. Any brine present in the repository is well mixed with waste.

2. Equilibria with halite and anhydrite, the most abundant Salado minerals at or near the stratigraphic horizon of the repository, are rapidly established.

3. Oxidation-reduction (redox) equilibria with waste materials were not assumed.

4. Brine compositions attained after equilibration of GWB or ERDA-6 with the MgO engineered barrier exist for the entire 10,000-year regulatory period.

Brine composition is important to the calculation of actinide concentrations. The inorganic complexants, ionic strength, and pH are direct inputs needed to calculate actinide solubilities for a given brine composition. These species and properties are also important in defining the potential for colloid formation in the WIPP.

SOTERM-2.3.2 Brine pH and pH Buffering

The brine pH is a very critical parameter in defining the solubility of actinides under conditions where brine-mediated releases (DBR and transport through the Culebra) would be important in the WIPP. The brine pH is established by a number of highly coupled processes that will occur when the emplaced WIPP waste is inundated with brine. The most important of these are the potential buffering capacity of the brine coming into the WIPP, the reactions of this brine with emplaced waste components (most notably reduced metals and MgO), and microbial processes. The reactions of the emplaced MgO barrier material are expected to sufficiently control and define the pH when the repository is saturated with brine.

The range of brine composition that is likely to be present in the WIPP repository was discussed in Section SOTERM-2.3.1 (see also Table SOTERM-2). These brines have an intrinsic buffering capacity that is highest at pH 8.5-9. ERDA-6 brine, although it has an ambient pH of 6.2, contains a number of constituents that, in the pH range of 8-10, add buffer capacity to the reacted brine: Carbonate/bicarbonate (16 mM), borate (63 mM), and divalent cations that tend to react with hydroxide or carbonate to influence pH (Ca^{2+} at 12 mM, and Mg^{2+} at 19 mM). The pK_a for boric acid and dissolved carbonate/bicarbonate species are 9.0 and 9.67, respectively, which explains the tendency of this brine to maintain the pH in the range of 8-10. Operationally, the simulated ERDA-6 brines prepared in the laboratory have relatively high buffering capacity,

and significant changes in brine concentrations and pH are not routinely observed once the pH is experimentally defined (Borkowski et al. 2008, Lucchini et al. 2009). An operational pH range for ERDA-6 has been defined as having an upper limit of pH ~10, which is the pH at which a cloud point (indicating Mg precipitation) is observed. The preexcavation ambient ERDA-6-like brine will naturally add to the buffering capacity of WIPP brine due to its acid-base components and will establish a relatively high buffer capacity at the mildly alkaline conditions expected in the WIPP.

The expected pH in the WIPP in the event of brine saturation, however, will be defined by the reaction of the Castile ERDA-6-like brine with the waste components and barrier material. This was evaluated as part of the documentation for the CRA-2004 PABC (Leigh et al. 2005, Brush et al. 2006, and Table SOTERM-2).

Under these repository-relevant conditions, the expected pH, when little or no carbonate is present, is 8.69 in GWB brine and 8.94 for ERDA-6 brine. In both cases, this pH is established/buffered by the brucite dissolution reaction. The presence of microbial activity will potentially contribute significant amounts of carbon dioxide and leads to a model-predicted pH of 8.69 and 9.02 for GWB and ERDA-6 brine, respectively.

The key role MgO has in the buffering of pH at 8 to 9 under WIPP-relevant conditions is the basis of current WIPP actinide solubility calculations. In the absence of significant amounts of CO_2, the following carbonation reaction will buffer the fugacity of carbon dioxide (f_{CO_2}) at a value of $10^{-5.48}$ atm in GWB and $10^{-6.15}$ atm in ERDA-6:

$$Mg(OH)_2 + Ca^{2+} + CO_2(aq \text{ or } g) \leftrightarrows CaCO_3 + Mg^{2+} + H_2O(aq \text{ or } g) \quad \text{(SOTERM.2)}$$

Under these conditions, the following brucite dissolution/precipitation reaction will buffer pH in the WIPP at a value of 8.69 in GWB and 8.94 in ERDA-6 (Brush et al. 2006).

$$Mg(OH)_2 \leftrightarrows Mg^{2+} + 2OH^- \quad \text{(SOTERM.3)}$$

The potential for significant CO_2 formation as the result of microbial activity changes the mechanism by which pH is buffered, but causes a relatively small change in the calculated pH for ERDA-6-like brines. Microbial consumption of CPR materials could produce significant quantities of CO_2, which could in turn acidify any brine present in the repository and increase the solubility of the actinides relative to that predicted for near-neutral and mildly basic conditions. Under these conditions, both laboratory and modeling studies predict that the following carbonation reaction:

$$5Mg(OH)_2 + 4CO_2(aq \text{ or } g) \leftrightarrows Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O \quad \text{(SOTERM.4)}$$

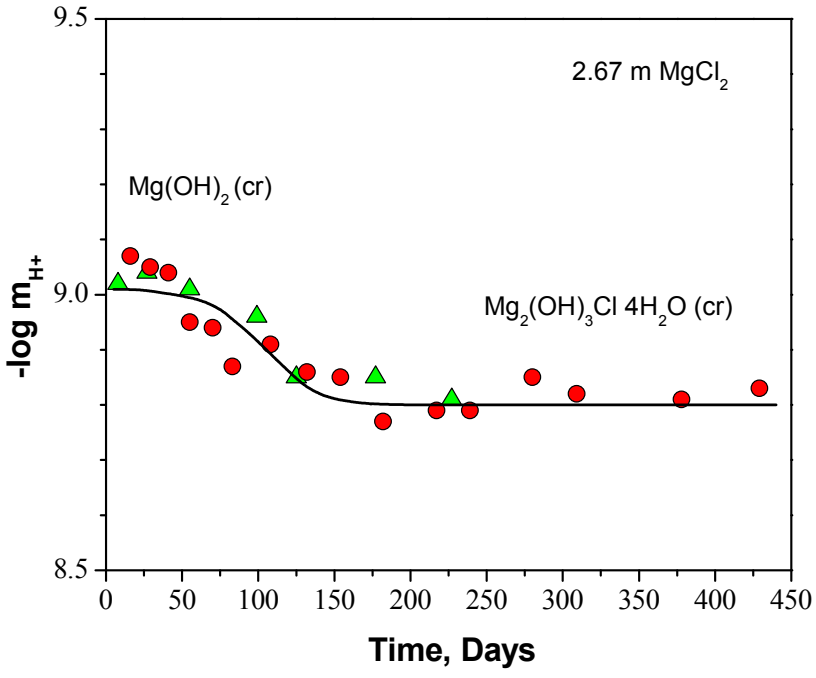
will buffer f_{CO_2} at a value of $10^{-5.50}$ atm in both GWB and ERDA-6. In this reaction, $Mg(OH)_2$ is the brucite, which is the main hydration product of the periclase (MgO) expected in the WIPP; $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ is the form of the hydromagnesite expected in the repository. Consideration of the possibility of high CO_2 levels leads to a calculated pH of 8.69 and 9.02 for GWB and ERDA-6 brine, respectively. This is a relatively small change in the predicted pH with no change predicted in GWB brine and only a 0.08 pH shift in ERDA-6 brine. These values

of f_{CO_2} and pH were used in the actinide speciation and solubility calculations for all CRA-2004 PABC vectors (Brush 2005).

Experiments that are relevant to the chemistry and pH buffering capacity of MgO, but not reflected in the CRA-2004 PABC, were performed by investigators at Karlsruhe (Schuessler et al. 2001 and Altmaier et al. 2003). This research was done to support the development of the German salt-based repository where MgO, calcium oxide (CaO), and clays are being evaluated as potential backfill material. Equilibration experiments with 2.67 and 5.15 molal magnesium chloride with excess magnesium hydroxide present were conducted for durations of over 400 days and show the establishment of a stable magnesium solution concentration with a pH of 8.7 to 8.8, which is in excellent agreement with current WIPP model predictions (see Figure SOTERM-1). This equilibration was also modeled using the Pitzer formulation in the software package for geochemical modeling of aqueous systems (EQ3/6), and excellent agreement was obtained. In this study, a change in magnesium (Mg) concentration was not noted during the equilibration with MgO, even though cement was dissolved in brine.

Based on Figure SOTERM-1, the dissolution of MgO in brine, when high chloride concentrations are present (> 2 m), demonstrates the self-buffering property of the brine-MgO system. The pH does not increase when MgO is dissolved. Moreover, with time, the system counteracts the potential decrease in pH that could result from solid phase transformations. To illustrate this better, the dissolution of 1 mole of MgO introduces 1 mol of Mg^{2+} and 2 moles of OH^- to the brine, which should increase the pH. To counter this and maintain pH, the magnesium chloride hydroxide hydrate ($Mg_2(OH)_3Cl{\cdot}4H_2O$) phase precipitates to reduce the pH. For the data shown in Figure SOTERM-1, the pH is reduced slowly as a consequence of equilibration with MgO. In this context, more hydroxide ions are precipitated than are introduced to the brine during the MgO dissolution step. There will also be more magnesium precipitated from the brine, resulting in a lower magnesium concentration in the brine.

There are no new WIPP-specific results to report that explicitly address the MgO buffering of WIPP brine since the CRA-2004. Some WIPP-specific experiments using simulated GWB and ERDA-6 brine, however, indirectly provide some information on this subject (Xiong and Lord 2008, Lucchini et al. 2009, Borkowski et al. 2008, Reed et al. 2009). A considerable number of the solubility experiments were performed in the pH range of 8-10 (below the cloud point of either ERDA-6 or GWB brine) and reflect strong buffering with no pH drift over the greater than 2-year duration of the experiments. Additionally, no significant Mg precipitation was noted in this pH range. The brines in these solubility studies were not equilibrated with MgO, but in some cases had excess iron in the system. Several experiments were performed outside of this pH range; in the presence of high carbonate (10 mM), a slow, downward pH drift was observed that was as much as 2 pH units over the duration of the experiments, even through preequilibration at the desired higher experimental pH was initially performed. In Xiong and Lord (2008), where the MgO and brucite reaction paths in GWB, ERDA-6 brine, and simplified brines were investigated, the equilibrium pH values measured were pH about 9 and were established by the reaction/dissolution of the MgO or $Mg(OH)_2$. Slightly higher pH was noted (up to pH 9.7) in some simplified brines when no carbonate or other brine components were



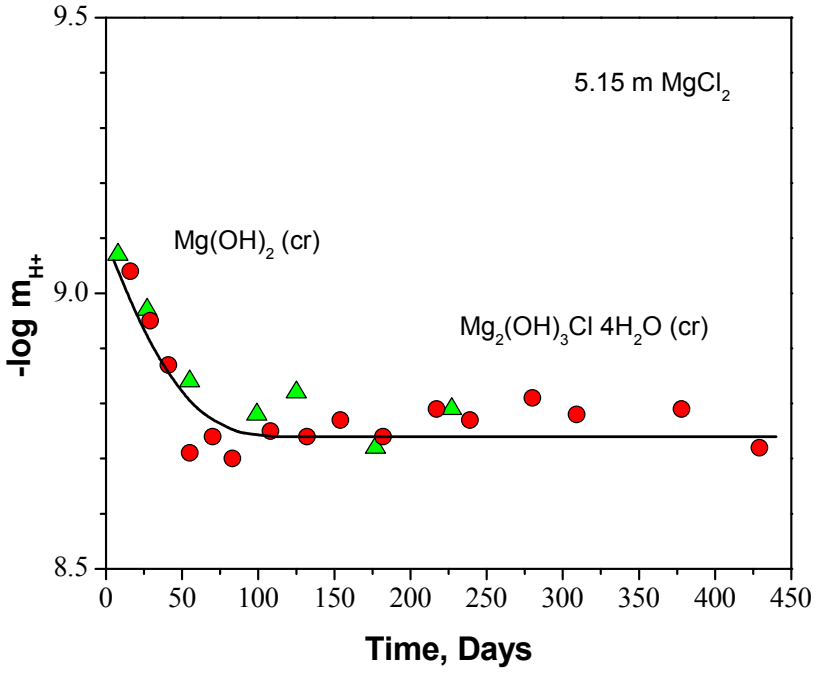


Figure SOTERM-1. Molal H^+ Concentration Measured as a Function of Time During the Solubility Experiments in 2.67 and 5.15 m $MgCl_2$ Solution. The Filled Circles and Triangles Show the Two Experiment Runs (Based on Data in Altmaier et al. 2003, Figure 3).

present. All of these data, although indirect, suggest that the MgO controls the pH to a pH = 9 ± 1. In this context, it is predicted that brine pH will remain in the range of 8-10 under a wide range of expected conditions. These experimental observations are also consistent with the experimental results and model predictions reported by Altmaier et al. (2003).

SOTERM-2.3.3 Selected MgO Chemistry and Reactions

MgO is the bulk, granular material emplaced in the WIPP as an engineered barrier. The MgO currently being placed in the WIPP contains 96 ± 2 mol % reactive constituents (i.e., periclase and lime) (Deng et al. 2006). The amount of MgO emplaced in the WIPP is currently calculated based on the estimated CPR content with an excess factor of 1.2, and it is estimated that in excess of 75,000 metric tons will be emplaced in the WIPP by the time of repository closure.

The chemistry of MgO is critical to the overall performance of the WIPP and is discussed in detail in Appendix MgO-2009 and in Xiong and Lord (2008). The MgO, as an engineered barrier in the WIPP repository design, has two important functions that directly support the PA calculation of actinide concentrations in brine. These are:

1. Sequester the excess CO_2 produced by the microbial consumption of CPR material and establish/maintain a low f_{CO_2} in the repository. This is currently estimated to be $10^{-5.5}$ atm for GWB and ERDA-6 brine.

2. Establish and buffer the brine pH by maintaining a magnesium solution concentration that reacts with CO_2 and hydroxide (see reaction SOTERM.2 and SOTERM.3) to buffer the pH at about 9. This was part of the pH discussion in Section SOTERM-2.3.2. This buffering removes uncertainty from the actinide concentration calculations.

Initially, MgO will undergo hydration to generate brucite ($Mg(OH)_2$). In time, brucite will react further to form magnesium chloride hydroxide hydrate ($Mg_3(OH)_5Cl{\cdot}4H_2O$) in Salado brine (Appendix MgO-2009, Section MgO-4.1). These phases combine to control the concentration of magnesium in high-magnesium brine (for example, GWB). The existence of magnesium as an aqueous cation in equilibrium with excess magnesium minerals helps to establish the solution pH.

For the reaction of MgO with GWB brine, PA uses a magnesium concentration of ~0.6 M (see Table SOTERM-2), which is supported by experimental results showing a magnesium concentration ~0.7 M (Snider 2003b). This reaction was also investigated by Altmaier et al. (2003) and Harvie, Møller, Weare (1984). Snider noted that the rate of MgO hydration is most likely linked to mineral phase changes between hydrated magnesium oxychloride and brucite. The existence of the hydrated magnesium oxychloride phase was inferred from scanning electron microscope (SEM) images, coupled with an energy dispersive x-ray spectroscopy system (EDS), to identify Mg–Cl phases. The Altmaier and Harvie studies showed that the hydration reaction was a solid-phase transformation between brucite and hydrated magnesium oxychloride that depends not on magnesium concentration, but on chloride concentration, with an invariant point predicted at 1.8 m MgCl concentration and a $-\log m_{H^+} = 8.95$.

The most important role of the MgO engineered barrier is to sequester carbon dioxide to maintain a low f_{CO_2} in the repository. Microbial consumption of CPR materials could produce

significant quantities of CO_2. Under these conditions, brucite and magnesium chloride hydroxide hydrate will react with the CO_2 generated. Both laboratory and modeling studies predict that the following carbonation reaction will buffer f_{CO_2} at a value of $10^{-5.50}$ atm in both GWB and ERDA-6:

$$5Mg(OH)_2 + 4CO_2(aq \text{ or } g) \leftrightarrows Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O \qquad \text{(SOTERM.5)}$$

This reaction effectively removes excess CO_2 from the repository and bicarbonate/carbonate from the brine. The initial product of MgO carbonation reaction is $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$. This is converted into $MgCO_3$, which is the expected stable mineral form of magnesium carbonate in the WIPP, according to Reaction (SOTERM.6).

$$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O + CO_2(aq \text{ or } g) + 10\ H_2O \leftrightarrows 5MgCO_3 \cdot H_2O \qquad \text{(SOTERM.6)}$$

Reaction (SOTERM.6) is slow and it is estimated that hundreds to thousands of years (Appendix MgO-2009) are needed for the conversion of hydromagnesite to magnesite. Consumption of CO_2 will prevent the brine acidification, and magnesium carbonate precipitation will maintain low carbonate concentration in the WIPP brine to avoid the formation of highly soluble actinide species with carbonate complexes. Although MgO will consume essentially all CO_2, residual quantities in equilibrium with magnesite under the WIPP conditions will persist in the aqueous and gaseous phases.

The importance of magnesium chemistry, and correspondingly the chemistry associated with the emplaced MgO on the calculation of actinide concentrations in brine is clear. MgO sequesters CO_2 and minimizes the buildup of carbonate in brine. At the expected pH, carbonate forms strong complexes with the An(III), An(IV), and An(VI) oxidation states. An increased carbonate concentration in brine would significantly increase actinide solubilities. Additionally, MgO helps establish the pH in brine. The removal of CO_2 prevents a decrease in the pH that could also significantly increase actinide solubility. An additional beneficial effect of MgO is to maintain a solution concentration of Mg^{2+} that will precipitate as brucite to keep the pH in the 8-10 range. The presence of MgO leads to a more predictable chemistry that lowers the uncertainty when calculating actinide concentrations in WIPP brine (see Borkowski et al. 2008 for data on An(III) and Altmaier et al. 2005 for data on An(IV)).

SOTERM-2.3.4 Iron Chemistry and Corrosion

The WIPP repository will contain a large quantity of reduced iron due to the use of iron-based containers for much of the emplaced TRU waste. Currently, it is estimated that the WIPP will contain upwards of 51,000 metric tons of iron (U.S. Department of Energy 2006) when all the waste is emplaced. The presence of this reduced metal will have an important role in the establishment of reducing conditions in the WIPP by removing oxygen. Reduced iron species (aqueous Fe(II) and Fe(0, II)-valent minerals) are important because they will reduce higher-valent actinides in the WIPP, leading to lower actinide solubilities (Reed et al. 2009, Reed et al. 2006).

It is expected that oxic corrosion of steels and aerobic microbial consumption of CPR materials will quickly consume the limited amount of oxygen (O_2) trapped within the repository at the time of closure. After O_2 is consumed, anoxic corrosion of metals will occur (Brush 1990, Brush

1995, Wang and Brush 1996a). In all of the vectors for the 2004 PA, the EPA's CCA 1997 Performance Assessment Verification Test (PAVT), the CCA PA, and the CRA-2004 PABC, there were significant amounts of uncorroded steels and other Fe-base alloys in the repository throughout the 10,000-yr regulatory period. WIPP-specific experiments (Telander and Westerman 1993 and 1997) showed that steels and other Fe-based alloys will corrode by the following reactions:

$$Fe + (x)H_2O \leftrightarrows Fe(OH)_2 \cdot (x-2)H_2O + H_2; \quad \text{(SOTERM.7)}$$

$$3Fe + 4H_2O \leftrightarrows Fe_3O_4 + 4H_2; \quad \text{(SOTERM.8)}$$

$$Fe + H_2O + CO_2 \leftrightarrows FeCO_3 + H_2; \text{ and} \quad \text{(SOTERM.9)}$$

$$Fe + H_2S \leftrightarrows FeS + H_2. \quad \text{(SOTERM.10)}$$

In reducing environments, reduced iron phases (Fe(II) oxides and zero valent iron) and aqueous ferrous iron will be present. These are all reducing agents towards key actinide species (see Table SOTERM-3) and will help establish the predominance of lower-valent actinides in the WIPP. The concentration of ferrous iron could be relatively high in the WIPP brine, although its solubility has not yet been explicitly determined. There are also many potential reactions that could control and/or define the iron chemistry. The expectation is that ferrous hydroxide will control the solubility of iron, leading to a predicted solubility in the range of 10^{-6} M to 10^{-4} M for pH between 8.5 and 10.5 (Refait and Génin 1994).

Table SOTERM-3. Redox Half-Reaction Potentials for Key Fe, Pb, Pu, and U Reactions at 25 °C and I<1 (Morss, Edelstein, and Fuger 2006, Chapter 23)

Metal Species Reduced	E_o (Acidic) in V	E_o at pH = 8 in V
$Pb^{4+} \rightarrow Pb^{2+}$	1.69	2.47
$PuO_2^{+} \rightarrow Pu^{4+}$	1.170	0.70
$PuO_2^{2+} \rightarrow PuO_2^{+}$	0.916	0.60
$Fe(OH)_3(s) \rightarrow Fe^{2+}$	Not Applicable	0.1
$FeOOH(s) \rightarrow FeCO_3(s)$	Not Applicable	-0.05
$UO_2^{2+} \rightarrow U^{4+}$	0.338	-0.07
$Pu^{4+} \rightarrow Pu^{3+}$	0.982	-0.39
$Pb^{2+} \rightarrow Pb$	-0.1251	-0.54
$Fe^{3+} \rightarrow Fe^{2+}$	0.77	-0.86
$Fe(II)(OH)_2 \rightarrow Fe(0)$	-0.44	-0.89
$U^{4+} \rightarrow U^{3+}$	-0.607	-1.95

Three important reactions of iron are considered for the WIPP PA. The first is the reaction of metallic iron with carbon dioxide to form strongly insoluble ferrous carbonate. The solubility product of this salt is log K = -10.8 at I = 0 (National Institute of Standards and Technology [NIST] 2004), and it is much smaller than magnesium carbonate. This suggests that the presence

of iron will likely remove CO_2 from the repository more effectively than MgO due to its lower solubility product. This reaction is not included in the WIPP PA because the CO_2 reacts with MgO before the iron.

The second is the reaction of iron and ferrous ions with the hydrogen sulfide that could be generated in the repository by sulfate-reducing microbes. This will lead to a very insoluble ferrous sulfide precipitate with a solubility product of log K_s = -17.2 (NIST 2004). This helps remove sulfide, which can complex actinides, from brine. This reaction is assumed to occur instantaneously in the PA.

Finally, iron species form strong complexes with organic ligands. The strongest of these complexes is EDTA. The net effect is that dissolved iron species will compete with actinides for organic ligands, and in many cases out-compete the actinides to counteract the potential enhancement of actinide solubility that would otherwise occur. This reaction is not currently included in the PA.

The chemistry of iron will have a pronounced effect on WIPP-relevant actinide chemistry in many ways. The linkages of iron chemistry to the redox chemistry are well-established in the literature (Farrell et al. 1999, Fredrickson et al. 2000, Qui et al. 2001, Nakata et al. 2004, and Behrends and Van Cappellen 2005). Iron will establish reducing conditions conducive to the overall reduction of higher-valent actinide species and precipitate an iron sulfide phase that removes sulfide from solution. Additionally, iron species could sequester carbon dioxide and compete with actinides for organic and inorganic complexants, although there is no explicit credit taken for this in the WIPP PA.

SOTERM-2.3.5 Chemistry of Lead in the WIPP

Lead is present in the repository in the metallic form as part of the waste. The reactivity of zero-valent lead is greatly mitigated by the formation of a thin, coherent, protective oxide, oxycarbonate, chloride, or sulfate protective layer. Metallic lead also reacts slowly with water at room temperature and undergoes corrosion to form oxides and oxyhydroxides. Under slightly alkaline conditions, the hydrolysis of lead leads to formation of a poly-oxyhydroxide cation, $[Pb_6O(OH)_6]^{4+}$. The following reactions are possible under WIPP-relevant conditions:

$$2Pb + O_2 \leftrightarrows 2PbO \qquad \text{(SOTERM.11)}$$

$$2PbO + H_2O + CO_2 \leftrightarrows (PbOH)_2CO_3 \qquad \text{(SOTERM.12)}$$

$$Pb + H_2O + CO_2 \leftrightarrows PbCO_3 + H_2 \qquad \text{(SOTERM.13)}$$

$$Pb + H_2S \leftrightarrows PbS + H_2 \qquad \text{(SOTERM.14)}$$

$$Pb^{2+} + 2Cl^- \leftrightarrows PbCl_2 \qquad \text{(SOTERM.15)}$$

$$Pb^{2+} + SO_4^{2-} \leftrightarrows PbSO_4 \qquad \text{(SOTERM.16)}$$

$$5Pb^{2+} + PbO + 6OH^- \leftrightarrows [Pb_6O(OH)_6]^{4+} \qquad \text{(SOTERM.17)}$$

The solubility of lead in WIPP brine is expected to be low, due in part to the passivation process, but also because of insoluble solids formation. Strong oxidants, e.g., radiolysis products, may locally enhance the dissolution of lead, but alkaline brine, which contains chlorides and carbonate/bicarbonate species, will overwhelm radiolytic effects to maintain a low concentration of lead in the brine. In solution, lead will exist as Pb^{2+} species that are redox-active toward high-valent actinides (see Table SOTERM-3) and will help establish and maintain reducing conditions in the brine.

Lead, as was the case with iron, can influence the redox chemistry (see Table SOTERM-3) and precipitate carbonate and sulfide from the WIPP brine. This leads to a redox chemistry that will help maintain reducing conditions and effectively lower carbonate concentration. Both of these will potentially lower actinide solubility in the WIPP. These impacts are not considered in the WIPP PA.

SOTERM-2.3.6 Organic Chelating Agents

Organic chelating agents are used in the processing and cleanup/decontamination of actinides throughout the DOE complex. For this reason, they are often present as cocontaminants with the TRU component in the WIPP waste. Some of these chelating agents strongly complex actinides and could have a significant effect on their solubility in brine. In this context, four organic chelating agents–oxalate, acetate, citrate, and EDTA–are tracked as part of the WIPP inventory process, and the potential effects of these complexants on the calculated actinide solubilities are evaluated as part of the WIPP PA (Leigh et al. 2005, Brush and Xiong 2005a).

The potential concentrations of the key organic ligands in the WIPP were calculated a number of times (Brush and Xiong 2003b, Leigh, Trone, and Fox 2005) and are based on the inventory provided by Crawford and Leigh (2003). The potential concentrations of these organics used in the CRA-2004 PABC were calculated by Brush and Xiong (2005a) and are based on the best understanding of the WIPP inventory data available at that time. These concentrations are summarized in Table SOTERM-4, where the potential maximum organic concentration in the WIPP is defined as the inventory of the organic ligand divided by the minimum free volume of brine needed for brine release (see Section SOTERM-2.2.4).

Dissolved metals will compete with the actinides to form organic complexes. As the metals in the repository corrode, additional transition metal ions will dissolve into the brine. These ionic species include iron (Fe) and lead (Pb). Other steel constituents, such as nickel (Ni), chromium (Cr), vanadium (V), and manganese (Mn), may also be present. Additionally, divalent cations in the brine, most importantly Mg^{2+} and Ca^{2+}, will also form complexes with these chelating agents and compete with the actinide species. The stability constants for Mg^{2+}, Ca^{2+}, Fe^{2+}, Pb^{2+}, and Ni^{2+} and deprotonation constants for the organic acids are shown in Table SOTERM-5 (National Institute of Standards and Technology 2004). These formation constants, in many respects, follow the same trends as the actinide species and, when present in high enough concentrations, will compete with the actinide to form complexes and effectively lower the effect of organic complexation on actinide solubility. However, this is not included in the PA.

Table SOTERM-4. Concentrations of Organic Ligands in WIPP Brine Calculated for Use in the CRA-2004 PABC (Brush and Xiong 2005a)

Organic Ligand	Compound	Inventory Amount (g)	Molecular Weight [a] (g/mol)	Potential Concentration[c] (M)	Total Potential Concentration[c] (M)
Acetate	Acetic acid Sodium acetate	1.42×10^{5} 8.51×10^{6}	60.05 82.03	2.36×10^{-4} 1.04×10^{-2}	1.06×10^{-2}
Oxalate	Oxalic acid Sodium oxalate	1.38×10^{7} 3.39×10^{7}	90.03 112.0	1.53×10^{-2} 3.02×10^{-2}	4.55×10^{-2}[b]
Citrate	Citric acid Sodium citrate	1.19×10^{6} 4.00×10^{5}	192.1 214.1	6.19×10^{-4} 1.87×10^{-4}	8.06×10^{-4}
EDTA	Sodium salt	2.56×10^{4}	314.2	8.14×10^{-6}	8.14×10^{-6}

[a] Molecular weight was calculated for monosodium salts to be conservative.
[b] Inventory, in moles, of the organic chelating agent divided by 10,011 m^3
[c] Concentration of oxalate will be limited by solubility, not inventory, in ERDA-6-like brine

Table SOTERM-5. Apparent Stability Constants for Organic Ligands with Selected Metals (National Institute of Standards and Technology 2004)

Organic Ligand	pK_a	Metal	Ionic Strength (m)	$\log_{10} \beta_i$
EDTA	k_1 8.86-9.05 k_2 6.10-7.02 k_3 2.79-2.54 k_4 2.05-2.20	Fe^{2+} Ni^{2+} Pb^{2+} Mg^{2+} Ca^{2+}	0.1 0.1 0.1 1 1	14.3 18.4 18 8.61 9.68
Citrate	k_1 5.58-5.30 k_2 4.25-4.38 k_3 2.85-3.06	Fe^{2+} Ni^{2+} Pb^{2+} Mg^{2+} Ca^{2+}	0.1 0.1 1.0 0.1 0.1	4.4 5.18 4.44 3.43 3.48
Oxalate	k_1 3.74-4.23 k_2 1.15-1.43	Fe^{2+} Ni^{2+} Pb^{2+} Mg^{2+} Ca^{2+}	1.0 0.1 1.0 0.1 0.1	3.05 4.16 4.20 2.75 2.46
Acetate	k_1 4.52-4.99	Fe^{2+} Ni^{2+} Pb^{2+} Mg^{2+} Ca^{2+}	3.0 0.1 0.1 0.1 0.1	0.54 0.88 2.15 0.51 0.55

There are two final, but important, observations about the organic chelating agents present in the WIPP. First, they are expected to have very different tendencies toward biodegradation, based on extensive experience with soil bacteria in the literature (Banaszak, Rittmann, and Reed 1999). Microbial activity, based on many general observations with soil bacteria, will likely readily degrade citrate, oxalate, and acetate to very low (submicromolar) steady-state concentrations. This important degradation pathway is not as certain for EDTA, which tends to resist biodegradation in most groundwaters. These degradation pathways have, however, not been demonstrated for the halophiles typically present in the WIPP, and it is currently assumed in the WIPP PA that no degradation pathways for these organic complexants, microbiological or chemical, exist.

The second important observation is that these chelating agents, under WIPP-relevant conditions, are expected to help establish reducing conditions in the WIPP because they tend to reduce higher-valent actinides. This has been demonstrated in WIPP brine for Np(V) and Pu(V/VI), but was not observed for U(VI) (Reed et al. 1998). These chelating agents also tend to oxidize III actinides to IV, which would have a beneficial effect on actinide solubility in the WIPP because the actinides in the IV oxidation state are approximately 10 times less soluble than actinides in the III oxidation state. These potentially beneficial effects of organic chelating agents on actinide speciation are also currently not included in the WIPP PA.

SOTERM-2.3.7 CPR in WIPP Waste

The WIPP waste contains a relatively high amount of organic material, since much of the waste is residue from laboratory operations where CPR materials were widely used. Current estimates project over 10,000 metric tons of plastic and cellulosic materials with a much lower amount of rubber material in the WIPP. This organic material is important from the perspective of repository performance in that it provides an organic "feedstock" for microbial activity that could lead to gas generation (carbon dioxide, hydrogen, hydrogen sulfide, and possibly methane), as well as degradation products that can complex actinides or form pseudocolloids. CPR degradation is represented in the PA to evaluate these potential impacts on the actinide concentrations and release.

SOTERM-2.4 Important Postemplacement Processes

There are three important postemplacement processes that take place in the WIPP after repository closure. These are metal corrosion, microbiological effects, and radiolysis. Metal corrosion was already discussed as part of the iron chemistry section (Section SOTERM-2.3.4). Microbiological effects and radiolysis are briefly discussed in this section.

SOTERM-2.4.1 Microbial Effects in the WIPP

Microbiogical processes can have a significant effect on many aspects of subsurface chemical and geochemical processes. This, particularly as it relates to contaminant transport and remediation, has been well established for soil bacteria in low-ionic-strength and near-surface groundwaters (Banaszak, Rittmann, and Reed 1998). In the WIPP, as a result of the high-ionic-strength brines present, halophiles (rather than soil bacteria) will predominate. What is understood about halophiles under WIPP-relevant conditions was established through a series of

long-term studies conducted as part of the Actinide Source Term Program (ASTP) project by researchers at Brookhaven (Brush 1990; Francis and Gillow 1994; Brush 1995; Wang and Brush 1996a). The important and potential effects of microbial activity on the WIPP PA are also discussed extensively (Leigh et al. 2005, U.S. Environmental Protection Agency 2006).

In the WIPP repository, many of the co-contaminants present (e.g., sulfates, phosphates, organics, nitrate) are important nutrients that drive microbial activity and, in part, select the primary degradation and growth pathways taken. There are WIPP-specific data which demonstrate that microbial processes can occur under humid and saturated conditions in the laboratory (Francis 1998). In the CRA-2004 PABC, a longer-term rate for microbial gas generation was implemented based on new laboratory data obtained by the project (Leigh et al. 2005; Nemer and Stein 2005; Nemer, Stein, and Zelinski 2005).

Under repository-relevant conditions, there are primarily two important potential effects on repository performance linked to the presence of microbial activity. The first is gas generation due to the biodegradation of the organics present as WIPP waste (see Section SOTERM-2.3.6 and SOTERM-2.3.7). This is currently addressed by the WIPP PA (Nemer and Stein 2005; Nemer, Stein, and Zelinski 2005). The second is the growing recognition of the linkages between microbial activity and actinide speciation under microbiologically active anaerobic and reducing conditions. This is not currently addressed in the WIPP PA, but adds an additional argument for the sustained predominance of lower-valent actinides under WIPP-relevant conditions (III and IV oxidation states).

SOTERM-2.4.1.1 Gas Generation and Microbial Degradation of CPR Materials

Microorganisms utilize organic compounds as the carbon source for their growth. This biodegradation also provides energy to the organism because the organic compound also functions as an electron donor that, when coupled with inorganic electron acceptors (oxidized metals, sulfate, nitrate, and or oxygen), will provide energy to the organism. Under anaerobic conditions, carbon dioxide, hydrogen, and/or methane are typically produced as gases.

The large quantity of CPR materials emplaced in the WIPP is the main carbon source that could lead to substantial gas generation from degradation by microorganisms. As with most subsurface microbial processes, there are large uncertainties surrounding the extent to which microbial consumption of CPR materials can occur during the 10,000-yr WIPP regulatory period. In this context, it is assumed that significant microbial consumption of CPR materials is possible, but this is by no means certain.

To incorporate these uncertainties in the PA, the conceptual model for biodegradation used in CRA-2004 (Wang and Brush 1996a and 1996b) used a probability of 0.50 for significant microbial activity. This was changed in the CRA-2004 PABC calculation to be a probability of 1.0, meaning that microbial activity was considered in all PA vectors. The presence of this microbial activity means it is assumed that microbes may consume 100% of the cellulosic materials in the repository, and that there is a probability of 0.25 that microbes may consume the plastic and rubber materials. Thus, there is microbial consumption of cellulosic materials, but not of plastic or rubber materials, in 75% of the PA realizations (vectors), and microbial consumption of all CPR materials in 25% of the vectors.

Microbial consumption of CPR materials could affect the actinide source term in four ways:

1. Production of significant quantities of CO_2, which could acidify the brine in the absence of an MgO buffer or increase the solubility of actinides by carbonate complexation at the expected mildly alkaline pH

2. Bioreduction of higher-valent actinide species leading to lower-valent, less-soluble actinide species

3. Degradation of solubilizing organic ligands, leading to lower actinide solubility

4. Production of humic and microbial colloids that could increase the amount of actinide pseudocolloids in the brine

The effect of CO_2 production is discussed in this section. The remaining three effects are implicitly considered in the analyses that address the oxidation-state distributions (Section SOTERM-4.2), the effects of organic ligands (Section SOTERM-2.3.6), and the effects of colloids (Section SOTERM-3.8). The simplifications used in the PA calculations for all four of these effects are discussed at the end of this section.

Microbial activity, if it occurs to a significant extent in the WIPP, would consume CPR materials by the following sequential reactions (Brush 1990, Francis and Gillow 1994, Brush 1995, Wang and Brush 1996a, and Francis 1998):

$$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \qquad \text{(SOTERM.18)}$$

$$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \qquad \text{(SOTERM.19)}$$

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \qquad \text{(SOTERM.20)}$$

Methanogenesis, described by Reaction (SOTERM.20), is not included as a degradation pathway in CRA-2004 PABC (Leigh et al. 2005) due to uncertainty about the availability of sulfate (see Section SOTERM-2.2.5) in the DRZ and its exclusion is a conservative assumption relative to the amount of carbon dioxide that could be produced. In effect, the CRA-2004 PABC and this PA assume that an excess of sulfate is always available to sustain sulfate-reduction biodegradation pathways. When unlimited sulfate is available from natural sources in the host rock, which is the assumption for the CRA-2004 PABC and for this PA, 4% of the gas generation occurs through denitrification and 96% occurs by way of sulfate reduction (Leigh et al. 2005, Section 2.4).

Microbial consumption of CPR materials, therefore, could produce significant quantities of CO_2, which could in turn acidify any brine present in the repository and increase the solubilities of the actinides relative to those predicted for neutral and mildly basic conditions. Therefore, the DOE is emplacing MgO in the repository to decrease actinide solubilities by consuming essentially all of the CO_2 that could be produced by microbial consumption of CPR materials, and by buffering (controlling) the f_{CO_2} and pH within ranges that are favorable from the standpoint of actinide speciation and solubility (see Section SOTERM-2.3.2).

Three effects of microbial consumption of CPR materials are recognized in the system performance modeling. A simplification has been made so the effects will be time-independent after 100 years. These effects are

1. CO_2 production. With the addition of excess MgO, the effects of CO_2 production are minimized, and it is assumed that the system may be modeled using the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) buffer.

2. Redox effects. After 100 years, the repository will have a reducing environment. This is, in part, established by the postclosure microbial consumption of oxygen, but is also due to the corrosion of steel. This combined effect leads to the formation of an anoxic reducing environment in the WIPP.

3. Production of humic and microbial colloids is possible/probable and likely to be the main colloidal contributor to actinide concentrations in DBR release.

SOTERM-2.4.1.2 Bioreduction of Multivalent Actinides

The bioreduction of higher-valent actinides is an important potential effect of microbial activity in the WIPP. This potential effect is beneficial to the WIPP licensing case since it strengthens the current PA assumption that lower-valent, and therefore less-soluble, actinide species will predominate in the WIPP. The bioreduction of actinides has recently been the focus of much research due to its expected role in microbially-mediated remediation and containment of subsurface contaminants (Banaszak, Rittman, and Reed 1998; Banaszak et al. 1999; Lloyd, Young, and Macaskie 2000; Reed et al. 2007; Icopini, Boukhalfa, and Neu 2007; and Francis, Dodge, and Gillow 2008). The extent that this applies to the halophiles typically present in the WIPP is, however, uncertain, although it is expected that similar trends in bioreduction will be observed.

The linkage between actinide oxidation state and microbiological processes for soil bacteria is shown in Figure SOTERM-2. Under anaerobic conditions, U(VI), Pu(V/VI), and Np(V) are reduced for a wide range of microbes and electron donors. U(VI) and Np(V) species are primarily reduced enzymatically by reductases formed. The end product in both of these cases is the actinide in the IV oxidation state. The Pu system, however, is more complex in that there are strongly coupled abiotic and biotic pathways (see Table SOTERM-3) and the formation of Pu(III), rather than Pu(IV), is sometimes observed when Pu(IV) solubilization mechanisms coexist.

Although there is a reasonable expectation that bioreduction of higher-valent actinides will occur for microbiologically active anaerobic systems in the WIPP, WIPP-specific data that support this expectation have not been obtained. For this reason, the potential effects of bioreduction on multivalent actinide systems are not considered in the WIPP PA.

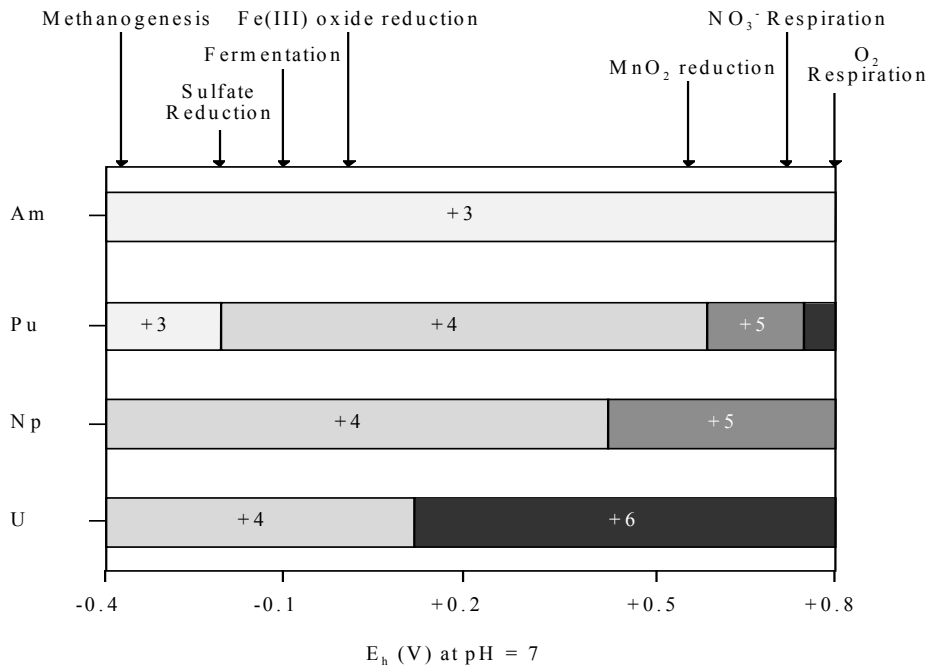


Figure SOTERM-2. Expected Dominant Actinide Oxidation States as a Function of the Standard Reduction Potential at pH = 7 in Water That is in Equilibrium With Atmospheric CO_2. The Linkages Between the Redox Potentials, Associated Specific Oxidation States, and Microbial Electron Acceptor Couples are Also Shown (Banaszak, Rittmann, and Reed 1998).

SOTERM-2.4.2 Radiolysis Effects in the WIPP

Radiolysis effects in the WIPP are caused by the interaction of ionizing radiation and particles (neutrons, α, β, and γ) with the gases, brines, and materials present in the repository. These effects have not been extensively studied under WIPP-related conditions, but there is a fairly good general understanding of their extent and nature. The strongly reducing and oxidizing transients generated radiolytically in aqueous systems can affect the oxidation state distribution of multivalent metals and actinides. In high–ionic-strength sodium chloride brines, this is primarily exhibited in the oxidation of Am(III) and Pu(III/IV) species to Am(V) and Pu(V/VI). Additionally, the radiolytic breakdown of water leads to the formation of molecular hydrogen, which adds to gas generation in the WIPP after brine inundation. Lastly, radiolytic effects can affect the stability and/or enhance the degradation of waste components (e.g., CPR degradation, iron/metal corrosion, and initial actinide oxidation state distribution) during the unsaturated and saturated phases in repository history.

The effects of radiolysis for most conditions expected in the WIPP are predicted to be transient and insignificant. In this context, there is a recognition that although radiolysis can lead to localized conditions and effects that could oxidize multivalent actinides, the brine chemistry, metal corrosion, and microbiological activity will combine to very rapidly overwhelm these effects. For this reason, radiolysis effects on actinide solubility are not explicitly included in the WIPP PA to calculate actinide concentrations. More specifics on the overall mechanisms, brine

radiation chemistry, and potential radiolytic effects on actinide speciation are given in this section.

SOTERM-2.4.2.1 Radiation Chemistry of Brine Systems

The radiolysis of high-ionic-strength brine systems has not been extensively studied, but some studies exist (Büppelman, Kim, and Lierse 1988; Kim et al. 1994; Kelm, Pashalidis, and Kim 1999; Ershov et al. 2002). The many components in the brine systems of interest to the WIPP will lead to a relatively complex radiation chemistry and the formation of numerous transients and free radicals.

In contrast to this, the radiation chemistry of pure and dilute aqueous systems has been extensively investigated, and detailed reviews of this research have been published (Draganic and Draganic 1971, Spinks and Woods 1990). The irradiation of pure water leads to the formation of molecular hydrogen peroxide (H_2O_2) and hydrogen (H_2). These molecular yields are relatively insensitive to a wide range of conditions in dilute systems for a given type of ionizing radiation. Molecular yields are G_{H2} = 0.45 molecule (molec)/100 electron-volt (eV) and G_{H2O2} = 0.7 molec/100 eV for low Linear Energy Transfer (LET) ionizing radiation (β, and γ) and G_{H2} = 1.6 molec/100 eV and G_{H2O2} = 1.5 molec/100 eV for high LET radiation (α and neutrons). The radiolytic formation of hydrogen in the WIPP brine due to self-irradiation effects of ^{239}Pu was established and a molecular yield of G_{H2} = 1.4 molec/100 eV was measured (Reed et al. 1993). This yield is consistent with the high LET literature, even though the irradiations were performed in brine.

The high concentrations of electron and free radical scavengers present in the WIPP brine have a pronounced effect on the radiation chemistry. Most importantly, halides react with the hydroxyl radical (OH·) or act as scavengers (such as Cl^- or Br^-) to gradually lower the molecular yield of H_2O_2 as the concentration of the scavengers is increasing (Kelm, Pashalidis, and Kim 1999). In this context, oxidizing transient species are "chemically" stored as oxychlorides and oxybromides, leading to a shift towards more oxidizing conditions. Figure SOTERM-3 gives an overview of the radiolytic pathways and mechanisms that are likely (Buppelmann, Kim, and Lierse 1988). In NaCl brine, the formation of chloride species (ClO^-, HOCl, Cl_2, and Cl_3^-) is favored, instead of H_2O_2 (Büppelmann, Kim, and Lierse 1988).

Kelm, Pashalidis, and Kim (1999) showed that the formation of hypochlorite ion increases with the chloride concentration and the dose (Figure SOTERM-4) in NaCl brine. The authors found that in solutions containing 37 gigabecquerel (GBq)/liter (L) of ^{238}Pu, the hypochlorite concentration increases with time (dose) and appears to approach a steady state (see Figure SOTERM-4). At a constant dose rate, the maximum hypochlorite concentration depends on the chloride concentration. It was also observed that hypochlorite ion generation was negligible when chloride concentrations were smaller than 2 M.

In the WIPP brine, however, some solutes other than chloride may play a role. Ershov et al. (2002) showed that small amounts of bromide in natural brines under radiolysis can give Cl_2^-, $ClBr^-$, and Br^- radical anions at the radical step, and then mixed halogen molecules and trihalide ions by radical recombination at the molecular step (Ershov et al. 2002). The hydrolysis of

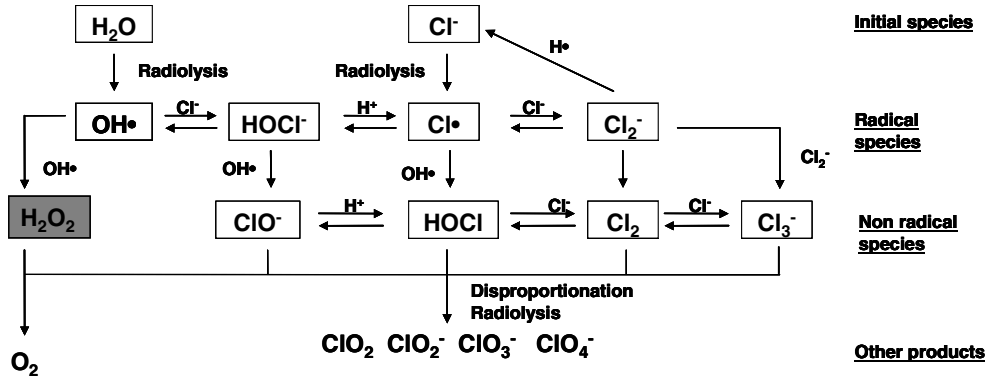


Figure SOTERM-3. NaCl Brine Radiolysis Species and Suggested Mechanism of Production. The Formation of Chloride Species (ClO^-, HOCl, Cl_2, and Cl_3^-) is Favored Instead of H_2O_2 (Based on Data in Büppelmann, Kim, and Lierse 1988).

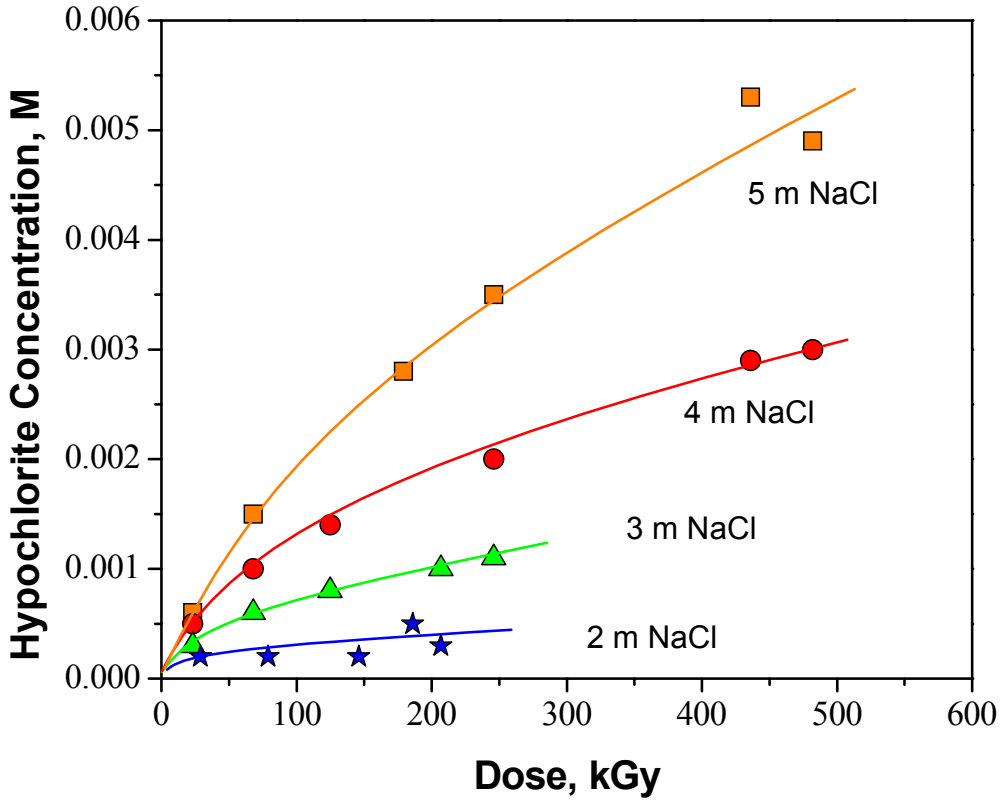


Figure SOTERM-4. Radiolytic Formation of Hypochlorite Ion in Solutions of Various NaCl Concentrations at a Constant Alpha Activity of 37 GBq/L at pH~12 (Based on Data in Kelm, Pashalidis, and Kim 1999)

mixed halogen molecules can then result in the formation of hypobromite (OBr^-) (acidic form: hypobromous acid [HOBr]), a starting substance to more stable bromates of higher oxidation state (Ershov et al. 2002).

Some WIPP-specific experiments were performed to establish the key radiolytic product in GWB and ERDA-6 brine (Lucchini et al. 2009). This study confirms that hydrogen peroxide (H_2O_2) and hypochlorite ion (OCl^-) are unstable in these WIPP brines, due in part to metallic impurities in the brine. There was, however, an accelerated decomposition of these species when bromide (Br^-) was present, which is the case for both ERDA-6 and GWB brines. Here, OCl^- readily and stoichiometricly reacted with Br^- to form hypobromite ion (OBr^-), which appeared to be the most important radiolytic transient observed under these conditions. OBr^-, like OCl^-, is also an oxidizing species (E^o=0.76V), that will likely lead to the oxidation of multivalent actinides in the WIPP, but this reactivity has not been established experimentally under representative WIPP conditions (Lucchini et al. 2009).

In the WIPP, most of the brine radiolysis is caused by the deposition of alpha particles from the TRU isotopes present in the WIPP waste. The range (distance traveled until the alpha particle's energy is lost) of these alpha particles is very short (<40 microns) and radiolysis of the brine solution will take place at the solid-liquid interface. Locally, the concentration of oxidative radiolytic products of brine, such as hypochlorite, chlorite, chlorate, and products of their reaction with brine components (e.g., hypobromite) may be high, and they may directly interact with the radioactive surface. These "very-near" radiolytic effects, however, are expected to be quickly mitigated by the bulk brine chemistry and the reaction of reducing agents (e.g., reduced iron) with the oxidizing molecular products formed.

SOTERM-2.4.2.2 Potential Radiolytic Effects on Actinide Speciation and Solubility

A buildup of oxidizing radiolytic products in brine may increase the redox potential of the brine (Büppelmann, Kim, and Lierse 1988), and consequently directly generate higher-valent actinide species. Alternatively, these radiolytic products could be inserted into some solid actinide phases. For example, Kim et al. (1994) studied the solubility of schoepite, $(UO_2)(OH)_2 \cdot xH_2O$, with hypochlorite ion in 0.1M NaCl at 25 °C (77 °F), in CO_2-free atmosphere (Kim et al. 1994). Their X-Ray Diffraction (XRD) patterns of the residual precipitates showed the introduction of hypochlorite ion in precipitates. Kim et al. (1994) observed that the presence of hypochlorite ion in the initial schoepite structure enhanced the solubility of the solid 10 to 100 times in the range of pH 6.0-9.8, compared with its solubility in the absence of hypochlorite ion (Kim et al. 1994). However, this effect was reduced when the molar ratio $[ClO^-]/[UO_2^{2+}]$ increased. This scenario is unlikely to occur in the WIPP because the potential buildup of oxidizing radiolytic products generated in brine is readily overwhelmed by the overall reducing capacity of the site (reduced metals and microbial processes).

The buildup of oxidizing radiolytic products due to brine radiolysis has also been shown to significantly affect the solution chemistry of Am. For example, Am(III) was oxidized to the more soluble forms of Am, namely AmO_2^+ and AmO_2^{2+} (Magirius, Carnall, and Kim 1985; Katz, Seaborg, and Morss 1986; Stadler and Kim 1988; and Meyer et al. 2002). Magirius, Carnall, and Kim (1985) reported on the radiation effects exerted upon a 5 M NaCl solution at the pH 8 to 9 range using precipitated $Am(OH)_3$ at a concentration of 1.03×10^{-3} M (1.07 curie [Ci]/L). They

observed that the precipitate began to show discoloration, changing from pink Am^{3+} to brown AmO_2^+, within 24 hours (h), with quantitative oxidation of all the Am to AmO_2^+ within 1 week. Because Pu is more readily oxidized than Am, the expectation is that Pu could also be oxidized in irradiated brine. The metastability of Pu(VI) in the WIPP brine when no reducing agents were present was established and attributed to self-radiolysis effects of the ^{239}Pu isotope used (Reed, Okajima, and Richmann 1994; Reed et al. 2006).

Stadler and Kim (1988) also report the existence of higher oxidation states of Am, due to self radiolysis. Solubility experiments on $Am(OH)_3$(solid[s]) in 3 M NaCl resulted in much higher Am concentrations than was calculated from the solubility product. This difference was assigned to the radiolytic oxidation of Am^{3+} to AmO_2^+. Spectrophotometric evidence of AmO_2^+ species in solution was reported. The authors report the value of $\log_{10}K_{S,0} = -9.3 \pm 0.5$ for the reaction

$$AmO_2OH(s) \leftrightarrows AmO_2^+ + OH^- \qquad \text{(SOTERM.21)}$$

The solubility product of AmO_2OH(s) is in general agreement with other solubility studies on different pentavalent actinides.

These results show there is clearly a potential for oxidized, higher-valent actinides to form in brine when no reducing agents are present. This, however, needs to be interpreted in the context of the strong reducing agents and processes that will predominate in the WIPP, such as bioreduction (Section SOTERM-2.4.1.2), iron reduction (Section SOTERM-3.4.2), and reduction by organic complexants (Section SOTERM-2.3.4). WIPP-specific data show that the presence of reduced iron (Fe(II/0)) leads to a rapid reduction of Pu(VI) to Pu(IV) species under a wide range of anoxic conditions (Reed et al. 2006, Reed et al. 2009). These results are expected to extend to the Am(V) system, since this species is more readily reduced than Pu(V/VI). Reduced iron will also react with radiolytically generated oxidizing species, such as hypochlorite or hypobromite, to prevent their buildup in the brine solution with time. In summary, these WIPP-specific results show that the reductants present in WIPP waste (reduced metals and organics) will overwhelm potential radiolytic effects under the expected conditions in the WIPP, and a significant and sustained radiolytic enhancement of actinide solubilities is not predicted.

SOTERM-2.5 Changes in WIPP Conditions since the CRA-2004 and the CRA-2004 PABC

There are no significant changes in the WIPP repository conditions, chemistry, and processes since the CRA-2004 and the last PA performed (Leigh et al. 2005). Specifically, the assumptions and parameters given in Table SOTERM-1 are the same as those used for the CRA-2004 PABC. This applies to all the discussions in Section SOTERM-2.1, Section SOTERM-2.2, Section SOTERM-2.3, and Section SOTERM-2.4.

Three WIPP-relevant processes were reviewed and updated. First, actinide reduction is a direct consequence of microbial activity under anoxic conditions (see Section SOTERM-2.4.1). This, in fact, strengthens the current PA position that reducing conditions will be maintained in the WIPP, although this is not accounted for in PA. Second, there is an increased understanding of the effects of ionizing radiation on actinide speciation in sodium chloride brine systems (Section SOTERM-2.4.2). This leads to recognition of the role of hypobromite in WIPP-specific brines.

Additionally, WIPP-specific data show that the effects of radiolysis, which can create locally more oxidizing zones in the repository, are readily overwhelmed by the effects of reduced iron. Third, further progress was made in understanding the reaction sequence and interactions of MgO in WIPP-relevant brine systems (see Section SOTERM-2.3.3).

The TRU inventory was updated. This update impacted the concentration of organic chelating agents (see Section SOTERM-2.3.6), the volume of the TRU waste inventory, and the amount of emplaced materials which increased the CPR inventory (see Section SOTERM-2.3.7).

It is important to note that the CRA-2004 PABC included changes to the CRA-2004 PA in response to comments received from the EPA (Cotsworth 2005). These are discussed in detail as part of the CRA-2004 PABC documentation (Leigh et al. 2005). The specific changes for CRA-2004 PABC that revised or clarified the microbial assumptions and input are as follows:

1. Gas generation rates were revised to account for slower, longer-term processes based on new WIPP-specific data (Nemer and Stein 2005; Nemer, Stein, and Zelinski 2005a).

2. All PA vectors are now assumed to be microbial (this was changed from a probability of 0.5 in CRA-2004 PA).

3. Gas generation is assumed to occur only through denitrification (~4%) and sulfate reduction (~96%). It is assumed that methanogenesis does not occur because sulfate is assumed to be always available for microbial processes.

SOTERM-3.0 WIPP-Relevant Actinide Chemistry

The speciation of actinides under WIPP-relevant conditions defines the source term for actinide release from the WIPP in release scenarios where dissolved actinide concentrations are important (e.g., DBR and transport through the Salado or Culebra). The key factors that establish the concentrations of dissolved actinides under subsurface conditions are known. The most important of these factors for the WIPP repository are listed below.

1. Actinide redox chemistry is a critical factor in establishing the concentration of actinides in brine. The solubility of reduced actinides (III and IV oxidation states) is significantly lower than oxidized forms (V and/or VI). In this context, maintaining reducing conditions in the WIPP and the strong coupling of the chemistry for reduced metals and microbiological processes with actinides are important.

2. The complexation of each actinide species is a critical factor in defining its solubility. For a given oxidation state, the inorganic and organic complexes present will define the solubility of the actinide. These complexants are in the preemplacement environment, are part of the TRU waste that is emplaced, or are produced as a result of subsurface processes, most notably microbial and corrosion processes.

3. Intrinsic and pseudoactinide colloid formation is a critical factor in defining the overall solution concentration of each actinide. The contribution of actinide colloids to the concentration of actinides in the WIPP is predicted to be significant. Many of the key TRU species in their expected oxidation states tend to form colloids or strongly associate with nonactinide colloids present (e.g., microbial, humic and organic).

The WIPP PA approach as established in the initial WIPP license application (U.S. Department of Energy 1996) and continued through the most recent PA calculations (Leigh et al. 2005) accounts for all three of these key factors.

The PA concept of actinide speciation in the WIPP is well grounded in what has been observed for actinide contaminants in near-surface groundwater. In natural systems, the following inorganic ligands are potentially important complexants of radionuclides in solution: CO_3^{2-}/HCO_3^-, OH^-, $C1^-$, SO_4^{2-}/S^{2-}, fluoride (F^-), and phosphate. Additionally, anthropogenic and bioderived chelating agents can strongly bind actinide species and will compete with the inorganic complexants present. Lastly, the tendencies of actinides to form intrinsic colloids and strongly associate or bind with colloidal particles are also well established. The relative importance of these complexants and processes depends on the pH, radionuclide oxidation state present, the presence of other metals, and the relative ligand concentrations. There are a number of general reviews on various aspects of actinide environmental chemistry (Allard 1982; Choppin, Liljenzin, and Rydberg 2004 [pp. 94–112]; Clark, Hobart, and Neu 1995; Banaszak, Rittmann, and Reed 1998; Runde 2000; Nitsche et al. 1992).

For the anoxic, reducing, and mildly basic brine systems expected in the WIPP (see Table SOTERM-1), the most important inorganic complexants are expected to be carbonate/bicarbonate and hydroxide. There are also important organic complexants that coexist in TRU waste with the potential to strongly influence actinide solubility. In this context, the

relative importance of actinides and overall oxidation state, based on the CRA-2004 PABC TRU waste inventory, with respect to the potential release of actinides from the WIPP, is:

Actinides: $Pu \approx Am >> U > Th >> Np \approx Cm$ (SOTERM.22)

Actinide Oxidation State: $An(III) > An(IV) >> An(VI) >> An(V)$ (SOTERM.23)

In the CRA-2004 PABC (Leigh et al. 2005), the contribution of Pu, Am, U, Th, Cm, and Np is expressly considered, although only Pu and Am contribute significantly to TRU release from the WIPP. The III oxidation state is the most important oxidation state based on current WIPP PA assumptions because Am always exists in the III state, Pu exists in the III state in 50% of the vectors, and the III oxidation state is more soluble than the IV (see Section SOTERM-4.0 for a more detailed discussion).

In this section, an update of the literature and a summary of new WIPP-specific data is provided (when available) for all the actinides that contribute in one way or another to the PA. Section SOTERM-3.1 gives an overview of the projected and current inventory of actinides in the WIPP; Section SOTERM-3.2, Section SOTERM-3.3, Section SOTERM-3.4, Section SOTERM-3.5, and Section SOTERM-3.6 contain an overview of the relevant environmental chemistry and WIPP-specific results for Th, U, Np, Pu, and Am/Cm, respectively; Section SOTERM-3.7 pertains to the complexation of actinides by organic chelating agents in the WIPP; Section SOTERM-3.8 provides an overview of the potential for the formation of actinide colloids in the WIPP; and Section SOTERM-3.9 is a summary of changes since the CRA-2004 and CRA-2004 PABC. An up-front overview of these sections appears in Table SOTERM-6. The PA implementation of this actinide environmental chemistry is discussed in Section SOTERM-4.0 and Section SOTERM-5.0.

SOTERM-3.1 Actinide Inventory in the WIPP

The actinide inventory for the WIPP, based on the Transuranic Waste Baseline Inventory Report-2004 inventory (U.S. Department of Energy 2006), is given in Table SOTERM-7. This is also the inventory used to calculate the CRA-2004 PABC (Brush and Xiong 2005b) actinide solubilities. Also included in this table are the calculated inventory limits of the various actinides and radionuclides considered by the WIPP PA.

Over long time frames, only Pu and Am are expected to make a significant contribution to releases from the WIPP. Curium (Cm), which is predominantly present as ^{244}Cm, is a factor of 10 below the calculated solubility for III actinides when fully dissolved and, with its very short half-life (18.11 years), will not be important beyond the 100-year period of institutional control. Although relatively large inventories of cesium (Cs) and strontium (Sr) are projected, these can only contribute significantly to the overall release from the WIPP for the first 100 years of repository history, so are not significant beyond the period of institutional control.

Table SOTERM-8 gives the panel-specific inventory of the actinides for Panels 1 and 2 in the WIPP. These data are based on characterization of containers in Panels 1 and 2 WIPP Waste Information System (WWIS). Also included in this inventory is the amount of key waste

Table SOTERM-6. Overview of the WIPP PA View/Role and Relevant Environmental Chemistry of the Key Actinide Species in the WIPP (References for Each Actinide are Provided in the Following Sections)

Actinide	WIPP PA View/Role	Environmental Chemistry
Thorium	Not a TRU component. Currently included in PA calculations, but not a significant contributor to actinide release. Used as an oxidation-state invariant analog for the IV actinides. Th data are used in Fracture-Matrix Transport (FMT) to calculate the solubility of Pu(IV), Np(IV), and U(IV).	Exists as Th^{4+} complexes and is sparingly soluble under a wide range of environmental conditions.
Uranium	Not a TRU component. Potentially useful as a VI analog for Pu(VI) species. Currently, U is conservatively assumed to be U(VI) in 50% of the PA vectors (set at a 1 mM solubility) and U(IV) in 50% of the PA vectors.	Exists as UO_2^{2+} and U^{4+} species that are strongly correlated with redox conditions. Can form highly insoluble U(VI) and U(IV) phases. Can persist up to mM concentrations in near-surface groundwater.
Neptunium	TRU component. Currently included in PABC calculations, but not a significant contributor to actinide release. Assumed to be IV in 50% of the PA vectors and V in 50% of the PA vectors. Expected to be in the IV oxidation state under the conditions expected in the WIPP.	Mobile and relatively soluble as the NpO_2^+ species under oxidizing conditions. Is fairly insoluble and immobile as Np^{4+} under reducing conditions.
Plutonium	TRU component. Major contributor to actinide release calculations. Assumed to be IV in 50% of PA vectors and III in the other 50% of PA vectors.	Relatively immobile and insoluble as a subsurface contaminant. Persists as Pu^{4+} except under biomediated, strongly reducing conditions where transitory Pu^{3+} species may be formed. Expected to be transported primarily through colloidal mechanisms.
Americium	TRU component. Major contributor to actinide release calculations. Exists in the III oxidation state in all vectors and its thermodynamic data is used by FMT for all III oxidation state calculations. Significant colloidal contribution due to strong association as a pseudocolloid.	Relatively immobile and insoluble as a subsurface contaminant. Persists as Am^{3+} complexes under a wide range of environmental conditions.
Curium	Small quantities of ^{243}Cm, ^{245}Cm, and ^{248}Cm are present in the WIPP. ^{244}Cm, although present, is not a TRU waste component due to its <20 year half-life. These are very minor contributors to actinide release. Chemistry is analogous to Am(III).	Not a very significant concern as a subsurface contaminant. Has the same chemistry as Am, so it will persist as a Cm^{3+} species.
Organic Chelating Agents	The effects of EDTA, citrate, oxalate, and acetate on actinide solubility are considered in WIPP PA. These are present in WIPP waste and it is assumed that they are neither destroyed nor created by WIPP-relevant subsurface processes.	EDTA can persist under a wide range of environmental conditions and strongly chelates actinides. Citrate, oxalate, and acetate will likely be degraded due to microbial activity.
Actinide Colloids	Pseudocolloids with actinides are formed. These are accounted for in WIPP PA and add to the conservatism of the actinide concentrations calculated.	Importance and role of An colloid-facilitated transport are the subject of much ongoing debate. Although colloids are formed, it is not clear that they lead to increased actinide migration.

Table SOTERM-7. WIPP Radionuclide Inventory (U.S. Department of Energy 2006) Decay-Corrected to 2002. This Inventory was the Basis of CRA-2004 PABC Calculations.

Radionuclide	Activity (Ci)	Amount (kg)	Element-Specific Inventory	Inventory-Defined Potential Solubility[a] (M)
Actinides				
^{229}Th	1.55E+00	7.82E-03	5.07 Ci 3.11E+04 kg	>> Solubility
^{230}Th	9.72E-02	4.71E-03		
^{232}Th	3.42E+00	3.11E+04		
^{233}U	1.23E+03	1.27E+02	1.68E+03 Ci 6.47E+05 kg	>> Solubility
^{234}U	2.27E+02	3.65E+01		
^{235}U	4.99E+00	2.31E+03		
^{236}U	2.78E+00	4.29E+01		
^{238}U	2.17E+02	6.45E+05		
^{237}Np	6.89E+00	9.77E+00	6.89 Ci 9.77 kg	4×10^{-6} M (≥ projected solubility)
^{238}Pu	1.45E+06	8.49E+01	4.22E+06 Ci 9.93E+03 kg	>> Solubility
^{239}Pu	5.83E+05	9.40E+03		
^{240}Pu	9.57E+04	4.20E+02		
^{241}Pu	2.09E+06	2.03E+01		
^{242}Pu	1.27E+01	3.23E+00		
^{244}Pu	5.53E-03	3.10E-01		
^{241}Am	4.89E+05	1.42E+02	4.89E+05 Ci 143 kg	6×10^{-5} M (≥ projected solubility)
^{243}Am	7.88E+01	3.95E-01		
^{244}Cm	7.26E+03	8.97E-02	7.26E+03 Ci 0.0897 kg	4×10^{-8} M
Fission Products[b]				
^{137}Cs	4.33E+05	5.02E+00	4.33E+05 Ci 5.02 kg	4×10^{-6} M
^{90}Sr	3.78E+05	2.77E+00	3.78E+05 Ci 2.77 kg	3×10^{-6} M

[a] Moles in the inventory divided by the minimum brine volume (10011 m^3)

[b] Fission products are not TRU, but are considered in the PA to calculate overall release

Table SOTERM-8. Total Amount (in Kilograms) of Key Waste Package Components and Actinides Present in WIPP Panels 1 and 2 (Based on Data in Lucchini et al. 2007)

Panel 1			
Radionuclides	**Amount in kg (Ci)**	**Materials**	**Amount (kg)**
^{241}Am	34.6 (1.19×10^5)	Iron-based metal alloys	3,327,871
Pu (total)	2,571	Aluminum-based metal alloys	5,459
^{239}Pu	2,416 (1.5×10^5)	Other metal alloys	46,793
U (total)	22,232	MgO	4,482,355
^{238}U	22,170 (7.5)	Cellulosics	706,141
^{237}Np	0.6 (0.42)	Plastic	522,688
Panel 2			
Radionuclides	**Amount in kg (Ci)**	**Materials**	**Amount (kg)**
^{241}Am	9.2 (3.2×10^4)	Iron-based metal alloys	4,922,035
Pu (total)	1,405	Aluminum-based metal alloys	17,730
^{239}Pu	1,306 (8.1×10^4)	Other metal alloys	121,526
U (total)	6,850	MgO	6,667,625
^{238}U	6,808 (2.3)	Cellulosics	477,213
^{237}Np	1.2 (0.85)	Plastic	876,399

components emplaced. From the perspective of actinide solubility and PA, the most important of these are MgO and iron. Over 8,000 metric tons of iron is already emplaced, contrasting with the much smaller amounts of TRU present (1.8 kg of Np, 43.6 kg of Am, and 3.8 metric tons of Pu). Approximately 11,000 metric tons of MgO are present. These data support and are consistent with current WIPP PA assumptions that sufficient MgO and an overwhelming amount of iron will be present in the WIPP to establish strongly reducing conditions and favorable carbonate levels.

SOTERM-3.2 Thorium Chemistry

Th is not a TRU component. An estimated 31 metric tons of Th will be in the WIPP. The release of Th as the ^{230}Th isotope was calculated in the CRA-2004 PABC and does not significantly contribute to the overall release of activity from the WIPP. Th is, however, important for the WIPP in that it is used as a redox-invariant analog for the IV actinides (Pu(IV), Np(IV), and U(IV)), and Th complexation data is used in the FMT code for the An(IV) solubility calculations (see Section SOTERM-4.4.3).

SOTERM-3.2.1 Thorium Environmental Chemistry

Th, under a wide range of conditions, has one stable oxidation state in aqueous solutions: the Th^{4+} tetravalent ion. For this reason, the environmental chemistry of Th is understood from the

perspective of the solubility and complexation of this species, which is also the species expected to be present in the WIPP environment when DBR and transport release scenarios are important.

Other oxidation states for Th in aqueous systems have been reported. Recent data by Klapötke and Schulz (1997) that suggests a Th^{3+} species as a somewhat stable species in slightly acidic solution is not correct; it has been discounted because the proposed reaction for the species' formation is shown to be thermodynamically impossible, and the azido-chloro Th^{4+} complex is incorrectly assigned to the Th^{3+} species (Ionova, Madic, and Guillaumont 1998).

The hydrolysis of Th^{4+}, as is true for all An(IV) species in the WIPP, is complex and a critically important interaction in defining the overall solubility of Th. This was recently investigated by Ekberg et al. (2000), Rai et al. (2000), Moulin et al. (2001), and Okamoto, Mochizuki, and Tsushim (2003) and critically reviewed by Neck and Kim (2001) and Moriyama et al. (2005). The authors have proposed a comprehensive set of thermodynamic constants that extends to all tetravalent actinides. The solubility products were determined for amorphous (am) $Th(OH)_4$ (Neck et al. 2002, Altmaier et al. 2005; Altmaier et al. 2006) and for crystalline ThO_2 (Neck et al. 2003), as well as for specific ion interaction theory parameters (Neck, Altmaier, and Fanghänel 2006). The thermodynamic stability constants are listed in Table SOTERM-9.

Table SOTERM-9. Thermodynamic Stability Constants for Key Th Hydrolytic Species

Hydrolytic Reaction/Species	Stability Constant
Mononuclear Species	
$Th(OH)_{4,am} \leftrightarrows Th^{4+} + 4OH^-$	$\log K_{s,am} = -47.8 \pm 0.3$
$Th(OH)_{4,cr} \leftrightarrows Th^{4+} + 4OH^-$	$\log K_{s,cr} = -53.2 \pm 0.4$
$Th^{4+} + OH^- \leftrightarrows Th(OH)^{3+}$	$\log \beta^0_1 = 11.8 \pm 0.2$
$Th^{4+} + 2OH^- \leftrightarrows Th(OH)_2^{2+}$	$\log \beta^0_2 = 22.0 \pm 0.6$
$Th^{4+} + 3OH^- \leftrightarrows Th(OH)_3^{+}$	$\log \beta^0_3 = 31 \pm 1$
$Th^{4+} + 4OH^- \leftrightarrows Th(OH)_{4,aq}$	$\log \beta^0_4 = 38.5 \pm 1$
Polynuclear Species	
$4Th^{4+} + 12OH^- \leftrightarrows Th_4(OH)_{12}^{4+}$	$\log \beta^0_{4,12} = 141$
$6Th^{4+} + 15OH^- \leftrightarrows Th_6(OH)_{15}^{9+}$	$\log \beta^0_{6,15} = 176$

The presence of carbonate in solution greatly increases the solubility of thorium dioxide (ThO_2). An increase by one order of magnitude of the carbonate concentration in the range of 0.1 – 2 M leads to a five-order-of-magnitude increase in the Th(IV) solubility due to the formation of mono- and penta-carbonate complexes. Östhols, Bruno, and Grenthe (1994) proposed the following equilibrium reactions and the corresponding stability constants:

$$ThO_2 + H^+ + H_2O + CO_3^{2-} \leftrightarrows Th(OH)_3\,CO_3^- \qquad \log K_{131} = 6.11 \pm 0.19 \qquad \text{(SOTERM.24)}$$

$$ThO_2 + 4H^+ + 5\,CO_3^{2-} \leftrightarrows Th(CO_3)_5^{6-} + 2H_2O \qquad \log K_{105} = 42.12 \pm 0.32 \qquad \text{(SOTERM.25)}$$

This speciation scheme, however, has been criticized in recent work (Altmaier et al. 2005) because it overpredicts the dependency of Th solubility on carbonate and underpredicts the effect

of hydrolysis at higher pH. That hydrolysis prevails at pH >10 is supported by relatively detailed experimental results (see Figure SOTERM-5). These data are explained by the predominance in this system of $Th(OH)(CO_3)_4^{5-}$ complex rather than $Th(CO_3)_5^{6-}$. A greater role for other ternary complexes of thorium (e.g. $Th(OH)_2(CO_3)_2^{2-}$), which are also likely to be present in the WIPP conditions, is also proposed, and formation constants for these complexation reactions are reported. The use of the pentacarbonyl complex for the IV actinides in the WIPP PA, for these reasons, is a conservative assumption that overpredicts the solubility of the IV oxidation state at pH > 10. A correction in the FMT database to the value of the $Th(OH)_4$(aqueous [aq]) to be consistent with Neck et al. (2002) was incorporated into the CRA-2004 PABC.

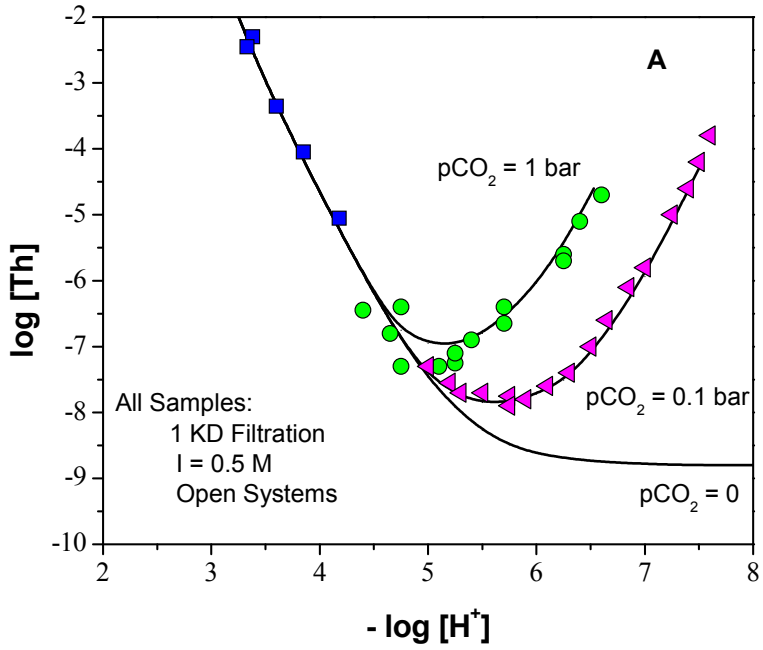
Oxyanions such as phosphate and, to a lesser extent, sulfate, also form Th^{4+} complexes that can precipitate at pH <5. The effect of phosphate on solubility of microcrystalline ThO_2 is very limited. The stability constants for $Th^{4+}/H_2PO_4^-$ and Th^{4+}/HPO_4^{2-} were reported (Langmuir and Herman 1980). Overall, the role of these oxyanions is expected to be unimportant for the mildly basic brines (pH ~8-10) present in the WIPP.

A new perturbation to the understanding of Th speciation, as well as other actinides in the IV oxidation state, is the recent observation that Ca, and to a lesser extent, magnesium (Mg), enhances Th solubility at pH >10 when carbonate is present. In recent publications, the formation of $Ca_4[Th(OH)_8]^{4+}$ and $Ca_4[Pu(OH)_8]^{4+}$ ion pairs in alkaline $CaCl_2$ solution is reported (Brendebach et al. 2007; Altmaier, Neck, and Fanghänel 2007). These species cause a rapid increase in the solubility of all tetravalent actinides at pH greater than 11. This increased solubility is only observed at $CaCl_2$ concentrations above 0.5 M for Th(IV), and correspondingly above 2 M for Pu(IV) species. This effect can be discounted for the WIPP PA because Ca concentrations in the WIPP are predicted to be approximately 14 mM or less with a pH of approximately 8.7. These are both well below the levels needed to see a significant effect for both Th and Pu.

Actinides in the IV oxidation state, because of the complexity of their solution chemistry and very high tendency towards hydrolysis, form colloidal species in groundwater. The potential effect of colloid formation on solubility of Th(IV) in concentrated NaCl and $MgCl_2$ solution was recently published by Altmaier, Neck, and Fanghänel (2004) and is shown in Figure SOTERM-6. In neutral-to-alkaline solutions, colloids could be formed as Th oxyhydroxide with log $[Th]_{(colloid\ [coll])} = -6.3 \pm 0.5$, independent of ionic strength. In Mg solutions, the formation of pseudocolloids (i.e., Th(IV)) sorbed onto $Mg_2(OH)_3Cl{\cdot}4H_2O$(coll) led to an apparent increase of the total Th concentration up to 10^{-5} M (Walther 2003, Degueldre and Kline 2007, Bundschuh et al. 2000). For these reasons, colloid formation is addressed in the WIPP PA.

SOTERM-3.2.2 WIPP-Specific Results since the CRA-2004 and the CRA-2004 PABC

There were no new WIPP-specific data on Th solubility and speciation obtained since CRA-2004. There were, however, a number of WIPP-relevant experiments reported in simplified brine systems, mainly by researchers at Karlsruhe. These results were summarized above in the context of their relationship to the environmental chemistry of Th in high-ionic-strength systems. These solubility data support the current WIPP PA assumptions on An(IV) solubility and extend



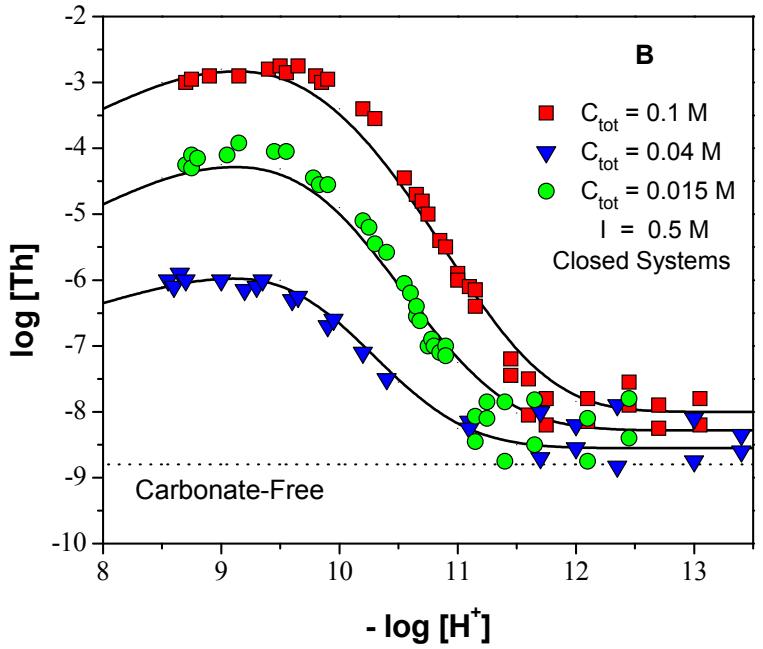


Figure SOTERM-5. Solubility of Amorphous Th(IV) Oxyhydroxide as a Function of Carbonate Concentration in 5 M for pH = 2–8 (A) and pH – 8–13.5 (B). The Solid Lines are the Calculated Solubilities (Based on Data in Altmaier et al. 2005).

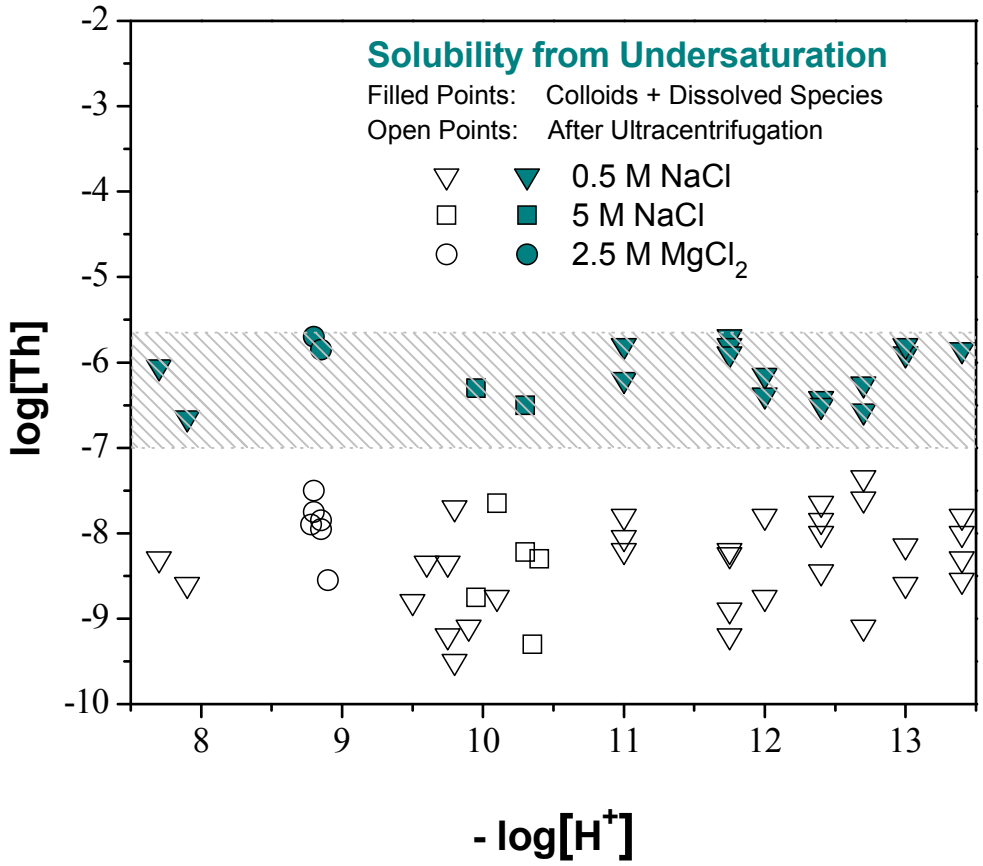


Figure SOTERM-6. Solubility of $Th(OH)_4(am)$ Determined from Undersaturation in 0.5 NaCl, 5.0 M NaCl, and 2.5 M $MgCl_2$. Filled Points: Total Th Concentrations (Including Colloids); Open Points: Th Concentrations Measured after Ultracentrifugation at 90,000 Revolutions Per Minute (5×10^5 g) (Based on Data in Altmaier, Neck, and Fanghänel 2004).

past project data to a broader range of pH and carbonate levels. These results also note that Ca-enhanced carbonate complexation, something that has only been understood in the last couple of years, can greatly increase the solubility of IV actinides. This complexation, however, requires relatively high pH in combination with very high Ca levels, something that is not expected in the WIPP. The expected pH and dissolved Ca levels predict little or no effect due to this complex.

SOTERM-3.3 Uranium Chemistry

U is not a TRU component, but is, by mass, expected to be the most prevalent actinide component in the WIPP. Current estimates predict that ~647 metric tons will be placed in the repository (see Table SOTERM-8). By mass, greater than 99% of this U will be the ^{238}U isotope, with minor amounts of ^{233}U, ^{234}U, ^{235}U, and ^{236}U. U does not contribute significantly to the calculation of actinide release through cuttings/cavings and spallings because of its low specific activity. U release can occur through the Culebra in very small amounts because of its potentially high solubility in the VI oxidation state.

U release, as the ^{234}U isotope, was calculated in the CRA-2004 PABC. In the WIPP PA, the oxidation state distribution assumption is that U speciates as U(IV) in 50% of the PA vectors and as U(VI) in the other 50% of the vectors. The U concentration for this oxidation state is currently set at 1 mM (U.S. Environmental Protection Agency 2005), since there is no An(VI) model in the WIPP. U(IV) solubility is calculated using the Th(IV) speciation data reported in the FMT model. For the current WIPP PA assumptions, uranium does not contribute significantly to the overall release of actinides from the WIPP.

SOTERM-3.3.1 Uranium Environmental Chemistry

U is by far the most studied of the actinides under environmentally relevant conditions. An extensive review of this chemistry, as it relates to the WIPP case, was completed (Lucchini et al 2009) and more general reviews can be found (Morss, Edelstein, and Fuger 2006, Guillaumont et al. 2003). An overview of U environmental chemistry is presented in this section.

SOTERM-3.3.1.1 Uranium Subsurface Redox Chemistry

U can theoretically exist in aqueous solution in the III, IV, V, and VI oxidation states (Hobart 1990; Keller 1971 [pp. 195–215]; Clark, Hobart, and Neu 1995). In the environment, however, only the IV and VI oxidation states, which exist as U^{4+} and UO_2^{2+} species, are present. U^{3+}, should it be formed, is metastable and readily oxidized in aqueous solution, and U(V) only exists as a very short-lived transient that instantaneously disproportionates to form U(IV) and U(VI) species. The corresponding reduction potential diagram for U at pH = 0, 8, and 14 is given in Figure SOTERM-7 (Morss, Edelstein, and Fuger 2006).

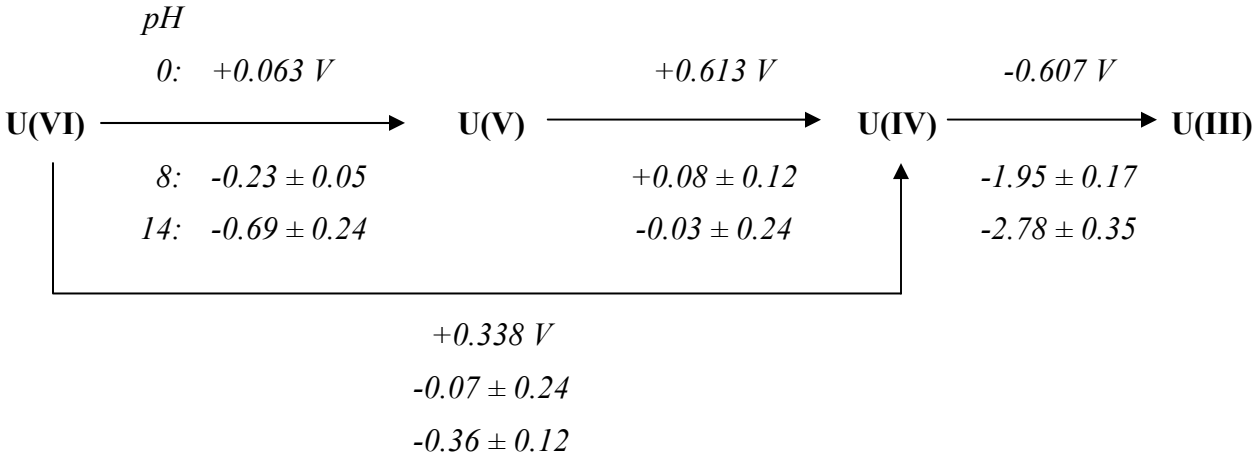


Figure SOTERM-7. Reduction Potential Diagram for U at pH = 0, 8, and 14 (Based on Data in Morss, Edelstein, and Fuger 2006). For the Expected Reducing and Mildly Basic pH Conditions in the WIPP, U(IV) is Predicted to be the Predominant Oxidation State.

Under oxidizing subsurface conditions typical of most near-surface groundwaters, U(VI) as UO_2^{2+} uranyl complexes, is the predominant oxidation state and is not easily reduced geochemically. Thermodynamically, uranyl species are stable even under mildly reducing

conditions and are not reduced by some Fe(II) phases (see Table SOTERM-3). In anoxic WIPP brine experiments with a hydrogen overpressure, uranyl persists as a stable hydrolytic or carbonate complex for over two years (Reed and Wygmans 1997).

In the anoxic and strongly reducing environment expected in the WIPP, however, potential reduction pathways exist. The two most important of these reduction pathways are reaction of uranyl with reduced iron phases (Fe[0/II]), and bioreduction through enzymatic pathways by anaerobic microbes, such as metal reducers, sulfate reducers, and methanogens (see Figure SOTERM-2). For these reasons, U(IV) is the oxidation state expected to predominate in the WIPP when brine inundation occurs.

The use of iron barriers in the removal of uranyl from groundwater is well established and has been reported for the removal of U(VI) from groundwater using zero-valent iron barriers (Gu et al. 1998, Fiedor et al. 1998, Farrell et al. 1999) and iron corrosion products formed in saline solution (Grambow et al. 1996). However, in those studies, it was unclear whether the removal of uranyl (UO_2^{2+}) resulted from reductive precipitation or from adsorption onto the iron corrosion products (Gu et al. 1998). In their experiments under saline conditions, Grambow et al. (1996) found that a large percentage of U was rapidly adsorbed onto the iron corrosion products consisting of over 97% hydrous Fe(II) oxide, and very little U(IV) was found. The complexity of the U-Fe-H_2O-CO_2 system explains the scarcity of the experimental data and the lack of a predominant mechanism (reduction-precipitation or adsorption) for the removal of U(VI) in the presence of iron.

Under anoxic conditions, Trolard et al. (1997) establishes that the corrosion of steel and iron generates Fe(II)/Fe(III) hydroxide species known as green rusts. Green rusts contain a certain amount of nonhydroxyl anions (carbonate, halides, or sulfate); they have a high specific surface area (Cui and Spahiu 2002) and a high cation sequestration capacity (O'Loughlin et al. 2003). They are considered metastable oxidation products of Fe(II) to magnetite Fe_3O_4 and Fe(III) oxyhydroxides (e.g., goethite α-FeOOH) (O'Loughlin et al. 2003). A few experimental studies demonstrate that U(VI) is reduced to U(IV) by green rusts (Dodge et al. 2002, O'Loughlin et al. 2003). The formation of a UO_2 phase was measured by Extended X-Ray Absorption Fine Structure (EXAFS) analysis (O'Loughlin et al. 2003) or by X-Ray Absorption Near Edge Structure (XANES) analysis and confirmed by X-ray Photoelectron Spectroscopy and Fourier Transform Infrared Spectroscopy (FTIR) (Dodge et al. 2002).

Banaszak, Rittman, and Reed (1998) have reviewed the important role of microbial processes in the reduction of multivalent metals under anaerobic/reducing conditions. For uranyl in particular, several studies exist that show that U(VI) is reduced to U(IV) species under a wide range of conditions (Lovley et al. 1991, Lovley et al. 1993, Barton et al. 1996, Huang et al. 1998, Abdelouas et al. 2000, Bender et al. 2000, Fredrickson et al. 2000). Most of this work pertains to groundwater bacteria, and is not directly applicable to the WIPP.

There are relatively few studies that investigate the interaction of U with the halophiles that are more typically present in WIPP brine. Some WIPP-relevant research was done (Francis et al. 2000), but this work was mostly focused on gas generation, not actinide interactions. It remains to be demonstrated that the mechanisms leading to the bioreduction of U(VI) also extend to the microbes present in the WIPP, although it is fully expected that this will be the case.

SOTERM-3.3.1.2 Solubility of U(IV)

Tetravalent U is expected to be the dominant oxidation state in the WIPP as a result of the reducing conditions that will prevail. The solubility of U(IV) under these conditions is analogous to that observed for Th (see Section SOTERM-3.2 and discussion in Section SOTERM-4.1) and is, in fact, calculated in the WIPP PA with the Th(IV) database.

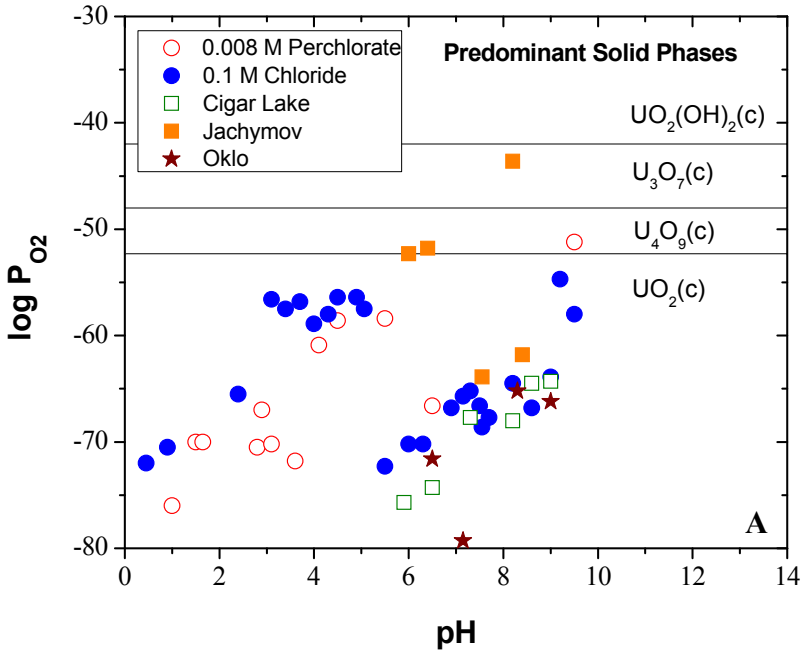
Under strictly reducing conditions, such as those expected in the WIPP, the most common and stable U solid is U dioxide (UO_2, uraninite) and associated hydrates. The aqueous species that predominates between pH 5-10, at low carbonate concentration, is the neutral tetra-hydroxide complex. This is described by the following equation:

$$U^{4+} + 4OH^- \leftrightarrow U(OH)_4(aq) \leftrightarrow UO_2(s) + 2H_2O \leftrightarrow UO_2 \cdot xH_2O\,(s) + (2-x)H_2O \quad \text{(SOTERM.26)}$$

The solubilities reported in the literature for hydrous $UO_2 \cdot xH_2O(s)$, amorphous (am) UO_2, or microcrystalline UO_2 are very scattered (Neck and Kim 2001). The explanation in the NEA review on U speciation (Guillaumont et al. 2003) is that the solubility data reported do not correspond to a unique material, but rather to a range of U oxide solids that have different thermodynamic stabilities. The species predominance diagrams for U are shown in Figure SOTERM-8 for aqueous and solid phases (Casas et al. 1998), based on the thermodynamic constants given for U at 25 ºC by Guillaumont et al. (2003).

Experimentally, U^{4+} is readily oxidized to UO_2^{2+}. This occurs even when only trace levels of oxygen, which are often below the limit of detection by most laboratory instrumentation, exist. This explains why there are relatively few studies of U^{4+}. It is also problematic because there are very large discrepancies in the literature as a result of experimental artifact. In particular, there are a number of published results (Rai, Felmy, and Ryan 1990, Gayer and Leider 1957, Ryan and Rai 1983, Tremain et al. 1981, Casas et al. 1998) that suggest amphotericity for U^{4+} at pH >10. This, however, likely resulted from combined effects of two experimental artifacts: (1) oxidation to UO_2^{2+}, which is much more soluble, and (2) the presence of carbonate, which is a strong complexant of U^{4+}.

The solubility of U(IV) phases were also determined in simplified brines under conditions that relate to the WIPP (Rai et al. 1997, Rai et al. 1998; Yajima, Kawamura, and Ueta 1995, Torerro et al. 1994). These data are shown in Figure SOTERM-9. Rai et al. (1997) determine the solubility of freshly precipitated $UO_2 \cdot xH_2O$(am) in NaCl and $MgCl_2$ solutions of various ionic strengths. They estimate the concentration of $U(OH)_4$(aq) in equilibrium with $UO_2 \cdot xH_2O$(am) to be about $10^{-8.0}$ M, and a number of data with greater concentrations in the neutral and alkaline range are ascribed to the presence of U(VI) in solution. This is in fair agreement with the value of $10^{-(8.7 \pm 0.4)}$ M proposed by Yajima, Kawamura, and Ueta (1995). It is important to note that U(IV) concentrations at pH >5 show no significant dependence on the initial solid phase (Figure SOTERM-9); both fresh precipitates in oversaturation experiments or electrodeposited microcrystalline UO_2(s) in undersaturation experiments gave the same results (Torrero et al. 1994).



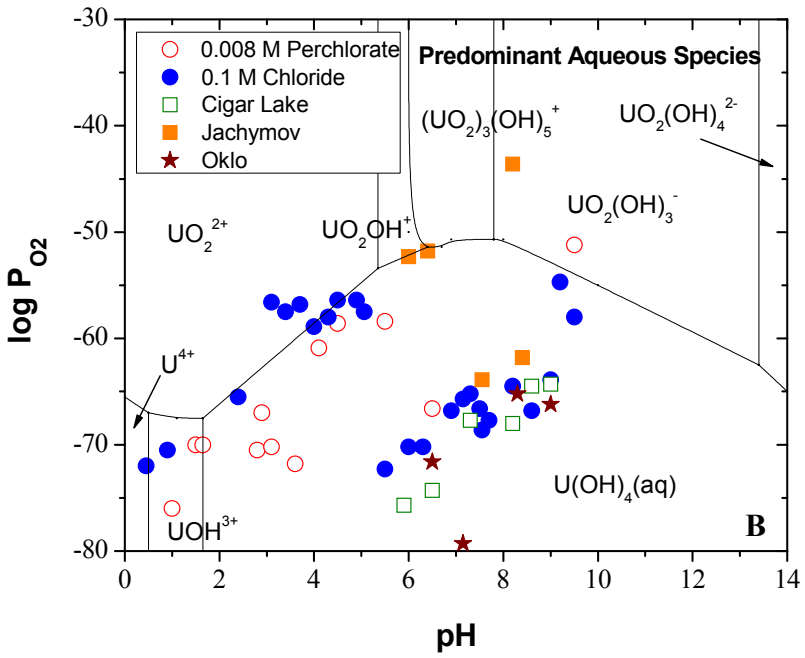


Figure SOTERM-8. Predominance Diagrams for U as a Function of Log P_{O2} and pH: (A) Predominant Solid Phases; (B) Predominant Aqueous Species. Experimental Log P_{O2} – pH Measurements of the Experiments from Casas et al. Open Dots: 0.008 M Perchlorate; Filled Dots: 1 M Chloride; Open Squares: Cigar Lake; Filled Squares: Jachymov; Stars: Oklo (Based on Data in Casas et al. 1998).

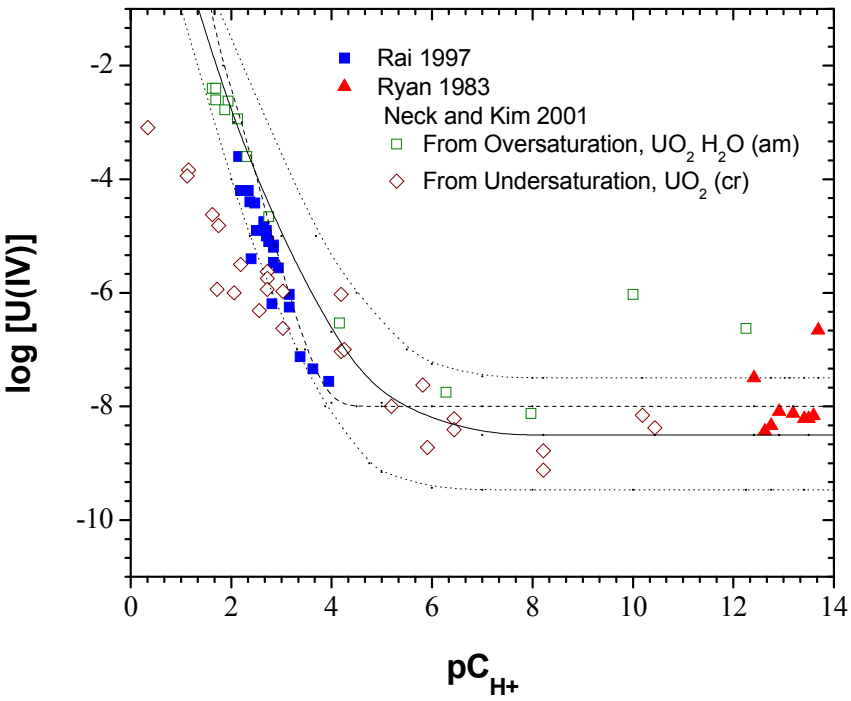


Figure SOTERM-9. Solubility of UO_2(s) as a Function of pH at 20–25 ºC (68–77 °F) in 1M NaCl (based on Neck and Kim 2001). The Experimental Data are from Ryan and Rai (1983), Rai et al. (1997), and Neck and Kim (2001). The Solid Line is Calculated by Neck with Log K_{sp} = (-54.5 ± 1.0) and the Hydrolysis Constants Selected in Neck and Kim (2001). The Dotted Lines Show the Range of Uncertainty. The Dashed Line is Calculated With the Model Proposed by Rai et al. (1997).

SOTERM-3.3.1.3 Solubility and Speciation of U(VI)

U(VI) phases and aqueous species, although not expected to predominate in the WIPP, could be present due to the localized effects of radiolysis (see Section SOTERM-2.4.2). The WIPP PA currently makes the conservative assumption that U(VI) species predominate in 50% of the PA vectors. The solubility of U(VI) is, however, not explicitly calculated in WIPP PA, since there is no model for actinides in the VI oxidation state. The potential contribution of U(VI) species to the overall solubility of U in the WIPP is implicitly considered in the WIPP PA in the 1 mM value for U solubility (U.S. Environmental Protection Agency 2005). Prior to this, the solubility of U was defined as 1.2×10^{-5} M based on an assessment of the literature and existing WIPP-relevant experimental data by Hobart and Moore (1996).

The role of carbonate (CO_3^{2-}) in the U(VI) solubility is indeed important (Clark, Hobart, and Neu 1995, Guillaumont et al. 2003). In the absence of competing complexing ligands, carbonate complexation will dominate the speciation of the uranyl ion under near-neutral pH conditions as long as there is ample carbonate-bicarbonate available. Complexation constants for binary U(VI) carbonate complexes at I = 0 M and 25 ºC (77 °F) are listed in Table SOTERM-10

Table SOTERM-10. Complexation Constants for Binary U(VI) Carbonate Complexes at I = 0 M and 25 ºC (Guillaumont et al. 2003)

Reaction and Solubility Product for UO_2CO_3(crystalline [cr])	
$UO_2CO_3(cr) \rightleftharpoons UO_2^{2+} + CO_3^{2-}$	$\text{Log } K^0_{SP(cr)} = -14.76 \pm 0.02$
Reactions and Formation Constants β^0_{nq} for $(UO_2)_n(CO_3)_q^{2n-2q}$	
$UO_2^{2+} + CO_3^{2-} \rightleftharpoons UO_2CO_3(aq)$	$\text{Log } \beta^0_{11} = 9.94 \pm 0.03$
$UO_2^{2+} + 2\ CO_3^{2-} \rightleftharpoons UO_2(CO_3)_2^{2-}$	$\text{Log } \beta^0_{12} = 16.61 \pm 0.09$
$UO_2^{2+} + 3\ CO_3^{2-} \rightleftharpoons UO_2(CO_3)_3^{4-}$	$\text{Log } \beta^0_{13} = 21.84 \pm 0.04$
$3\ UO_2^{2+} + 6\ CO_3^{2-} \rightleftharpoons (UO_2)_3(CO_3)_6^{6-}$	$\text{Log } \beta^0_{36} = 55.6 \pm 0.5$

(Guillaumont et al. 2003). The three monomeric complexes of general formula $UO_2(CO_3)$, $UO_2(CO_3)_2^{2-}$, and $UO_2(CO_3)_3^{4-}$ are present under the appropriate conditions. There is also evidence from electrochemical, solubility, and spectroscopy data that support the existence of $(UO_2)_3(CO_3)_6^{6-}$, $(UO_2)_2(CO_3)(OH)_3^-$, and $(UO_2)_{11}(CO_3)_6(OH)_{12}^{2-}$ polynuclear species, which can only form under the conditions of high-metal-ion concentration or high ionic strength (Clark, Hobart, and Neu 1995). At uranyl concentrations above 10^{-3} M, the trimeric cluster $(UO_2)_3(CO_3)_6^{6-}$ can also be present in significant concentrations. When the uranyl ion concentration begins to exceed the carbonate concentration, hydrolysis will play an increasingly important role (Clark, Hobart, and Neu 1995).

It is generally accepted that the major complex in solution at high carbonate concentrations is $UO_2(CO_3)_3^{4-}$ (Kramer-Schnabel et al. 1992, Peper et al. 2004). However, at I = 0.5 M and I = 3 M, the polynuclear $(UO_2)_3(CO_3)_6^{6-}$ species becomes an important competitor of $UO_2(CO_3)_3^{4-}$. Grenthe et al. (1984) indicated that the formation of $(UO_2)_3(CO_3)_6^{6-}$ is favored at high ionic strengths as a result of possible stabilization of the complex by ions of the background electrolyte.

The solubility of U(VI) in the WIPP is defined by the combined contribution of two processes: hydrolysis with oxyhydroxide phase formation, and carbonate complexation with U carbonate phase formation. These are both very complex systems, and there are many proposed speciation schemes. In carbonate-free or low-carbonate solutions, the speciation of U(VI) is dominated by hydrolysis.

The solubility of uranyl carbonate UO_2CO_3 and the formation constants for the associated complexes were determined at 25 ºC (77 °F) in 0.1M $NaClO_4$ by Kramer-Schnabel et al. (1992). The authors noticed a change in the composition of the solid when the pH increased above 6.5. Using ^{14}C-labeled carbonate and X-ray analysis, they observed that UO_2CO_3 changed to a mixed uranyl-hydroxy-carbonate at pH >6.5 and to uranyl hydroxide or sodium diuranate at pH >8. The different transition states were not characterized in detail. In an earlier investigation, the existence of hydroxycarbonato uranyl species in the neutral pH range at 25 ºC was also determined. An important observation from these studies is that the U concentration in solutions decreases with increasing ionic strength when UO_2CO_3 is the major aqueous U species.

At high pH, Yamamura et al. (1998) demonstrate that hydrolysis overwhelms carbonate complexation. The solubility of U(VI) was measured in highly basic solutions ($11 \leq pH \leq 14$) at an ionic strength of I = 0.5 – 2 M over a wide range of carbonate concentrations (10^{-3} – 0.5 M) using both oversaturation and undersaturation approaches. In the oversaturation experiments, the solubility of U(VI) decreased with increasing equilibration time from one week to one year and was explained as an increase in the crystallinity of the solid phase with aging. The solid phase was identified as $Na_2U_2O_7 \cdot xH_2O$ by XRD. The undersaturation experiments conducted for one month with the solid phase indicated a rapid equilibrium. These data were interpreted by considering the formation of $UO_2(OH)_3^-$, $UO_2(OH)_4^{2-}$, and $UO_2(CO_3)_3^{4-}$ (Yamamura et al. 1998).

The influence of carbonate on U(VI) solubility in highly saline solutions was investigated by Lin et al. (1998) and Fanghänel and Neck (2002). Lin et al. (1998) evaluated U(VI) solubilities with up to 5M NaCl in a range of carbonate concentrations. At carbonate-ion concentrations greater than 10^{-7} M, $UO_2(CO_3)_3^{4-}$ was the dominant U(VI) complex in solution. At higher CO_2 partial pressures, the solubility-controlling solid phase was found to be UO_2CO_3(s), whereas at lower partial pressures, sodium uranate was identified as the solid phase in NaCl-saturated solutions. This study, although interesting, is of questionable use to the WIPP because the details were not fully published.

The solubility-controlling U(VI) solid phases are schoepite-type phases $UO_3 \cdot xH_2O$(s). This was reported by Sandino and Grambow (1994) as corrosion products of spent fuel in long-term leaching experiments under oxidizing conditions. However, in complex systems where many other elements are present, the uranyl hydroxides are not predicted to predominate in the long term. Specifically, they undergo a transformation into different phases that can include divalent cations (e.g., Ca^{2+}, Pb^{2+}, Ba^{2+}) and monovalent cations, such as K^+ or Na^+ (Sandino and Grambow 1994). The transformation reaction is generally dependent on pH and groundwater composition. As an example, Fanghänel and Neck (2002) observed the formation of a sodium (Na) uranate phase [clarkeite, $NaUO_2O(OH) \cdot H_2O$] in 5M NaCl experiments at pH 8. The extent to which these alkali uranate salts contribute to U solubility in the higher-complexity brines expected in the WIPP is not clear.

The U solid phases formed in the presence of carbonate were also investigated. Meinrath and Kimura studied solid-liquid equilibria of U(VI) at 100, 0.98 and 0.03% CO_2 partial pressures in the pH range 2.8-4.6 in 0.1M $NaClO_4$ solution at (24 ± 2) ºC (Meinrath and Kimura 1993). The solid phase formed under 100% CO_2 partial pressure was found as a faint, yellow-greenish powder. It was identified by XRD as rutherfordine (UO_2CO_3). At 0.98 and 0.03% CO_2 partial pressures, the solids generated were bright yellow, and identified by XRD as schoepite ($UO_3 \cdot 2H_2O$). The authors established that the phase transition between these two phases (rutherfordine and schoepite) occurs at a CO_2 partial pressure of 2.8% (Meinrath and Kimura 1993). This estimated value is in agreement with the experimental results of Grenthe et al. (1984) who report rutherfordine as a solubility-limiting solid phase at partial pressures ≥ 4.8% CO_2.

SOTERM-3.3.2 WIPP-Specific Results since the CRA-2004 and the CRA-2004 PABC

The solubility of U(VI) in the absence of carbonate was extensively studied since CRA-2004 in simulated GWB and ERDA-6 brine (Lucchini et al. 2009). An overview of these results is shown in Figure SOTERM-10, and a comparison of these results with other solubility data in the literature is given in Table SOTERM-11. The measured U(VI) solubilities were about 10^{-6} M in GWB brine at $pC_{H+} \geq 7$ and about 10^{-8} - 10^{-7} M in ERDA-6 at $pC_{H+} \geq 8$. These results put an upper bound of ~10^{-5} M for the solubility of uranyl in the carbonate-free WIPP brines for the investigated range of experimental conditions. At the expected pC_{H+} in the WIPP (~8.7), the measured uranium solubility was between 10^{-7} M and 10^{-6} M.

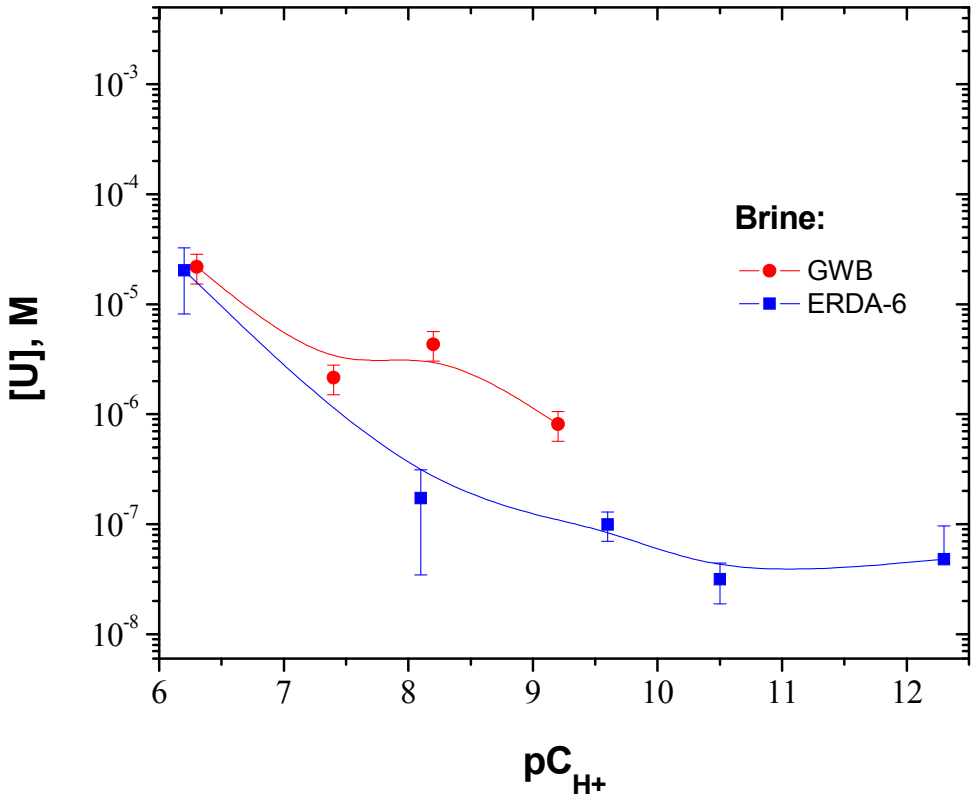


Figure SOTERM-10. U(VI) Solubility in Carbonate-Free Brine Versus pC_{H+} for GWB (Top Curve) and ERDA-6 (Bottom Curve). These Correspond to Data Obtained After 705-day Equilibration Using an Oversaturation Approach (Lucchini et al. 2009).

Table SOTERM-11. Solubility of U(VI) in High-Ionic-Strength Media

U(VI) Concentration (M)	pC_{H+}	Solution	Time (days)	Solid	Reference
$(2.8 \pm 1.8) \times 10^{-5}$	8.9	5M NaCl	≈ 50	$Na_{0.68}UO_{3.34} \cdot (2.15 \pm 0.10)H_2O$	Diaz-Arocas and Grambow 1998
$(8.2 \pm 4.6) \times 10^{-5}$	7.6	5M NaCl	≈ 110	$Na_{0.45}UO_{3.23} \cdot (4.5 \pm 0.1)H_2O$	Diaz-Arocas and Grambow 1998
$(4.2 \pm 1.9) \times 10^{-4}$	7.1	5M NaCl	≈ 170	$Na_{0.29}UO_{3.15} \cdot (2.9 \pm 0.2)H_2O$	Diaz-Arocas and Grambow 1998
$(2.8 \pm 0.9) \times 10^{-6}$	6.5	5M NaCl	≈ 170	$Na_{0.14}UO_{3.07} \cdot (2.5 \pm 0.1)H_2O$	Diaz-Arocas and Grambow 1998
$(1.82 \pm 0.01) \times 10^{-3}$	8.4	Brine (air atmosphere)	100	α-schoepite (oversaturation)	Yamazaki et al. 1992
$(1.81 \pm 0.01) \times 10^{-3}$	8.4	Brine (air atmosphere)	100	α-schoepite (oversaturation)	Yamazaki et al. 1992
$(1.40 \pm 0.05) \times 10^{-3}$	8.4	Brine (air atmosphere)	244	α-schoepite (undersaturation)	Yamazaki et al. 1992
$(1.80 \pm 0.05) \times 10^{-3}$	8.4	Brine (air atmosphere)	244	α-schoepite (undersaturation)	Yamazaki et al. 1992
$(3.8 \pm 0.4) \times 10^{-7}$	10.4	Brine (initial 0.11mM HCO_3^-)	150	$Mg(OH)_2$ and $K_2U_2O_7$ (oversaturation)	Yamazaki et al. 1992
$(3.1 \pm 0.3) \times 10^{-7}$	10.4	Brine (initial 0.11mM HCO_3^-)	150	$Mg(OH)_2$ and $K_2U_2O_7$ (oversaturation)	Yamazaki et al. 1992
$(1.7 \pm 1.4) \times 10^{-7}$	8.1	ERDA-6	705	To be determined (oversaturation)	Lucchini et al. 2009
$(9.9 \pm 3.0) \times 10^{-8}$	9.6	ERDA-6	705	To be determined (oversaturation)	Lucchini et al. 2009
$(3.1 \pm 1.3) \times 10^{-8}$	10.5	ERDA-6	705	To be determined (oversaturation)	Lucchini et al. 2009

The most important observations from these U(VI) solubility studies were

- The measured solubility of U(VI) in the absence of carbonate was ~10 – 100 times lower that those reported by others in the literature and well below the current 1 mM limit used in the WIPP PA (which applies to all conditions, including carbonate). These lower solubilities reflect the lack of oxygen and carbonate in the brine systems investigated.

- U(VI) solubility does not exhibit amphoteric behavior.

- A difference in U(VI) solubility between the two brines investigated was noted, with U concentrations in GWB ~10 times higher at pH > 8. This is caused by the complexation of U(VI) with the higher borate and sulfate concentrations in GWB.

The new WIPP-specific data do not address the more important issue of the effects of carbonate complexation on U(VI) solubility, but they do establish a baseline to determine this effect.

SOTERM-3.4 Neptunium Chemistry

The WIPP repository is projected to contain ~10 kg of Np, primarily as the ^{237}Np isotope (see Table SOTERM-8). Its inventory increases with time from the decay of ^{241}Am and the possibility of ^{238}U (n, 2n) reactions, but this increase is projected to be less than a factor of two during the regulatory period of the WIPP. In the WIPP PA, Np speciates as Np(IV) in 50% of the PA vectors and as Np(V) in the other 50% of the PA vectors. The contribution of Np to actinide release from the WIPP was included in the CRA-2004 PABC (Brush and Xiong 2005a; Leigh et al. 2005) calculation, but its effect on release was negligible. Arguments have also been made that it should be excluded from consideration in the WIPP PA based on its low inventory (Brush and Garner 2005).

SOTERM-3.4.1 Neptunium Environmental Chemistry

The environmental chemistry of Np is somewhat unique in the actinide series as a result of the relatively high stability of the NpO_2^+ species, which is in the V oxidation state, under a wide range of conditions typically found in the subsurface. This oxidation state is prevalent when oxidizing conditions predominate (Hobart 1990). It is mobile because it has a relatively high solubility and it is not strongly sorbed or complexed. It does not hydrolyze strongly, with little or no measurable hydrolysis until pH >7 (Neck, Kim, and Kanellakopulos 1992; Itagaki et al. 1992). Much of the complexation data for inorganic and organic complexes for Np pertains to the V oxidation state for this reason (Lemire et al. 2001). The log K_{sp} for NpO_2OH (s) is 4.5 ± 0.06 (Neck, Kim, and Kanellakopulos 1992).

Np can, however, actually exist in up to five oxidation states in aqueous media. The redox potentials under basic conditions are (Marinot and Fuger 1985):

$$NpO_5^{3-} \xrightarrow{+0.58\ V} NpO_2(OH)_2 \xrightarrow{+0.6\ V} NpO_2OH \xrightarrow{+0.3V} NpO_2 \xrightarrow{-2.1V} Np(OH)_3 \quad \text{(SOTERM.27)}$$

Only the Np(IV) and Np(VI) oxidation states, in addition to Np(V), can exist under the right conditions in reducing or oxidizing groundwater (Hobart 1990; Keller 1971 [pp. 195–215]; Clark, Hobart, and Neu 1995). These exist as Np^{4+} complexes and NpO_2^{2+} complexes. Np(VI), unlike Np(V), is strongly hydrolyzed at near-neutral pH and is readily reduced by many constituents typically found in groundwater (e.g., organics and most reduced metals). For these reasons, it does not tend to persist in groundwater under most conditions.

Under reducing anoxic conditions, Np^{4+} species can predominate. These Np^{4+} species readily undergo hydrolysis and are comparable to Pu^{4+} in this regard. This system is highly irreversible

and probably polymeric in nature, as is observed for Pu^{4+}. The measured solubility of Np^{4+} is $10^{-8.5}$ to $10^{-8.1}$ M with $Np(OH)_4$, not $Np(OH)_5^-$, as the predominant aqueous species (Rai and Ryan 1985, and Eriksen et al. 1993). The importance and predominance of the Np(IV) oxidation state in reducing conditions is even more pronounced when anaerobic bacteria are present. Np(V) was readily reduced by sulfate-reducing bacteria (Banaszak, Reed, and Rittmann 1998) and methanogenic consortia (Banaszak et al. 1999), and precipitated as Np(IV) solids.

In WIPP-specific experiments, Reed and Wygmans (1997) found spectroscopic evidence for reduction of Np(VI) to Np(V) in ERDA-6 (Castile) brine at pH 10, and have observed complete reduction of Np(VI) to Np(V) in G-Seep (Salado) brine at pH 7 when no iron or microbial activity were present. In the presence of oxalate, citrate, and EDTA, Reed and Wygmans (1997) have observed rapid and complete reduction of Np(VI) to Np(V) coupled with a slower formation of Np(IV) species. The stability of Np(V) under these conditions is further confirmed by Neck, Runde, and Kim (1995), who showed that Np(V) carbonate complexes are stable in 5M NaCl.

In the expected WIPP environment, however, where anoxic and reducing conditions with microbial activity and reduced iron are expected to be present, Np(IV) is expected to be the predominant oxidation state (Rai and Ryan 1985, Rai, Strickert, and McVay 1982a, Kim et al. 1985, Pryke and Rees 1986). This is based on studies of the solubility of NpO_2OH in 1 M and 5 M NaCl solutions at pH 6.5 where the reduction of Np(V) to Np(IV) was observed (Kim et al. 1985, Neck, Kim, and Kanellakopulos 1992).

SOTERM-3.4.2 WIPP-Specific Results since the CRA-2004 and the CRA-2004 PABC

There are no new WIPP-relevant results on the chemistry and speciation of Np since CRA-2004 and the CRA-2004 PABC.

SOTERM-3.5 Plutonium Chemistry

Pu is a key TRU component that contributes significantly to the potential for TRU release from the WIPP under all release mechanisms considered by PA. Pu isotopes, estimated to be ~10 metric tons at the time of closure, represent approximately 89% of the Ci content for actinides in TRU waste (see Table SOTERM-7). There are five isotopes of Pu that make a significant contribution to the Pu inventory, but ^{239}Pu, ^{238}Pu, and ^{241}Pu are the major contributors to the Ci content. Under the conditions expected in the WIPP, Pu(IV) is expected to be the predominant oxidation state (Weiner 1996). A more extensive review of Pu subsurface speciation issues as they pertain to the WIPP case was completed (Reed et al. 2009).

In the WIPP PA, all of the Pu is assumed to be reduced and present in the III or IV oxidation state. Half of the PA vectors contain 100% Pu(III), with the other half of the vectors containing 100% Pu(IV) species. Because the solubility of Pu(III) is roughly 10 times higher, the assumption that it is present is a conservatism built into the WIPP PA. The two higher-valent Pu oxidation states, Pu(V) and Pu(VI), are not considered in the PA because they cannot persist under the expected reducing and anoxic conditions in the WIPP.

SOTERM-3.5.1 Plutonium Environmental Chemistry

Generally, Pu can exist in oxidation states III, IV, V, VI, and VII (Katz, Seaborg, and Morss 1986, p. 781). Of these, only Pu(V), Pu(IV), and Pu(III) are expected to be important under environmentally relevant oxidizing and reducing conditions. Pu(VII) is very unstable and exists only in extremely basic solutions (for example, 7 M NaOH) that are not expected in the WIPP. Pu(VI) can persist in the WIPP in the absence of reductants, but is readily reduced in the presence of Fe(II/0) species, reduced by many organic chelators (Reed et al. 1998), and reduced in anaerobic, biologically active systems (Reed et al. 2007; Icopini, Boukhalfa, and Neu 2007). The reduction of Pu(VI), under WIPP-relevant conditions, was shown by Clark and Tait (1996), Reed and Wygmans (1997), and Reed et al. (2007).

SOTERM-3.5.1.1 Importance of Redox for Plutonium Speciation

The role and importance of redox reactions in determining actinide mobility and solubility are beyond question (Van Luik et al. 1987; Allard 1982; Choppin and Rao 1992). The redox potentials for the various oxidation states at pH 7 are (Cleveland 1979, pp. 11–46)

$$PuO_2(OH)_2\,(aq) \xrightarrow{+0.77\ V} PuO_2^{+} \xrightarrow{+1.11\ V} PuO_2{\cdot}H_2O\,(s) \xrightarrow{-0.63\ V} Pu^{3+} \qquad \text{(SOTERM.28)}$$

$$+0.94\ V$$

A typical phase diagram for Pu in groundwater that illustrates the importance of redox is shown in Figure SOTERM-11.

Higher-valent Pu, specifically Pu(V) and Pu(VI), can be present in near-surface oxidizing groundwaters (Orlandini, Penrose, and Nelson 1986). The association of Pu(V) with organic colloidal material was proposed as the mechanism by which subsurface migration occurred. Pu(VI), in near-neutral systems, is strongly and irreversibly hydrolyzed (Okajima and Reed 1993). It is also readily reduced by organics and reduced metal species even when oxygen is present to form Pu(V), and is not generally stable under most groundwater-relevant conditions.

Pu(V), by analogy with Np(V), does not undergo hydrolysis until pH >7 and tends to form weak complexes. It readily disproportionates to form Pu(IV) and Pu(VI) at high concentrations and is relatively easy to reduce in the environment under anoxic conditions. Fe^{2+}(aq), Fe(II) minerals, and metallic iron reduce Pu(V) to Pu(IV).

In geochemical systems, redox control is often interpreted in terms of the iron, and in a broader sense, reduced metal, mineralogy, and associated aqueous chemistry (Sanchez, Murray, and Sibley 1985, White, Yee, and Flexser 1985). In the WIPP case, iron will undergo anoxic corrosion, producing Fe^{2+}. Both metallic iron (Fe^0) and Fe^{2+} have been shown to quantitatively reduce Pu(VI) in the WIPP brines to either Pu(IV) or Pu(III). Clark and Tait (1996) and Felmy et al. (1996) have experimentally observed the reduction of Pu(VI) carbonates by either Fe^0 or Fe^{2+} to Pu(IV). In the absence of carbonates, a quantitative reduction of Pu(VI) is also observed, but the oxidation state of the resulting species cannot be definitively determined because its

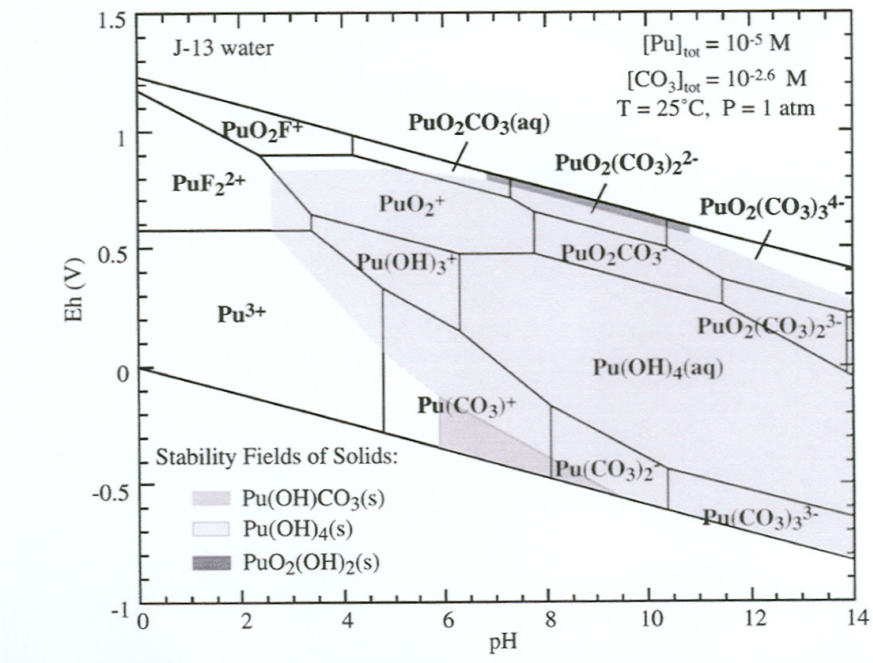


Figure SOTERM-11. Speciation Diagram for Plutonium in Carbonated Low-Ionic-Strength Groundwater (Based on Data Presented in Runde et al. 2002). This Illustrates the Expected Lower Solubility of Reduced Pu, Shows Pu(IV) Rather Than Pu(III) Species at Near-Neutral pH, and Suggests That the Dominant Pu Species in the pH 8-9 Range are Hydrolytic Species with Lesser Contributions From Carbonate.

concentration is below the lower detection limit of the oxidation state analytical process (about 10^{-9} M). However, since this concentration is well below the expected solubility of Pu(V) species, it was reasonably assumed that the Pu must have been reduced to either the IV or III oxidation state. Neretnieks (1982) has shown that when dissolved actinides in moving groundwater came in contact with Fe(II), the actinides were reduced to a much-less-soluble oxidation state and precipitated.

Pu(III) is not predicted to be stable under the expected WIPP conditions. There are some mechanisms, however, identified in which Pu(III) species can be formed. Felmy et al. (1989) observed some Pu(III) in the WIPP brines at neutral and slightly basic conditions. PA conservatively takes account of these minor mechanisms by assuming that Pu is speciated as Pu(III) in 50% of the PA vectors.

SOTERM-3.5.1.2 Bioreduction of Higher-Valent Plutonium

Comprehensive and critical reviews of how actinide species and microorganisms interact have been published (Banaszak, Rittmann, and Reed 1998; Neu, Ruggiero, and Francis 2002). General aspects of this were discussed in Section SOTERM-2.4.1.2. Additionally, the important role of microbial activity through biotic transformations (Francis 1990; Zitomer and Speece 1993; Banaszak, Rittmann, and Reed 1998; Rittmann, Banaszak, and Reed 2002; Reed et al.

2007) in defining oxidation state distribution of multivalent metals and actinides has been recognized.

Although the bioreduction of uranyl and neptunyl species is well established, there are relatively few studies of the bioreduction of plutonyl species. Reed et al. (2007) demonstrate that *Shewanella alga*, a ubiquitous metal-reducing soil bacteria, reduces Pu(V) to Pu(III/IV) species. Icopini, Boukhalfa, and Neu (2007) have shown that *Geobacter* and *Shewanella odeinensis* also reduce higher-valent Pu to Pu(III/IV) species.

These Pu data are consistent with the oxidation state predictions in microbially active systems shown in Figure SOTERM-2. It is particularly important to note that Pu(IV) is the expected oxidation state under a wide range of anoxic subsurface conditions, with no Pu(V) or Pu(VI) species expected. The recent Pu bioreduction results confirm that highly reducing conditions are being generated by metal-reducing bacteria under anaerobic growth conditions and support the current WIPP PA assumption that higher-valent actinides cannot persist when the concentration of dissolved actinides is important and microbial activity is prevalent.

There are no studies on the bioreduction of Pu(V/VI) under WIPP-relevant conditions. Halophiles (Gillow et al. 2000) typically found and expected to predominate in the WIPP environment have not been studied in the context of their tendency and ability to reduce higher-valent actinides. Since there is a high expectation that geochemical reactions alone will produce an anoxic, strongly reducing environment in the WIPP, halophiles, by analogy, are also expected to cause the bioreduction of multivalent actinides in the WIPP by both indirect cometabolic and direct enzymatic pathways.

SOTERM-3.5.1.3 Thermodynamic Stability of Higher-Valent Plutonium: PuO_{2+x}

It has long been held that Pu oxide, as PuO_2, is the thermodynamically favored form of Pu oxide. This oxide is likely the predominant form of Pu in TRU waste and is believed to be the most important phase under WIPP-related conditions. In the last few years, however, there have been a number of studies that question this key and fundamental assumption.

Haschke, Allen, and Morales (2000) report that near-stoichiometric plutonium dioxide reacts with water vapor at temperatures between 25 °C and 350 °C (77 °F and 662 °F) according to the following reaction:

$$PuO_2(s) + xH_2O(g) \rightarrow PuO_{2+x}(s) + xH_2(g) \qquad \text{(SOTERM.29)}$$

Here, water vapor is reduced by polycrystalline PuO_2 to produce hydrogen (H) and a previously unknown higher-oxide PuO_{2+x} with x as large as 0.27. If only Pu(IV) and Pu(V) are present in $PuO_{2.27}$, this oxide has 46% Pu(IV) and 54% Pu(V). Once formed, the PuO_{2+x} may dissolve in contact with groundwater to form aqueous PuO_2^+ or PuO_2^{2+} species (Haschke and Ricketts 1995).

There remains some controversy about the mechanisms that led to the observation of higher-valent Pu in the PuO_{2+x}. This process only occurs under unsaturated conditions at high relative humidities. Haschke, Allen, and Morales (2000) argue that this conversion is due to a chemical

reaction (that is, the above reaction has a Gibbs energy less than zero) rather than a radiolysis-induced reaction because the reaction rate is temperature dependent. However, there seems to be some contribution from radiolysis in this process and this may be the dominant mechanism (LaVerne and Tandon 2002). Neither of these mechanisms are expected to impact WIPP repository performance.

The behavior of PuO_2 in contact with water was studied as a function of time by means of the short-lived isotope ^{238}Pu, as well as the longer-lived ^{239}Pu (Rai and Ryan 1982b). This study concluded that crystalline PuO_2, amorphous PuO_2, and amorphous $PuO_3 \cdot xH_2O$ all convert to a material intermediate between crystalline PuO_2 and a hydrated amorphous material that contains both Pu(IV) and Pu(VI). These authors hypothesized that alpha particles generated by ^{238}Pu or ^{239}Pu irradiated water to generate OH radicals that reacted to form Pu(V) and/or Pu(VI) on the oxide surface. These observations are why the formation of localized oxidizing zones, where some higher-valent Pu can persist, is recognized in the WIPP PA. Reduction of these species, however, leads to a reformation of Pu(IV) hydrous oxide precipitates.

The overall issue of a thermodynamic driver for higher-valent Pu oxides, although it has received much recent attention in the literature, is not yet resolved, but has a relatively insignificant impact on the WIPP regardless of the mechanisms at work. A prolonged unsaturated phase in the WIPP could lead to the formation of some PuO_{2+x}, but this will be quickly overwhelmed in an aqueous environment and the higher-valent Pu will be reduced to Pu(III/IV) species, as described in Section SOTERM-3.5.1.1 and Section SOTERM-3.5.1.2. Both DBR and transport-release scenarios assume brine inundation and, correspondingly, the rapid introduction of reducing conditions.

SOTERM-3.5.2 WIPP-Specific Results since the CRA-2004 and the CRA-2004 PABC

General studies of Pu in brine have been done by a number of investigators (Büppelmann et al. 1986; Büppelmann, Kim, and Lierse 1988; Clark, Hobart, and Neu 1995; Nitsche et al. 1992; Nitsche et al. 1994; Pashalidis et al. 1993; Villareal, Bergquist, and Leonard 2001; Reed et al. 1993; Reed, Okajima, and Richmann 1994; Reed and Wygmans 1997). There has also been an assessment of the actinide chemistry in the WIPP CCA (Oversby 2000; Brush, Moore, and Wall 2001; U.S. Environmental Protection Agency 2006). These studies confirm reduction of higher-valent Pu under the expected WIPP conditions and establish the key speciation trends for Pu in the WIPP. These trends, however, are captured in the WIPP PA through analogy with Am(III) for Pu(III) and with Th(IV) for Pu(IV).

WIPP-specific experiments and progress were made in two important areas since CRA-2004 and CRA-2004 PABC. The first is that a series of experiments to determine the solubility of neodymium (Nd) in the WIPP brine were completed (Borkowski et al. 2008). Nd is an oxidation-state-invariant analog for the III actinides and, in this context, is an analog for the solubility of Pu(III). These results are summarized in Section SOTERM-3.6.2 and support the current WIPP PA solubilities in the CRA-2004 PABC.

The second area of progress was in the completion and publication of WIPP-specific experiments that establish the reduction of higher-valent Pu(V/VI) species by reduced iron in the

brine. A series of WIPP-specific experiments performed by researchers at Argonne were confirmed and published (Reed et al. 2006). Additionally, experiments were performed to further confirm the reduction of higher-valent Pu and establish its reactivity with iron oxides (Reed et al. 2009).

Iron and lead (Pb) have an important role as reducing agents for Pu in the V and VI oxidation state. Under the conditions expected in the WIPP, iron can exist as Fe(0), Fe(II), and small amounts of Fe(III) species, and lead can exist as Pb(0) and Pb(II) species. The expected importance of these two metals is based on the redox-half-reaction potentials for the reduced metal oxidation states Fe(0/II) and Pb(0/II) relative to Pu(V/VI), and the significant amount of these two metals present in the WIPP. Whereas, for U, the existence of favorable redox potentials are somewhat dependent on the speciation of Fe and Pb, the existence of reduced iron and Pb always lead to favorable redox conditions for the reduction of both Pu(V) and Pu(VI) species under a wide range of conditions.

Two key figures from Reed et al. (2009) that demonstrate the reduction of Pu(V/VI) are shown (Figure SOTERM-12 and Figure SOTERM-13). In Figure SOTERM-12, both powder and coupon forms of zero-valent iron led to the rapid (few days) reduction of Pu(V/VI). XANES analysis confirmed that Pu(IV) was produced.

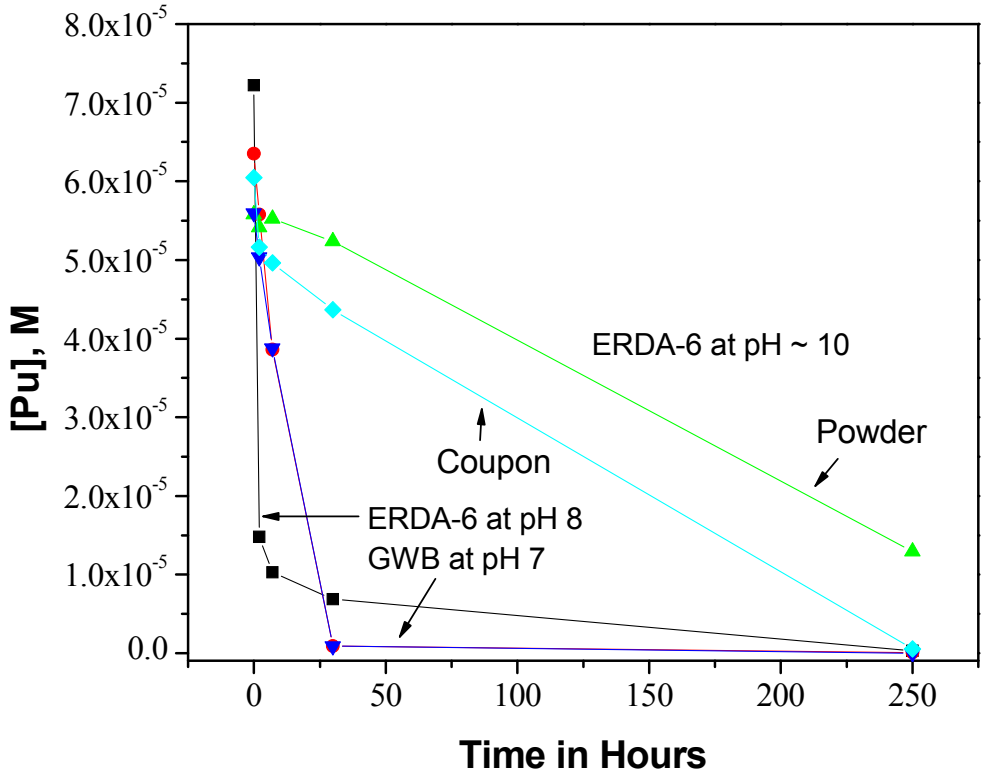


Figure SOTERM-12. Comparison of the Reactivity of Iron Powder and Iron Coupon Towards Pu(VI). Rapid Reduction/Removal from Solution was Observed at pH 7 (GWB brine) and pH 8 (ERDA-6 brine). This was Somewhat Slower at pH 10 in ERDA-6 Brine (Reed et al. 2009).

In Figure SOTERM-13, the effect of Fe(II) in the iron phases is shown. Overall, the reduction of Pu(V/VI) is observed over a wide range of conditions in the WIPP brine when either zero-valent iron, aqueous Fe^{2+}, or Fe(II) phases are present in the WIPP brine. When Fe(III) phases are present, only sorption, not reduction, is observed. These data provide strong and WIPP-specific evidence that reduced iron phases will reduce higher-valent Pu to Pu(IV) and support the current WIPP PA assumptions on oxidation state distribution.

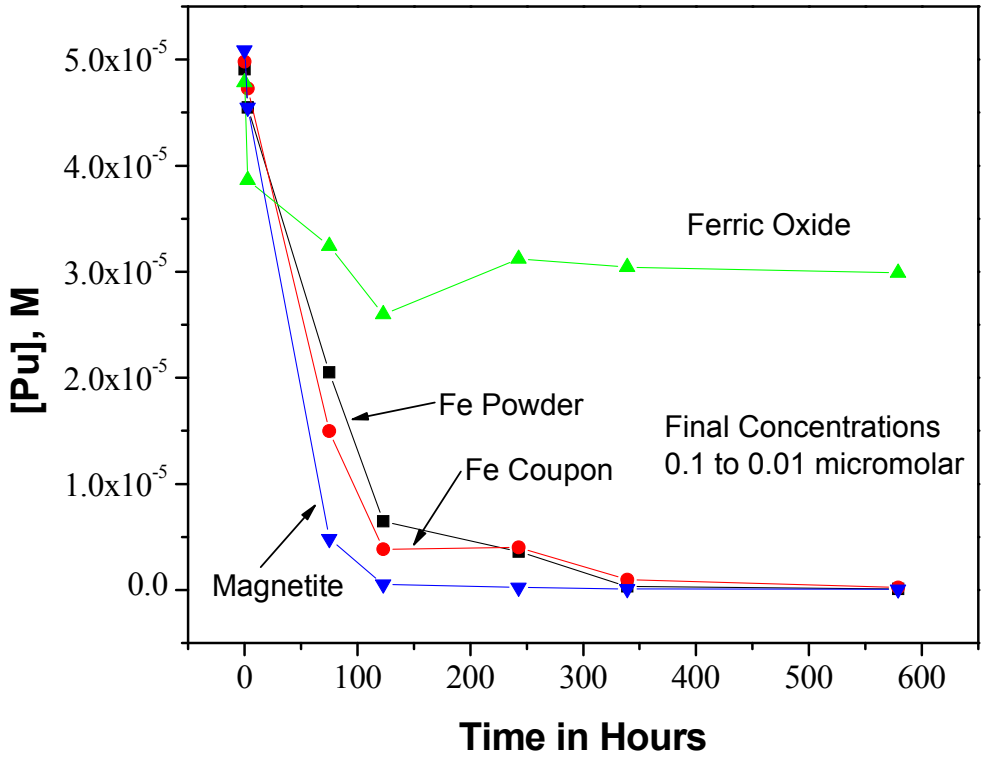


Figure SOTERM-13. The Concentration of Pu as a Function of Time in the Presence of Iron Powder, Iron Coupon, Ferric Oxide, and Magnetite (Mixed Iron Oxide) (Reed et al. 2009)

SOTERM-3.6 Americium and Curium Chemistry

There are relatively small quantities of Am in TRU waste (see Table SOTERM-8), but the high activity of ^{241}Am ($t_{½}$ = 432 years, 3.443 Ci/g) make Am a key contributor to potential actinide release from the WIPP. In the WIPP PA, Am is in the trivalent state in all vectors and the aqueous concentration consists of Am^{3+} complexes and colloidal species.

Cm is also present in very small quantities in the WIPP (Table SOTERM-8) and exists primarily as the ^{244}Cm isotope. The high activity of this isotope ($t_{½}$ = 18.11 years) makes Cm an important species in the WIPP at only the very early stages of repository history. It is essentially unimportant for the PA because it has decayed away by the end of the 100-year period for active institutional controls. However, other Cm isotopes with longer half-lives are present in the inventory and are considered by the WIPP PA. The environmental chemistry of Am and Cm are

very similar, and most of what is said in this section about the environmental chemistry of Am also applies to Cm.

A more detailed review of the literature for Am can be found as part of a recent WIPP report (Borkowski et al. 2008). The solubility of An(III) was measured in the WIPP brine over a wide range of conditions using Nd(III) as a redox-invariant analog. These data support current WIPP PA calculations for the solubility of Pu(III) and Am(III) in the WIPP brine and are also summarized in Borkowski et al. (2008).

SOTERM-3.6.1 Americium and Curium Environmental Chemistry

Am is a 5f electron element and, like other elements of the actinide group, can exist in aqueous solution in several oxidation states. The electrode potentials for some Am couples are presented in Figure SOTERM-14. The trivalent state of Am is the most stable aqueous oxidation state

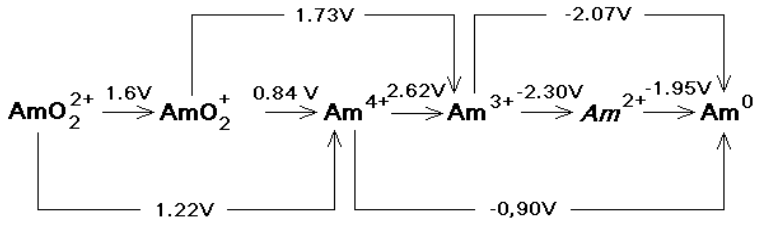


Figure SOTERM-14. Redox Potential for Some Am Redox Couples (Silva et al. 1995, p. 74)

(Katz, Seaborg, and Morss 1986, p. 912), and it is quite difficult to oxidize in aqueous solution (Hobart, Samhoun, and Peterson 1982). The trivalent Am ion has an ionic radius of 97.5 picometers (pm) (coordination number [CN]=6) and its chemical properties can be used as an analog for Pu(III), which has a similar ionic radius (100 pm at CN=6) and charge density, as well as for Cm(III) (97 pm at CN=6).

The *Am(II)* species is italicized to stress that it is only a transient species. As discussed by Marinot and Fuger (1985), there is evidence for the formation of *Am(II)* in aqueous perchlorate solution in the pulse radiolysis experiment. The half-life of this species was estimated to be approximately 5 μs. This species is not observed during the electroreduction of Am(III) to the metal in noncomplexing media (David, Maslennikov, and Peretrukhin 1990).

Cm is also distinguished by the relatively great stability of the III oxidation state with respect to oxidation or reduction (Katz, Seaborg, and Morss 1986, p. 970). The stability of Cm(III) may be attributed to the half-filled f-shell electronic configuration ($5f^7$). The oxidation of Cm(III) is achieved only with the strongest oxidizing agents, and only one report claims evidence for an oxidation state higher than IV (Korpusov, Patrusheva, and Dolidze 1975). The Cm(III) to Cm(IV) transition has not been successfully induced by ozone or electrochemically, and the Cm(IV) phosphotungstate produced by oxidizing with peroxysulfate is considerably less stable than the Am(IV) analog (Katz, Seaborg, and Morss 1986, p. 971). In the reducing environment of the WIPP repository, any higher-valent Cm produced radiolytically would be unstable. For all these reasons, the predominant oxidation state for Cm in the WIPP environment is Cm(III).

Higher-valent Am species have also been noted. Am(IV) species, with an ionic radius estimated by Shannon (1976) to be 85 pm, is only stable in the presence of strongly complexing anions such as carbonate, fluoride, phosphate, or phosphotungstate, and was never found in any appreciable amount in trivalent Am solutions.

The pentavalent and hexavalent dioxoamericium ions AmO_2^+ and AmO_2^{2+} can be generated under strongly oxidizing conditions. Free radicals produced from α particles in water readily reduce these dioxoamericium ions back to Am^{3+}. In concentrated NaCl solution, in which the radiolysis products are strong oxidants, pentavalent and hexavalent Am are the predominant species (Büppelmann et al. 1986). Without an oxidant, the pentavalent dioxoamericium ion slowly disproportionates to AmO_2^{2+} and Am^{3+}. These higher oxidation states are not stable in natural waters and can be readily reduced by action of reductants naturally present in those waters.

The speciation of Am in groundwater under mildly alkaline conditions is primarily defined by hydrolysis and carbonate complexation. Hydrolysis is generally represented by the following reaction:

$$Am^{3+} + nH_2O \leftrightarrows Am(OH)_n^{(3-n)} + nH^+ \qquad \text{(SOTERM.30)}$$

Silva measured the $^{243}Am(OH)_3$(crystalline [cr]) and $Nd(OH)_3$(cr) solubilities in 0.1 M $NaClO_4$ solution at 25±1 °C within the pH range 6 to 10 (Silva et al. 1995, p. 79-97). This is the only study with Am hydroxide using an x-ray-characterized crystalline solid. The solid phase was prepared by rigorously controlled, high-temperature transformation of $Am(OH)_3$(am). Optical viewing by SEM of the solid samples at the end of the solubility experiments showed no changes in the crystal. The use of the ^{243}Am isotope diminished α-particle damage of the crystal as a result of the 17-times-lower specific activity compared to ^{241}Am. The weakness of this experiment was the relatively short equilibration time of only 48 days. A log (K_{sp}) of 16.6 ± 0.4 was obtained for the $Am(OH)_3$ phase. The corresponding hydrolysis constants are listed in Table SOTERM-12. Similar values for Nd(III) hydrolysis were derived from the $Nd(OH)_3$(cr) solubility measurements.

Stadler and Kim (1988) investigate the pH dependence of $Am(OH)_3$(s) solubility in 0.1 M $NaClO_4$ and more concentrated Na chloride and perchlorate solutions at 25 ± 0.5 °C. The effect of α-induced radiolysis on solubility was also studied using different total concentrations of ^{241}Am. The solid phase was not characterized in this work. Although the solid used in this work was different than that used by Silva et al. (1995, pp. 275–76), the reported solubility products are in agreement. It is unclear, however, if the same phase controls the Am solubility in these two cases, because of markedly different preparation conditions of the starting solids.

Kim et al. (1984) measured the solubility of $Am(OH)_3$(s) at I = 0.1 and 0.3 M $NaClO_4$, in the absence of CO_2 and at $pCO_2 = 10^{-3.5}$ atm, and attributed the solubility measured in terms of contributions from the hydroxy, carbonato- and mixed Am hydroxy-carbonato complexes. No characterization of the solid was reported in this work, so it was assumed to be $AmCO_3OH$(s). Several investigators found that changes in the solid phase in aqueous suspensions of Am(III) hydroxide due to aging conditions become evident in hours and continue for weeks. Similar

Table SOTERM-12. Hydrolysis Constants of Am(III) (in Logarithmic Units) Corresponding to Equation (SOTERM.30)

$AmOH^{2+}$	$Am(OH)_2^{+}$	$Am(OH)_3(aq)$	Medium	Reference
-7.93 ± 0.35	-14.77 ± 0.25	-24.71 ± 0.11	0.1 M $NaClO_4$	Kim et al. 1984
-7.5 ± 0.3	-15.4 ± 0.4	-26.9 ± 0.5	0.1 M $NaClO_4$	Stadler and Kim 1988
-7.8 ± 0.4	-15.4 ± 0.5	-26.9 ± 0.5	0.1 M NaCl	Stadler and Kim 1988
-8.1 ± 0.3	-15.8 ± 0.4	-27.0 ± 0.5	0.6 M NaCl	Stadler and Kim 1988
-7.7 ± 0.3	-16.7 ± 0.7	-25.0 ± 0.3	0.1 M $NaClO_4$	Silva et al. 1995, p. 81
-6.9 ± 0.2		-23.8 ± 0.9	0.1 M $NaClO_4$	Rösch et al. 1989
<-8.2	-17.1 ± 0.7	<-27.0	I → 0	Rai et al. 1983
-6.40 ± 0.11	-13.40 ± 0.16	-20.31 ± 0.17	3 M $NaClO_4$	Pazukhin and Kochergin 1989
Recalculated from literature data				
-7.0 ± 0.4	-15.1 ± 0.4	-26.4 ± 0.5	0.1 M $NaClO_4$	Silva et al. 1995, p. 294

results were reported by Felmy, Rai, and Fulton (1990). These authors measured the solubility of $AmCO_3OH(cr)$ at $pCO_2 = 10^{-3}$ atm. The change in total Am concentration measured in this work as a function of pH was similar to that reported by Kim et al. (1984). Similar plots for the solubility of Nd in 5 M NaCl were measured by Borkowski et al. (2008); however, the Nd concentrations obtained for the comparable pC_{H+} values were two to three orders of magnitude greater as a result of the higher ionic strength present.

Am complexation by carbonate was extensively investigated by solvent extraction, spectrophotometry, electromigration, and solubility (Kim et al. 1984; Rösch et al. 1989; Felmy, Rai, and Fulton 1990; Meinrath and Kim 1991; Nitsche et al. 1995; Torretto et al. 1995). Many different soluble species have been proposed for the Am-water-carbonate system: pure carbonate, bicarbonate, and/or mixed hydroxy-carbonate complexes. Silva et al. (1995) carefully studied and reinterpreted the literature data. It is the consensus in these studies that $Am(CO_3)_n^{(3-2n)}$, with n = 1, 2 and 3, are the predominant carbonate complexes. According to Silva et al. (1995), there is no experimental evidence for the existence of a complex with n = 4 even at the highest carbonate concentrations. The report also suggests that there is no evidence for the formation of Am(III)-bicarbonate or hydroxy-carbonate complexes in solution. These data are, however, in disagreement with the more recent work done by Fanghänel and Kim (1998), which reports spectroscopic evidence for the formation of the n = 4 species.

Data reported by Kim et al. (1984) indicate that up to pC_{H+} = ~8.0, the carbonate complexation does not affect the solubility of Am(III). For the higher pC_{H+}, the presence of carbonate in 0.1-0.3 M $NaClO_4$ increases solubility of Am(III) in relation to carbonate-free systems, and at pC_{H+} = 10 this difference is almost 4 orders of magnitude. The predominance of carbonate

complexation is observed in the pC_{H+} range from 7.5 to 10. At higher pC_{H+}, hydrolysis predominates over carbonate complexation.

SOTERM-3.6.2 WIPP-Specific Results since the CRA-2004 and the CRA-2004 PABC

An extensive series of experiments were performed to determine the solubility of Nd(III) as an analog for Pu(III) and Am(III) solubility in the brine (Borkowski et al. 2008). In this study, the solubility was determined in GWB and ERDA-6 brine, over a pH range of 6-12, and as a function of carbonate concentration. These solubility data extend earlier studies in simplified brines to simulated WIPP brine compositions and cover a broader range of experimental conditions.

There are a number of key results and observations from this Nd(III) solubility experimental study. The most important of these are

1. The solubility data reported for Nd(III) in WIPP-relevant brine systems support current WIPP PA calculations of An(III) solubility, in that the calculated values remain conservative for the reference WIPP conditions. This observation is, however, qualified somewhat by the observations summarized below.

2. Specific observations and results related to the Nd(III) solubility data include the following:

   A. Excellent agreement with comparable literature values for Nd(III) solubility in carbonate-free, simplified 5 M NaCl brine study was obtained. This provided an external corroboration of the experimental approach for the only system investigated that can be directly compared to other non-WIPP studies.

   B. Excellent agreement was obtained between the oversaturation and undersaturation experiments performed. This is a strong indicator that the solubility, rather than steady-state metastable concentrations, was being measured.

   C. The solubility of Nd(III) in simulated WIPP brine was not strongly influenced by the range of carbonate concentrations considered (as high as a total concentration of 0.01 M). This is largely due to the complexation of Nd^{3+} by borate, already present in the WIPP brine at much higher concentrations, which masks the effects of carbonate.

   D. The solubility of Nd, in the simplified and simulated brine systems considered, does not exhibit amphoteric behavior. In this context, the solubility of Nd at $pC_{H+} > 10$ is mostly controlled by hydroxide concentration and decreases with increasing pC_{H+}. A shoulder to a varying degree, however, is noted in the Nd solubility graphs for $7.5 < pC_{H+} < 10.5$ as a result of complexation in all three brines investigated.

   E. The shoulder in the Nd solubility data for ERDA-6 and GWB brine is caused by borate complexation. This establishes borate as the predominant complexant in brine in the pC_{H+} range of 7.5 to 10 (this includes the current reference pC_{H+}). The formation constant for this complex was established to be log K of approximately 3 to 4.

It is important to emphasize that the measurement of Nd(III) solubility in GWB and ERDA-6 brines with carbonate showed that there was little effect of carbonate on Nd solubilities in these brines. This was due to the competition between borate and carbonate in these systems. Borate is, in fact, the key complexant in the WIPP brine, with its current GWB and ERDA-6 formulations, for An(III). These solubility data, however, support the current calculated III solubilities in the WIPP PA. It is the competition between borate and carbonate that makes carbonate a relatively unimportant complexant for the conditions expected in the WIPP. A composite of all literature values, including our WIPP-specific data, is shown in Figure SOTERM-15.

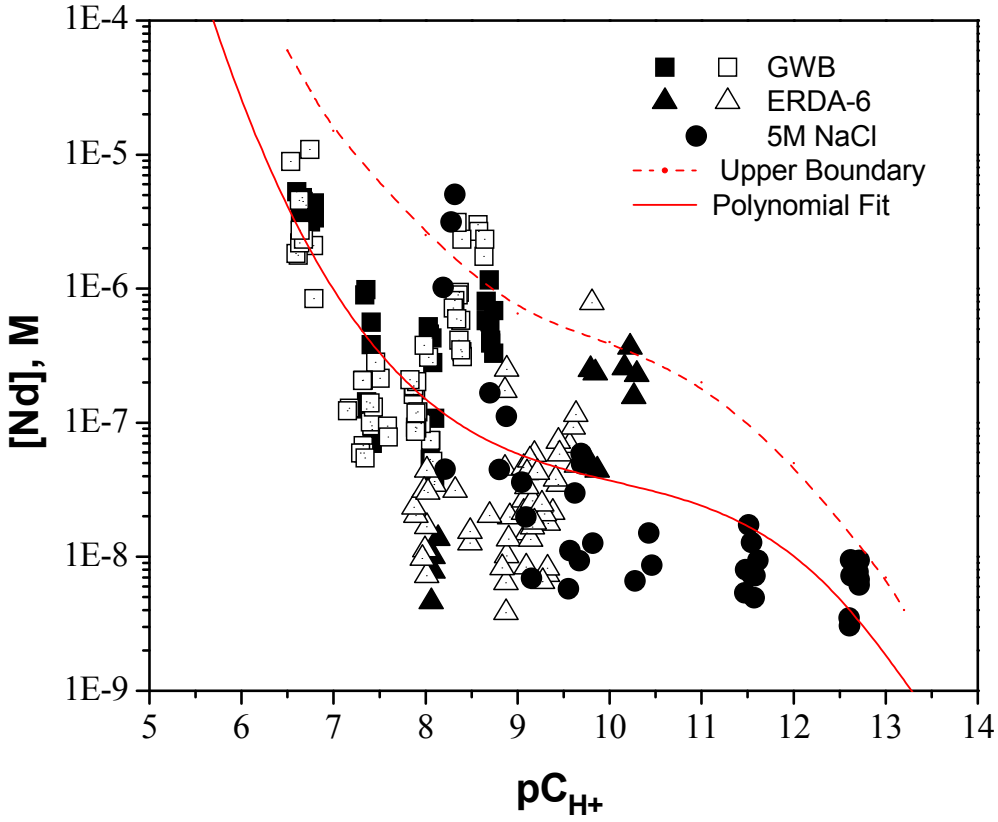


Figure SOTERM-15. Composite of Nd Solubility Trends Under All Conditions Investigated (Borkowski et al. 2008). Open Symbols Correspond to Undersaturation Experiments and Closed Symbols Correspond to Oversaturation Experiments.

Based on these results, there should be no significant change to the solubility of An(III) concentrations used in the WIPP PA for the reference case. In effect, although borate complexation is not currently in the model, the concentrations of III actinides calculated are conservatively high when compared to the experimental results. The WIPP-relevant data summarized in this report support current PA calculations performed with the use of the Pitzer model (U.S. Department of Energy 2004, Appendix PA, Attachment SOTERM) for the values of 3×10^{-7} M and 1.7×10^{-7} M in GWB and ERDA-6, respectively, at pC_{H+}~8.5. The data show

that this solubility is at or near the maximum solubility over a wide range of pH, brine composition, and carbonate concentrations.

SOTERM-3.7 Complexation of Actinides by WIPP Organic Chelating Agents

The stability constants for organic ligand-actinide complexation were determined as part of the WIPP ASTP at Florida State University (Choppin et al. 1999). These data are summarized in Table SOTERM-13 and demonstrate some key trends in actinide complexation. For acetate,

Table SOTERM-13. Apparent Stability Constants for the Complexation of Organic Ligands with Actinides in NaCl Media (Choppin et al. 1999)

Organic Ligand	Actinide Ion	NaCl (molality)	$\log_{10} \beta_1$
Acetate	Am^{3+}	0.3 to 5	1.44 - 2.2
	Th^{4+}	0.3 to 5	3.68 - 4.18
	NpO_2^{+}	0.3 to 5	1.05 - 1.8
	UO_2^{2+}	0.3 to 4	2.23 - 3.09
Oxalate	Am^{3+}	0.3 to 5	4.17 - 4.63
	Th^{4+}	0.3 to 5	7.04 - 7.47
	NpO_2^{+}	1.0 to 5.0	3.62 - 4.63
	UO_2^{2+}	0.3 to 5	5.82 - 6.7
Citrate	Am^{3+}	0.3 to 5	4.84 - 5.9
	Th^{4+}	0.1 to 5	9.31 - 10.18
	NpO_2^{+}	0.1 to 5	2.39 - 2.56
	UO_2^{2+}	0.3 to 5	7.07 - 7.32
EDTA	Am^{3+}	0.3 to 5	13.76 - 15.1
	Th^{4+}	0.3 to 5	15.56 - 16.94
	NpO_2^{+}	0.3 to 5	5.45 - 6.7
	UO_2^{2+}	0.3 to 4	10.75 - 12.16

oxalate, and citrate, the strength of the complex formed is in the same order: IV > VI > III > V. For EDTA, the VI and III are switched. For the most part, the III and IV actinides, which are the two most important oxidation states in the WIPP, are strongly affected by organic complexation and thus can out-compete carbonate and hydrolysis if the organic concentrations are high enough. Of the four organic chelating agents considered, only citrate and EDTA are expected to form strong enough complexes to influence the speciation of actinides and potentially increase actinide concentrations under the expected conditions in the WIPP.

SOTERM-3.8 Actinide Colloids

Actinide colloids in the WIPP are potentially important since the actinide source term is defined by the WIPP PA as the sum of contributions from dissolved actinide species and mobile colloidal actinide species (see U.S. Department of Energy 2004, SOTERM 2004) for a more detailed

discussion of WIPP-relevant colloids). The importance of colloids in the migration and transport of actinide contaminants, although it continues to receive attention in the literature, remains somewhat controversial and difficult to prove. In this context, the consideration of colloidal enhancement of actinide concentrations by the WIPP PA is, at least in part, a conservatism that is built into the overall PA approach. In this context, the sorption of colloidal actinides onto fixed substrates and their filtration in low-porosity media will also reduce the mobile colloidal actinide source term, but no credit is currently being taken for this potentially significant reduction in colloidal concentrations.

Actinide colloids or pseudocolloids may be generated in the WIPP repository as a result of

1. Hydrolysis (intrinsic chemistry).

2. The interactions of dissolved actinide species with microbially derived colloids or colloids formed due to the corrosion of steel and waste constituents.

3. The hydrodynamic entrainment of colloidal-sized mineral fragments, as well as several other mechanisms. The formation of colloids could enhance actinide release in two ways. First, increased actinide concentration will increase the magnitude of DBR release and the effective actinide source term concentration for transport through the Culebra. Second, colloids have very different transport properties than dissolved species, and are predicted to migrate more rapidly in the subsurface. This transport mechanism could enhance the overall actinide release in the WIPP through migration pathways in the Culebra member and the Salado.

In this section, the general environmental aspects of colloid-enhanced transport in the subsurface are discussed, along with an update of relevant WIPP-specific results since the CRA-2004 PABC.

SOTERM-3.8.1 Actinide Colloids in the Environment

The potential for colloidally-enhanced transport of actinides in the subsurface continues to receive much attention in the literature. A key role of colloids in actinide transport has been proposed to explain actinide migration at Rocky Flats (LoPresti, Conradson, and Clark 2007), the Nevada Test Site (Kersting et al. 1999; Zavarin et al. 2003), Hanford (Dai, Buesseler, and Pike 2005), the Savannah River Site (Dai, Kelly, and Buesseler 2002), and the Mayak site (Novikov et al. 2006). Colloidal transport at these sites provides an explanation for subsurface actinide migration that exceeds the rates predicted for dissolved actinide species. There continues to be very weak evidence for significant transport of colloids, once formed, in natural systems.

An important theme to recent field observations of actinide colloids is the tendency of Pu, as Pu(IV), to form iron and manganese (Mn) oxide pseudocolloids. The colloidal transport of Pu in the far-field was investigated by Novikov et al. (2006) at the Mayak site in Russia. They found that the mobility of Pu in groundwater was facilitated by submicron-sized colloids. Pu(IV) hydroxides or carbonates adsorbed on amorphous iron oxide colloids were most transported. These Pu colloids were essentially removed from groundwater, leading to a drop in the Pu concentration from 1000 becquerel (Bq)/L to 0.16 Bq/L over a distance of 3 km.

The field observations are supported by laboratory studies that show a high tendency of lower-valent actinides to form iron and Mn pseudocolloids in environmentally relevant systems. Zavarin et al. (2003) shows that, at pH 8, there is a strong sorption of Pu(IV) in groundwater to birnessite (Mn-oxide) and goethite (Fe-oxide) rather than clinoptilolite (a zeolite) and calcite. Sorption was rapid and equilibrium was reached after 24 hours. Complexation with carbonate reduced Pu(IV) sorption to clinoptilolite about 15%. For iron and Mn oxides, Pu(V) sorption was also rapid, but led to the reduction of Pu(V) to Pu(IV). Khasanova et al. (Khasanova et al. 2007) also studied iron and Mn oxide interactions with actinides and saw a strong association between the dissolved actinide species and the oxides.

The potential formation of actinide pseudocolloids by association of dissolved actinides with biogenic and humic (natural) organics has also been established in the laboratory and the field. Santschi et al. (Santschi, Roberts, and Guo 2002), Asbury et al. (Asbury et al. 2001), and Orlandini, Penrose, and Nelson (1986) all show that actinides associate strongly with natural organics. These have been implicated as a potential explanation for actinide migration at Rocky Flats and in near-surface groundwater transport as a result of fallout.

Lastly, the formation of intrinsic colloids (colloids that are polymers of actinides) are important because they potentially add to the concentration of actinides in groundwater, but also because they potentially contribute to measured solubilities if care is not taken to properly account for their formation. The tendency of actinides to hydrolyze and to polymerize to form intrinsic colloids follows the order (Cleveland 1979, pp. 11–46; Choppin 1983; Kim 1991; Lieser et al. 1991)

$$An^{4+} >> AnO_2^{2+} > An^{3+} > AnO_2^{+} \qquad \text{(SOTERM.31)}$$

The most well known and well studied actinide intrinsic colloid is the Pu(IV) intrinsic colloid, which has been used as a basis of comparison for investigating intrinsic colloids of other actinides. A discussion of colloidal Th, also in the IV oxidation state, was presented in Section SOTERM-3.2.

The most convincing and consistent explanation for the chemistry of these Pu(IV) intrinsic colloid is presented by Johnson and Toth (1978). Pu polymerization occurs nearly immediately after the first hydrolysis occurs. The following reaction involving polymerization of two hydrolyzed species by loss of H_2O (olation) is proposed:

$$2\{[(H_2O)_{d-2}Pu(OH)(H_2O)]^{(y-1)+}\} \leftrightarrows [(H_2O)_{d-2}Pu(OH)(OH)Pu(H_2O)_{d-2}]^{2(y-1)+} + 2H_2O \qquad \text{(SOTERM.32)}$$

Aging or maturation of the polymer then occurs by loss of H_2O (olation) as follows:

$$[Pu(OH)(OH)Pu(OH)(OH)Pu(OH)(OH)...]_n \leftrightarrows [Pu(O)Pu(O)Pu(O)...]_n + 3nH_2O \qquad \text{(SOTERM.33)}$$

An important insight into the important role of Pu polymer formation was reported by Neck et al. (2003), which investigated the solubility of Pu hydroxides/hydrous oxides under reducing conditions and in the presence of oxygen. The experimental data and thermodynamic calculations show that, under reducing conditions in the stability field of water, $Pu(OH)_3(s)$ is not

stable and it converts to PuO_2(s,hyd). It also found that small Pu(IV) colloids/polymers, present in neutral to alkaline solutions at the constant level of $\log[Pu(IV)]_{coll} = -8.3 \pm 1.0$, play an important role in defining the redox potentials in these systems. The experimental results in these systems including colloid species can be described in terms of equilibrium thermodynamics. These data argue for a thermodynamically stable Pu(IV) oxidation state in the WIPP.

Lastly, there is a growing debate about the care needed in solubility studies to account for colloids in the solubilities measured—which is not a trivial problem, as the colloids are often very small (< 20 nm) and difficult to detect experimentally. The role of colloid formation, especially for An(IV) solubilities, was discussed by Fanghänel and Neck, who state, "The formation of amorphous and crystalline solids and the discrepancies between the corresponding experimental solubility data may be explained as an effort of particle size. … the predicted solubilities are often significantly lower than experimental data indicating that that solubility is controlled by the surface properties" (Fanghänel and Neck 2002). In this context, existing solubility data in the literature may include significant colloidal enhancement and overestimate the corresponding solubility.

In conclusion, there is ample evidence that colloids can form and are readily generated in the laboratory. Intrinsic colloids tend to be very low in concentration and comparable to the solubilities observed. Significant enhancement can be observed when actinides associate with oxide mineral colloids and natural and biogenic organic species. However, there remains high uncertainty in the ability of these colloidal species to migrate in the subsurface. This key issue was raised by Kersting et al. (1999) for the Nevada Test site, Dai et al. for the Hanford and Savannah River site (Dai, Kelly, and Buesseler 2002; Dai, Buessler, and Pike 2005), and strong attenuation was noted at the Mayak site (Novikov et al. 2006). In the WIPP, with its very low porosity, it is reasonable to predict that the transport of colloids is likely to be negligible; the only significant concern would be the colloidal contribution to dissolved concentrations for DBR-type release.

SOTERM-3.8.2 WIPP-Specific Results since the CRA-2004 PABC

There are no new experiments since the CRA-2004 PABC that investigate the formation and transport of actinide colloids under WIPP-relevant conditions. Recently published results (Wall and Mathews 2005) demonstrate that the presence of MgO in the WIPP brine will significantly reduce the concentration of humic acids (HA); this occurs after a relatively short period of time (12 to 60 days) when a negligible concentration of HA was observed in the system. This important observation was attributed to MgO-facilitated HA precipitation and/or sorption of the HA onto the MgO surface. Treatment of colloids in the PA are the same as in CRA-2004 and CRA-2004 PABC.

SOTERM-3.9 Changes in Actinide Speciation Information since the CRA-2004 and the CRA-2004 PABC

There are no significant changes in the general approach and assumptions used to understand and predict actinide behavior in the WIPP from a PA perspective. Specifically,

- Oxidation state distributions for the TRU actinides, and correspondingly, assumptions regarding their solubility calculations using redox-invariant analogs, have not changed.

- Predicted and calculated solubilities for Pu and Am oxidation states, which are the key actinides from the perspective of PA, have not changed.

- Inventory assumptions regarding the amounts of organic chelating agents and actinides in TRU waste are being updated annually.

- The recognition that microbial colloids are the most likely to be generated in the WIPP has not changed. Treatment of colloids in PA are the same as in CRA-2004 and CRA-2004-PABC.

There are new data, within and outside the WIPP project, that continue to support and/or expand the robustness of the current PA assumptions. The most important of these are

- Extensive data from the Karlsruhe (German) program for III and IV actinides in simplified brine systems. These data support existing PA assumptions and show that they extend beyond the relatively narrow pH range considered in the WIPP PA. This is especially important for higher-pH environments, where it was previously thought that solubilities increase greatly.

- WIPP-specific results are reported in three key areas:

  - An(III) solubility in simulated WIPP brines over a wide range of conditions using Nd(III) as an analog for Pu(III) and Am(III). These data support current PA solubilities for the III actinides, but show that complexation with borate explains the observed trends with pH and little or no effect of carbonate.

  - The reduction of Pu(V/VI) in WIPP brine by reaction with reduced iron species. These results provide additional support to past observations that higher-valent actinides cannot persist in the WIPP in the presence of reduced iron. This strongly supports current PA assumptions on oxidation state distribution for both Am and Pu.

  - The solubility of U(VI) in simulated WIPP brine over a wide range of conditions in the absence of carbonate. These data support the current WIPP PA assumptions about the solubility of U(VI).

Lastly, there are some new developments reported in the literature that, although not directly relevant to the WIPP, indirectly affect how the actinide chemistry in the WIPP is viewed. The most important of these are

- The potential role of Ca^{2+} and Mg^{2+} to form soluble species in the presence of carbonate at high pH. This has been evaluated in the WIPP case and is not likely to affect actinide solubility in the range of conditions expected in the WIPP.

- Growing recognition that microbes, under most anaerobic conditions, reduce higher-valent actinides in the subsurface.

- Additional results on the potential effects of radiolysis on brine systems. It is clear that mechanisms exist that can lead to the oxidation of actinides when no reducing agents are present in the brine. This could create localized oxidation in the WIPP, but WIPP-specific experiments show this to be easily overwhelmed by the expected microbial and reduced-iron effect on actinide redox.

SOTERM-4.0 Calculation of the WIPP Actinide Source Term

The calculation of the WIPP actinide source term was performed for the CRA-2004 PABC (Brush and Xiong 2005a) using the computer code FMT. This is the baseline PA currently being used for CRA-2009. A general description of the modeling approach to establish the actinide source term for the WIPP PA is described in this section. The approach used in the CRA-2004 PABC calculations and the results obtained were published in a series of reports and documents. These are listed below with supporting letters and documentation.

Table SOTERM-14. List of Documents and Reports that Support the CRA-2004 PABC

PABC Analysis	Title/Subject of Report
CRA-2004 PABC (Leigh et al. 2005)	2004 Compliance Recertification Application Performance Assessment Baseline Calculation
Analysis Plan (AP)-120, Rev. 0 (Brush and Xiong 2005b)	Calculation of Actinide Solubilities for the WIPP Performance-Assessment Baseline Calculations
Letter Report: Organic ligand concentrations Task 1, AP-120, Rev. 0 (Brush and Xiong 2005a)	Calculation of Organic-Ligand Concentrations for the WIPP PABC
FMT_050405.CHEMDAT Task 2, AP-120, Rev. 0 (Xiong 2005)	CRA-2004 PABC version of FMT thermodynamic data base
Letter Report: Uncertainty Analysis Task 3, AP-120, Rev. 0 (Xiong, Nowak, and Brush 2005)	Updated Uncertainty Analysis of Actinide Solubilities for the Response to EPA Comment C-23-16, Rev. 1
Letter Report: Actinide Solubilities Task 4, AP-120, Rev. 0 (Brush 2005)	Results of Calculations of Actinide Solubilities for the WIPP PABC
CRA-2004 PABC Inventory Document (Leigh, Trone, and Fox 2005)	TRU Waste Inventory for the 2004 CRA PABC
Actinide Concentration input to PANEL (Garner and Leigh 2005)	Analysis Package for PANEL: CRA-2004 PABC
Supporting Letter or Document	**Title/Subject of Report**
Sandia National Laboratories (SNL) Report (Brush et al. 2006)	Consumption of Carbon Dioxide by Precipitation of Carbonate Minerals Resulting for Dissolution of Sulfate Minerals in the Salado Formation In Response to Microbial Sulfate Reduction in the WIPP
Letter Report: Stein to Brush, 4/13/2005 (Stein 2005)	Estimate of Volume of Brine in Repository that Leads to a Brine Release
Letter Report: Brush to Kessel, 2/1/2005 (Brush and Garner 2005)	Additional Justification for the Insignificant Effect of Np on the Long-Term Performance of the WIPP
Telecon: EPA with DOE/SNL/Los Alamos National Laboratory (LANL), 3/2/2005 (U.S. Environmental Protection Agency 2005)	Change in U(VI) Solubility Assumption to a Concentration of 1 mM
Letter: Cotsworth to Triay, 3/4/2005 (Cotsworth 2005)	Untitled: EPA documentation of requested changes to the CRA-2004 PA
EPA Response and Comments on CRA-2004 PABC (U.S. Environmental Protection Agency 2006)	Evaluation of the Compliance Recertification Actinide Source Term and Culebra Dolomite Distribution Coefficient Values

SOTERM-4.1 Overview of WIPP Approach to Calculate Actinide Solubilities

The overall approach used to establish the actinides important in WIPP releases and calculate their solubilities for use in the WIPP PA is summarized in this section. This approach consists of the following:

- Assessing the WIPP inventory and regulations that govern the application of the WIPP certification to determine the likely actinides of interest and, correspondingly, the key waste components that may affect their solubility.

- Establishing a conceptual model for the key subsurface interactions and release mechanisms and using a combination of literature review and WIPP-specific experimental results to establish the likely oxidation state distribution, the species that affect actinide solubility, and the parameters required to model the system at high ionic strength. This approach featured the following:

  – Conservative assumptions, within the bounds of the conditions expected, for the oxidation state distribution.

  – Use of redox-invariant analogs for multivalent actinides to determine formation constants and establish oxidation-specific solubilities.

  – Use of the Pitzer formalism and associated parameters to model solubilities at the high ionic strengths present. The Pitzer approach is recognized as the best approach for $I > 0.3$ M in brine systems.

- Calculating the solubility of the key actinides in the WIPP using the FMT code. The solubilities are modeled in reacted GWB and ERDA-6 brines, which are expected to bracket the range in the composition of the brine expected. This code assigns the actinides to the key species by minimizing the total free energy of the system while satisfying charge-balance and mass-balance constraints based on the standard chemical potentials assigned to each species.

- Establishing the effects of colloids and organic complexation, separately and simultaneously, on the solubilities calculated.

- Tabulating and assigning uncertainty distributions in the range of expected conditions and brine compositions to these solubility data.

This range of possible solubilities for a wide range of possible conditions defines the actinide source term provided to the WIPP PA for the calculation of TRU release from the WIPP.

SOTERM-4.2 Use of Oxidation-State-Invariant Analogs

The solubility and speciation of multivalent actinides are often investigated with lanthanide and actinide analogs that mimic the property of interest but, for varying reasons, provide an advantage to the experimenter. The best example of this, used extensively in the WIPP modeling approach, is the use of redox-invariant analogs for the multivalent actinides, most notably Pu, to

determine oxidation-state-specific properties (e.g., solubility or complexation). The advantage of these types of analogs is that they remove the uncertainty of oxidation-state change from the experiment, which is a complexity that can often lead to uncertain or incorrect interpretations of the results obtained.

For the TRU actinides, the redox-invariant analogs used are lanthanides or other actinides. Lanthanides, as 4f-electron elements, possess physical and chemical characteristics that make them good analogs for the actinides when they are redox-invariant under the conditions of the experiment. Correspondingly, actinides with their 5f-electron character also have good physical and chemical properties to be analogs for other actinides if they also have redox stability under WIPP-relevant conditions. This analog approach, although sometimes criticized in the literature, considerably simplifies experimental design and consequently improves the reliability of the experimental data (Choppin 1999).

A key argument for the use of analogs in WIPP-related experiments is that key complexants that define actinide solubility in the WIPP are hard-donor complexants (e.g., hydroxide, carbonate, borate, chloride, and/or sulfate). The use of lanthanides as analogs for actinides is based on observations in many extraction systems, along with the associated crystallographic data (Siekierski 1988) that show they are good analogs for compounds containing hard donor ligands (oxygen) where the cation-anion interactions are primarily electrostatic in nature. In this context, Nd(III) is a good analog for the chemical behavior of Am(III) and Pu(III) under most circumstances in the WIPP. Not only do these species have the same 3+ charge, they also have similar ionic radii for coordination number 6 (CN=6): 97.5 pm for Am^{3+}, 98.3 pm for Nd^{3+}, and 100 pm for Pu^{3+} (Shannon 1976). In this context, the magnitudes of electrostatic attractions between these metal ions and corresponding ligands will be similar, yielding comparable thermodynamic stabilities.

Th is used by the WIPP as a redox-invariant analog for Pu(IV), U(IV), and Np(IV). The use of the Th^{4+} stability constants to represent the other An(IV) species is conservative. Th^{4+} is the largest of the tetravalent actinide ions. It therefore has the lowest charge density and, correspondingly, relatively weaker ionic interactions when compared to the other tetravalent actinides. This is best exhibited by its lower tendency towards hydrolysis and intrinsic polymer formation relative to the other actinides (see Section SOTERM-3.2). For these reasons, the use of Th^{4+} as an analog is conservative, as Th will likely be the most soluble of the actinides in the tetravalent state under comparable WIPP-relevant conditions.

To a lesser extent, actinides are analogs for each other, depending on the oxidation state. Np(V), which has much greater redox stability than Pu(V) and much more favorable spectroscopy, is often used as an analog for Pu(V). U(VI), which is much more redox stable than Pu(VI) and Np(VI), is also used as an analog for these TRU actinides, although this breaks down somewhat quickly. Am(III) and Cm(III) are also excellent analogs for Pu(III) as a result of their much greater redox stability and comparable ionic radii.

SOTERM-4.3 Actinide Inventory and Oxidation State Distribution in the WIPP

The actinide inventory used in CRA-2004 PABC is given in Table SOTERM-15 (Leigh, Trone and Fox 2005). This is based on the inventory given in Table SOTERM-7 projected to the year 2033, which is the projected year for the closure of the WIPP.

Table SOTERM-15. WIPP Radionuclide Inventory at Closure (in 2033) Used in PABC-2005 Calculations (Leigh, Trone, and Fox 2005)

Radionuclide	Activity (Ci)	Amount (kg)	Element-Specific Inventory
^{229}Th	5.21E+00	2.64E-02	8.81 Ci 3.11E+04 kg
^{230}Th	1.80E-01	8.73E-03	
^{232}Th	3.42E+00	3.11E+04	
^{233}U	1.23E+03	1.27E+02	1.80E+03 Ci 6.47E+05 kg
^{234}U	3.44E+02	5.52E+01	
^{235}U	5.01E+00	2.32E+03	
^{236}U	2.87E+00	4.43E+01	
^{238}U	2.17E+02	6.44E+05	
^{237}Np	1.22E+01	1.73E+01	12.1 Ci 17.3 kg
^{238}Pu	1.13E+06	6.60E+01	2.26E+06 Ci 9.87E+03 kg
^{239}Pu	5.82E+05	9.38E+03	
^{240}Pu	9.54E+04	4.19E+02	
^{241}Pu	4.48E+05	4.35E+00	
^{242}Pu	1.27E+01	3.23E+00	
^{244}Pu	5.53E-03	3.09E-01	
^{241}Am	5.17E+05	1.51E+02	5.179E+05 Ci 151 kg
^{243}Am	7.87E+01	3.94E-01	
^{244}Cm	2.13E+03	2.63E-02	2.13E+03 Ci (0.0263 kg)
^{137}Cs (see Note [a])	2.07E+05	2.40E+00	2.07E+05 Ci (2.40 kg)
^{90}Sr (see Note [a])	1.76E+05	1.29E+00	1.76E+05 Ci (1.29 kg)

[a] Fission products are not TRU, but are considered in the PA to calculate overall release

The oxidation states used by the WIPP PA to model actinide solubility are tabulated in Table SOTERM-16. Also included are the assumed abundance percent of each oxidation state and the speciation data set used in FMT for each oxidation state. This table is based on a general understanding of the corresponding actinide chemistry summarized in Section SOTERM-3.0.

A number of conservative assumptions are reflected in this table. The most important assumptions are

Table SOTERM-16. Oxidation States of the Actinides in the WIPP as Used in the CRA-2004 PABC

Actinide Element	Oxidation States, Abundance (%), and Analog Used (If Any)				
	Oxidation State[a,b]				FMT Speciation Data Used
	III	IV	V	VI	
Thorium	—	100 %	—	—	Thorium
Uranium	—	50 %	—	50 %	1 mM assumed for VI, Th for IV
Neptunium	—	50%	50 %	—	Np for V Th for IV
Plutonium	50 %	50 %	—	—	Am for III Th for IV
Americium	100 %	—	—	—	Americium
Curium	100 %	—	—	—	Americium

[a] Oxidation state distributions (percentages) refer to the percent of PA vectors that have 100% of the specified oxidation state.

[b] In PA calculations the distribution of oxidation states is correlated for U, Np, and Pu such that the states for all three elements are simultaneously either in the lower oxidation state (U(IV), Np(IV), and Pu(III)) or in the higher oxidation state (U(VI), Np(V), and Pu(IV)).

1. Use of 1 mM concentration for the solubility of U(VI). The actual solubility of U(VI) in the WIPP under the expected range of conditions is estimated to be <0.1 mM.

2. Use of Th as an analog for the IV actinides (see Section SOTERM-4.1 and Section SOTERM-3.2).

3. The assumption that 50% of the vectors have Pu(III) and 50% of the vectors have Pu(IV). The predominant Pu species expected is Pu(IV), although some Pu(III) is possible as a transient (see discussions in Section SOTERM-3.3). This is conservative because Pu(III) is approximately 6 to 10 times more soluble than corresponding Pu(IV) phases.

4. The assumption is that 50% of the vectors have U(IV) and 50% of the vectors have U(VI). The predominant uranium species expected is U(IV), which is approximately four 4 orders of magnitude less soluble than U(VI), based on current assumptions.

SOTERM-4.4 Actinide Speciation Reactions Used in the FMT Model

The version of the FMT code used in the CRA-2004 PABC was FMT_050405.CHEMDAT (Xiong 2005). The data in FMT was previously described in a series of memoranda by Giambavlo (Giambavlo 2002a, 2002b, 2002c, 2002d, 2002e, 2003). The most recent database iteration included some minor changes from previous versions that go beyond those described in these memoranda:

- The chemical potential for the solubility of $Th(OH)_4$ (s) was changed.
- The effects of hydromagnesite and calcite precipitation were added.

SOTERM-4.4.1 The III Actinides: Pu(III), Am(III), Cm(III)

The thermodynamic database for the III actinides currently used in FMT was described by Giambalvo (2002a). Nd, Am, and Cm are generally used to establish solubility of An(III) because, unlike plutonium, they have redox-stable trivalent oxidation states. Speciation and solubility data for the III actinides were parameterized for use in the Pitzer activity-coefficient model by Felmy et al. (1989) for the Na^+- Pu^{3+}-Cl^--H_2O system; by Felmy, Rai, and Fulton (1990) for the Na^+-Am^{3+}-OH^--HCO_3^--H_2O system; by Rai, Felmy, and Fulton (1995) for the Na^+-Am^{3+}-PO_4^{3-}-SO_4^{2-}-H_2O system; and by Rao et al. (1996) for the Na^+-Nd^{3+}-CO_3^{2-}-HCO_3^--H_2O system. For this reason, FMT uses the Am(III) data to calculate the solubility for all the III actinides. A diagram of the predominant species for Am is shown in Figure SOTERM-16.

The inorganic aqueous and solubility-limiting species featured in the model for Am(III) are

Am(III) Reactions	**log K**	
$Am^{3+} + CO_3^{2-} \rightleftharpoons AmCO_3^+$	8.1	(SOTERM.34)
$Am^{3+} + 2CO_3^{2-} \rightleftharpoons Am(CO_3)_2^-$	13.0	(SOTERM.35)
$Am^{3+} + 3CO_3^{2-} \rightleftharpoons Am(CO_3)_3^{3-}$	15.2	(SOTERM.36)
$Am^{3+} + 4CO_3^{2-} \rightleftharpoons Am(CO_3)_4^{5-}$	13.0	(SOTERM.37)
$Am^{3+} + OH^- \rightleftharpoons AmOH^{2+}$	6.4	(SOTERM.38)
$Am^{3+} + 2OH^- \rightleftharpoons Am(OH)_2^+$	12.3	(SOTERM.39)
$Am^{3+} + 3OH^- \rightleftharpoons Am(OH)_3(aq)$	16.3	(SOTERM.40)
$Am^{3+} + Cl^- \rightleftharpoons AmCl^{2+}$	0.24	(SOTERM.41)
$Am^{3+} + 2Cl^- \rightleftharpoons AmCl_2^+$	-0.74	(SOTERM.42)
$Am^{3+} + SO_4^{2-} \rightleftharpoons Am(SO_4)^+$	3.25	(SOTERM.43)
$Am^{3+} + 2SO_4^{2-} \rightleftharpoons Am(SO_4)_2^-$	3.7	(SOTERM.44)
$Am^{3+} + OH^- + CO_3^{2-} \rightleftharpoons AmOHCO_3(s)$	22.7	(SOTERM.45)
$Na^+ + Am^{3+} + 2CO_3^{2-} + 6H_2O \rightleftharpoons NaAm(CO_3)_2 \cdot 6H_2O(s)$	21.4	(SOTERM.46)
$Am^{3+} + PO_4^{3-} \rightleftharpoons AmPO_4(cr)$	24.8	(SOTERM.47)

In these reactions, "aq," "cr," and "s" are the abbreviations for aqueous, crystalline, and solid, respectively. The An(III) database was extended to mixed Na^+-CO_3^{2-}-Cl^-- media, and was shown to reproduce the independently measured solubility of $NaAm(CO_3)_2(s)$ in 5.6 M NaCl (Runde and Kim 1994) and the measured Nd(III) solubility in the WIPP brine (Borkowski et al. 2008).

SOTERM-4.4.2 The IV Actinides: Th(IV), U(IV), Pu(IV), Np(IV)

The IV actinides addressed by the WIPP PA are Th(IV), U(IV), Pu(IV), and Np(IV). The variation in charge-to-radius ratio for the tetravalent actinides is greater than for actinides in other oxidation states (Cotton and Wilkinson 1988, pp. 11–46), and larger differences in the chemical behavior among the IV actinides is expected. The application of the Th(IV) model to the other IV species is more uncertain, yet still conservative because Th(IV) is the most soluble of these elements under WIPP conditions. The model was evaluated against data for Pu(IV) and Np(IV) solubility and demonstrated to predict the chemical behavior of these actinides conservatively.

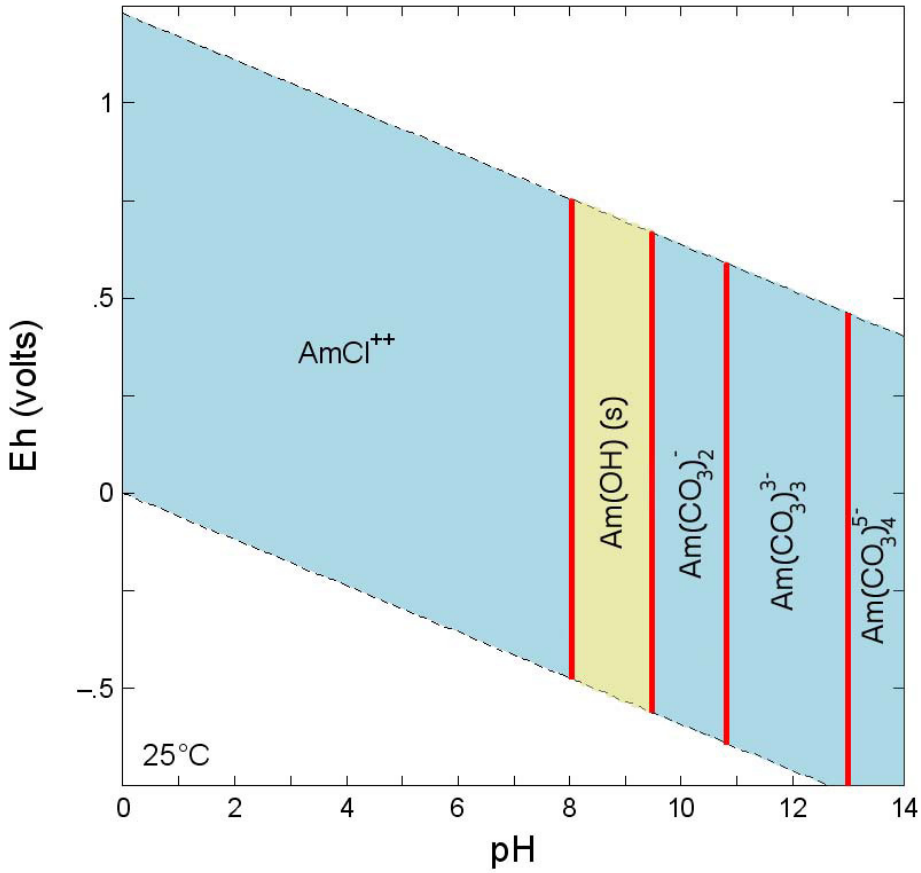


Figure SOTERM-16. Predominant Am Species as a Function of pH and E_h Based on the Speciation Reactions (SOTERM.34) to (SOTERM.47) (Richmann 2008)

The thermodynamic database for the IV actinides currently used in FMT was described by Giambalvo (2002c). Speciation and solubility data for Th(IV) were parameterized for the Pitzer activity-coefficient model for the Na^+-K^+ -Mg^{2+}-Cl^-- SO_4^{2-}-CO_3^{2-}-HCO_3^- -OH^--H_2O system. This model requires the species Th^{4+}, $Th(OH)_2SO_4$ (s), $Th(SO_4)_3^{2-}$, $Th(SO_4)_2$ (aq), ThO_2, $Th(OH)_4$(aq), $Th(OH)_3CO_3^-$, and $Th(CO_3)_5^{6-}$ to describe the data pertinent to the WIPP (Felmy, Mason, and Rai 1991; Rabindra et al. 1992; Felmy et al. 1996). A diagram of the predominant Th speciation, based on Reactions (SOTERM.48) to (SOTERM.59), is shown in Figure SOTERM-17.

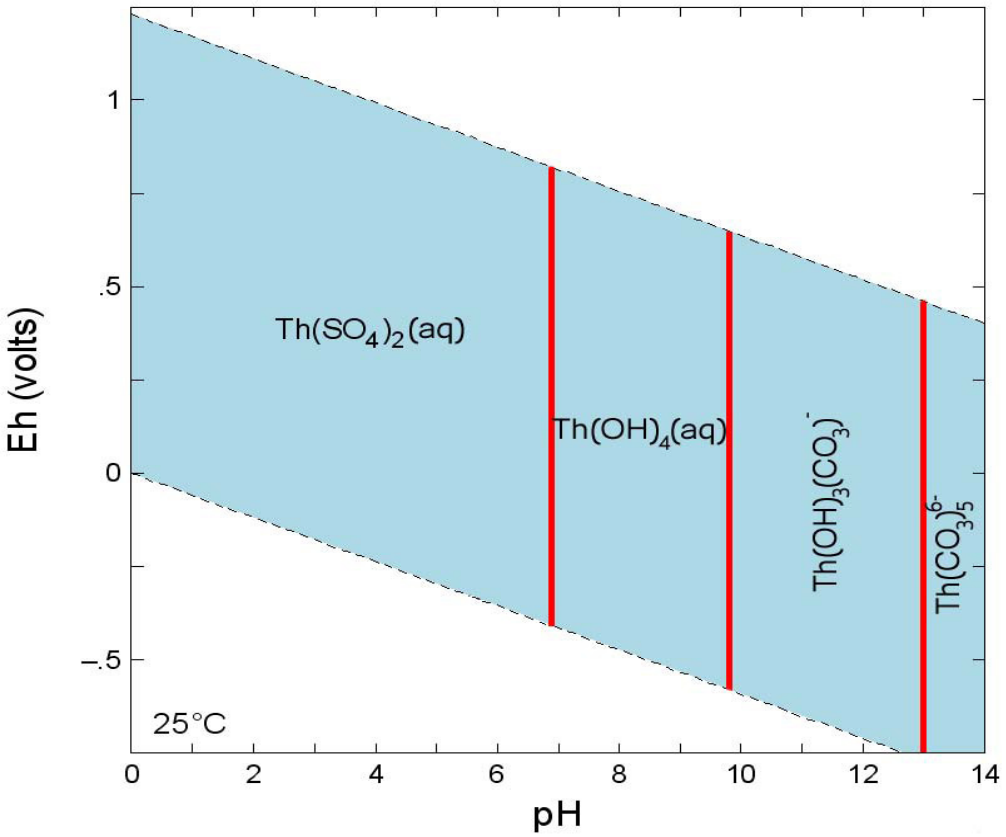


Figure SOTERM-17. Predominant Species of Th as a Function of pH and Redox Conditions (Richmann 2008). Thorianite is Predicted to Predominate at the Conditions Expected in the WIPP Repository.

The inorganic aqueous and solubility-limiting species featured in the IV model are:

Th(IV) Reactions	log K	
$ThO_2(am) + 2H_2O \rightleftharpoons Th(OH)_4(aq)$	-7.0	(SOTERM.48)
$Th^{4+} + 4OH^- \rightleftharpoons Th(OH)_4(aq)$	38.5	(SOTERM.49)
$Th^{4+} + 3OH^- + CO_3^{2-} \rightleftharpoons Th(OH)_3CO_3^-$	38.3	(SOTERM.50)
$Th^{4+} + 5CO_3^{2-} \rightleftharpoons Th(CO_3)_5^{6-}$	27.1	(SOTERM.51)
$Th^{4+} + 2SO_4^{2-} \rightleftharpoons Th(SO_4)_2(aq)$;	11.6	(SOTERM.52)
$Th^{4+} + 3SO_4^{2-} \rightleftharpoons Th(SO_4)_3^{2-}$;	12.4	(SOTERM.53)
$Th^{4+} + 2SO_4^{2-} + 9H_2O \rightleftharpoons Th(SO_4)_2 \cdot 9H_2O(s)$;	13.0	(SOTERM.54)
$Th^{4+} + 2SO_4^{2-} + 8H_2O \rightleftharpoons Th(SO_4)_2 \cdot 8H_2O(s)$	12.9	(SOTERM.55)
$Th^{4+} + 2Na^+ + 3SO_4^{2-} + 6H_2O \rightleftharpoons Th(SO_4)_2 \cdot Na_2SO_4 \cdot 6H_2O(s)$	17.6	(SOTERM.56)

$Th^{4+} + 2K^+ + 3SO_4^{2-} + 4H_2O \rightleftharpoons Th(SO_4)_2 \cdot K_2SO_4 \cdot 4H_2O(s)$	18.1	(SOTERM.57)
$Th^{4+} + 4K^+ + 4SO_4^{2-} + 2H_2O \rightleftharpoons Th(SO_4)_2 \cdot 2K_2SO_4 \cdot 2H_2O\ (s)$	21.2	(SOTERM.58)
$Th^{4+} + 7K^+ + 5.5SO_4^{2-} \rightleftharpoons Th(SO_4)_2 \cdot 3.5K_2SO_4(s).$	24.7	(SOTERM.59)

SOTERM-4.4.3 The V Actinides: Np(V)

The only V actinide of interest to the WIPP is Np(V), which exists as the neptunyl ion, NpO_2^+. Pu(V), which can be formed under some conditions, is transitory and not expected to persist in significant quantities in the WIPP. The base model for Np(V) comes from Fanghänel, Neck, and Kim (1995), constructed for the German repository program.

The thermodynamic database for the V actinides currently used in FMT is described by Giambalvo (2002d). Np(V) speciation and solubility were parameterized in the Pitzer activity-coefficient model for the Na^+-K^+-Mg^{2+}-Cl^--SO_4^{2-}-CO_3^{2-}-HCO_3^--OH^--H_2O system. The model requires the aqueous species NpO_2^+, $NpO_2OH(aq)$, $NpO_2(OH)_2^-$, $NpO_2CO_3^-$, $NpO_2(CO_3)_2^{3-}$, and $NpO_2(CO_3)_3^{5-}$, and the solid species $NpO_2OH(am)$, $NpO_2OH(aged)$, $Na_3NpO_2(CO_3)_2(s)$, $KNpO_2CO_3 \cdot 2H_2O(s)$, $K_3NpO_2(CO_3)_2 \cdot 0.5H_2O(s)$, and $NaNpO_2CO_3 \cdot 3.5H_2O(s)$ to explain the available data. The predominant species for Np(V) are shown in Figure SOTERM-18.

The inorganic aqueous and solubility-limiting species used are:

Np(V) Reactions	**log K**	
$NpO_2^+ + OH^- \rightleftharpoons NpO_2OH(aq)$	2.7	(SOTERM.60)
$NpO_2^+ + OH^- \rightleftharpoons NpO_2OH(s, am)$	8.8	(SOTERM.61)
$NpO_2^+ + OH^- \rightleftharpoons NpO_2OH(s, aged)$	9.5	(SOTERM.62)
$NpO_2^+ + 2OH^- \rightleftharpoons NpO_2(OH)_2^-$	4.5	(SOTERM.63)
$NpO_2^+ + CO_3^{2-} \rightleftharpoons NpO_2CO_3^-$	5.0	(SOTERM.64)
$NpO_2^+ + 2CO_3^{2-} \rightleftharpoons NpO_2(CO_3)_2^{3-}$	6.4	(SOTERM.65)
$NpO_2^+ + 3CO_3^{2-} \rightleftharpoons NpO_2(CO_3)_3^{5-}$	5.3	(SOTERM.66)
$Na^+ + NpO_2^+ + CO_3^{2-} + 3.5H_2O \rightleftharpoons NaNpO_2(CO_3) \cdot 3.5H_2O(s)$	11.1	(SOTERM.67)
$3Na^+ + NpO_2^+ + 2CO_3^{2-} \rightleftharpoons Na_3NpO_2(CO_3)_2(s)$	14.2	(SOTERM.68)
$K^+ + NpO_2^+ + CO_3^{2-} \rightleftharpoons KNpO_2(CO_3)(s)$	13.6	(SOTERM.69)
$3K^+ + NpO_2^+ + 2CO_3^{2-} + 0.5H_2O \rightleftharpoons K_3NpO_2(CO_3)_2 \cdot 0.5H_2O(s)$	-4.8	(SOTERM.70)

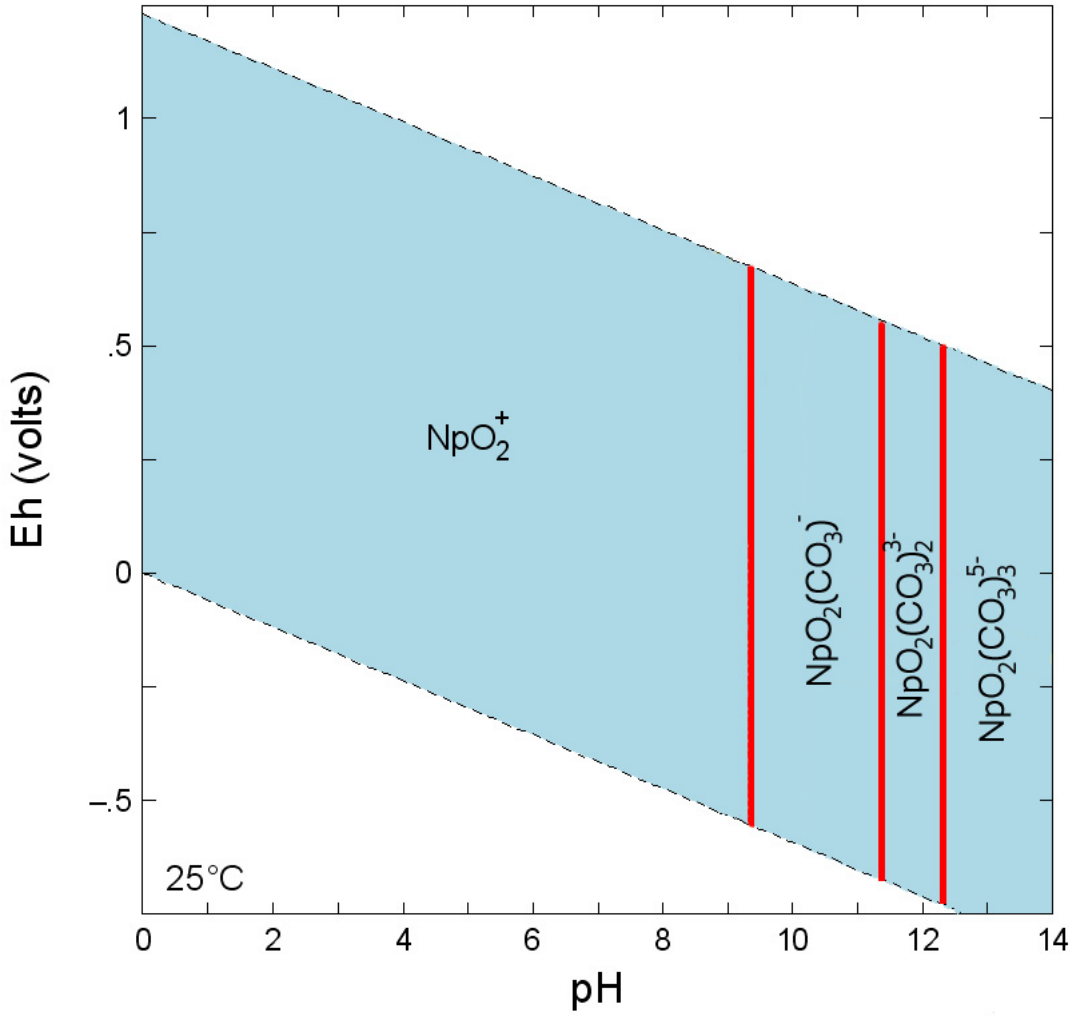


Figure SOTERM-18. Predominant Species Diagram for Np as a Function of pH and E_h Based on the Np Speciation Data Reactions (SOTERM.60) to ((SOTERM.70) (Richmann 2008)

SOTERM-4.4.4 The VI Actinides: U(VI)

The An(VI) FMT model has not been developed sufficiently for reliable use in predicting concentrations of this oxidation state in the WIPP brines under various solution conditions. Although uranyl carbonate can be successfully modeled, the hydrolysis behavior of U(VI) is quite complicated and no satisfactory predictive models applicable to WIPP-like conditions are yet available. Because the implementation of an MgO backfill limits the pmH and f_{CO_2} to discrete values, empirical measurement of the solubility of U(VI) in WIPP and/or WIPP–like brines became practical. As documented in Hobart and Moore (1996) and used in prior PA calculations, the solubility of U(VI) at pH 10, in the absence of carbonate, was determined to be 8.8×10^{-6} m. This is augmented by additional data from U(VI) solubility studies in WIPP-relevant carbonate-free brines reported in Section SOTERM-3.3.2 (Lucchini et al. 2009). Here, the measured U(VI) solubility was 10^{-7} M to 10^{-6} M for GWB and ERDA-6 brine, respectively.

The solubility of U(VI) currently used in WIPP PA was established through discussions with the EPA to be 1 mM (U.S. Environmental Protection Agency 2005) to account for the potential and expected effects of carbonate.

SOTERM-4.5 Calculations of Actinide Solubility Using the FMT Computer Code

Details of the implementation of FMT and an early version of the CHEMDAT database are given in Novak (1995, Appendix D) and in the FMT User's Manual (Babb and Novak 1995 and 1997). FMT calculates chemical equilibrium for user-specified total element amounts in aqueous or aqueous/mineral geochemical systems. The FMT calculations of actinide solubility in the WIPP system performed for WIPP PA included preequilibration with halite, anhydrite, brucite, and magnesite (Novak, Moore, and Bynum 1996; Novak and Moore 1996), which are the minerals present in large quantities in the repository. The effects of the MgO backfill are realized by equilibrating brine with brucite, magnesite, and hydromagnesite.

SOTERM-4.5.1 Pitzer Approach for High-Ionic-Strength Brines

The Pitzer formalism is substantially different in approach from the classic Debye-Hückel (D-H) theory of the behavior of ionic solutions. The latter is a theoretical approach to describing the behavior of dilute solutions; more importantly, because many ionic solutes do not behave ideally even at very low concentrations, it provides a means to calculate the activity, a_i, of a desired species. This is of great importance, as the Gibbs free energies of the various species in solution can be used to calculate solution equilibria if one knows the effective concentration of those species, i.e. their "activity" in solution. The activity of a given species i is tied to the molality of that species as $a_i = \gamma_i m_i$. Since the molality of species i is known, the unknown that must be calculated to determine a_i is, therefore, γ_i. The simplest form relating activity to molality from the D-H law is

$$\log \gamma_i = -A_\gamma z_i^2 \left(\frac{\sqrt{I}}{1+\sqrt{I}} \right) \qquad \text{(SOTERM.71)}$$

where $A\gamma$ is the Debye-Hückel parameter, z_i is the charge of the ith species and I is the overall solution ionic strength. The fundamental difficulty with the D-H formalism is that even with extensions (Davies equation, B-dot equation), the D-H law begins to deviate significantly from real solution behavior somewhere in the general region of I = 0.3 molal. As the WIPP brines (and many other highly concentrated ionic species of interest) are well above this level of ionic strength, many times with $I > 5$, another description is required to properly describe the activities of the ionic species.

In 1973, Pitzer proposed a set of semiempirical equations to describe a_i. Pitzer (1973) wrote the Gibbs excess energy of a solution as a virial expansion, where a portion of the overall expansion can be tied down to a formalism similar to the D-H law and the majority of the remaining constants are empirically determined from measurements of the desired ions. The most general form of the equation is

$$\ln \gamma_i = \left(\frac{z_i^2}{2}\right) f'(I) + 2\sum_i \lambda_{ij}(I) m_j + \sum_{ik}\left(\left(\frac{z_i^2}{2}\right)\lambda'_{jk}(I) + 3\mu_{ijk}\right) m_j m_k , \qquad \text{(SOTERM.72)}$$

where $f(I)$ is a Debye-Hückel function, $f'(I)$ is its derivative df/dI, the λ_{ij} are second-order interaction coefficients, $\lambda'_{ij}(I)$ is the derivative $d\lambda_{ij}/dI$, and the μ_{ijk} are third-order interaction coefficients. The experimentally observable values $\beta^{(0)}$, $\beta^{(1)}$, $\beta^{(2)}$, α_1, α_2, C^{φ}, and so forth are used to calculate the λ_{ij} and μ_{ijk} values needed to calculate γ_i (for more detail, see Wolery and Daveler 1992).

This approach has proven highly effective and has successfully described the behavior of solutions at high ionic strength. The disadvantage of this technique is that binary and ternary coefficients for the expansion are normally needed to completely describe all the activities of the different species; in addition, if the number of species in solution grows, the number of calculations grows that much faster, i.e., on the order of the cube of the number of species. This problem would be even worse, except that many of the terms describing neutral species can be legitimately neglected in geochemical systems.

This parameter-determination problem is of particular interest in the description of actinide behavior in the WIPP, since the GWB and ERDA-6 brines of interest contain a wide variety of ions in and of themselves, in addition to the actinides introduced into the repository. As a result of this, it was necessary to constrain the total number of possible species in solution, aqueous, solid or gas, and in addition, to determine Pitzer parameters for many species by analogy to others rather than by experimental measurement. This is the basis of the parameter and species selection in the current database, FMT_050405.CHEMDAT, which contains the parameters (free energies, Pitzer parameters, etc.) for those species incorporated into the limited species set description. In practice, this has worked well to describe solution behavior in the WIPP within a limited set of pH values at 25 ^{o}C, but does not describe the WIPP system in all regions of interest.

SOTERM-4.5.2 Calculated Actinide Solubilities

The oxidation-state-specific actinide solubilities calculated with the FMT thermodynamic model are summarized in Table SOTERM-17 for the CRA-2004 PABC. For historical perspective, the calculated solubilities from prior PA analyses are tabulated in Table SOTERM-18. In the CRA-2004 PABC, the data are shown for two brines in the presence of organics, and as a function of equilibration with hydromagnesite or magnesite. The hydromagnesite case is recognized by the project as the most relevant to WIPP. It is important to note that, overall, the calculated solubilities have not changed much over time (generally within a factor of two) when organics are not considered.

Table SOTERM-17. Solubilities of the Oxidation-State Analogs (M) with MgO Backfill Calculated for the CRA-2004 PABC (Brush 2005)

Brine	FMT Name	Solubilities of the Actinide Oxidation States from the FMT Calculations for PABC			
		(III)	(IV)	(V)	(VI[a])
GWB	Run 7 (hydromagnesite with organics [hmag. w orgs.])	3.87×10^{-7}	5.64×10^{-8}	3.55×10^{-7}	1×10^{-3}
ERDA-6	Run 11 (hmag. w orgs)	2.88×10^{-7}	6.79×10^{-8}	8.24×10^{-7}	1×10^{-3}
GWB	Run 5 (mag. w orgs)	3.87×10^{-7}	4.57×10^{-8}	6.59×10^{-6}	1×10^{-3}
ERDA-6	Run 9 (mag. w orgs)	2.87×10^{-7}	4.84×10^{-8}	1.08×10^{-5}	1×10^{-3}

hmag. – hydromagnesite
mag. – magnesite
[a] Not calculated with the FMT model

Table SOTERM-18. Historical Actinide Solubilities (M) Calculated (III, IV, and V) or Estimated (VI) for the CRA-2004 PA, the CCA PAVT and the CCA PA (U.S. Department of Energy 2004)

Actinide Oxidation State, and Brine	CRA Solubilities, Microbial Vectors	CRA Solubilities, Nonmicrobial Vectors	PAVT Solubilities	CCA Solubilities
III, Salado brine	3.07×10^{-7}	3.07×10^{-7}	1.2×10^{-7}	5.82×10^{-7}
III, Castile brine	1.69×10^{-7}	1.77×10^{-7}	1.3×10^{-8}	1.3×10^{-8}
IV, Salado brine	1.19×10^{-8}	1.24×10^{-8}	1.3×10^{-8}	4.4×10^{-6}
IV, Castile brine	2.47×10^{-8}	5.84×10^{-9}	4.1×10^{-9}	6.0×10^{-9}
V, Salado brine	1.02×10^{-6}	9.72×10^{-7}	2.4×10^{-7}	2.3×10^{-6}
V, Castile brine	5.08×10^{-6}	2.13×10^{-5}	4.8×10^{-5}	2.2×10^{-6}
VI, Salado brine	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}	8.7×10^{-6}
VI, Castile brine	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}	8.8×10^{-6}

The calculated solubility of the III actinides was 2.87×10^{-7} M to 3.87×10^{-7} M in the CRA-2004 PABC (Brush and Xiong 2005b). These data are also fairly consistent with recently measured results for Nd(III) solubility in brine (Borkowski et al. 2008). A somewhat broader range was noted historically: 1.3×10^{-8} M to 5.82×10^{-7} M. The expected solubility of the IV actinides ranges between 4.57×10^{-8} M and 6.79×10^{-8} M. This is also somewhat consistent with prior calculations (Table SOTERM-18) and has increased slightly. Overall the solubility of the IV actinides is four to eight times lower than that predicted for the III actinides. The main reason for increases noted in CRA-2004 PABC was the presence of organics in the brines.

Uncertainties in the solubility data and uncertainty in the NONLIN least-squares refinement, for Pitzer parameter determination, result in uncertainty in the model predictions. This distribution was sampled and used in PA as discussed in Section SOTERM-5.0 (Xiong, Nowak, and Brush 2005).

SOTERM-4.6 Calculation of the Effects of Organic Ligands on Actinide Solubility

Four organic ligands are included in FMT calculations of actinide solubilities. These are acetate ($CH_3CO_2^-$), citrate [$(CH_2CO_2)_2C(OH)(CO_2)^{3-}$], EDTA [$(CH_2CO_2)_2N(CH_2)_2N(CH_2CO_2)_2^{4-}$], and oxalate ($C_2O_4^{2-}$). The current projected inventory of these complexing agents, with their inventory-limited solubilities in the WIPP, were summarized in Table SOTERM-5. These ligands are included in the solubility calculations because (1) approximately 60 organic compounds were identified among the nonradioactive constituents of the TRU waste to be emplaced in the WIPP (Brush 1990; Drez 1991; U.S. Department of Energy 1996); (2) 10 of these 60 organic compounds could, if present in the WIPP, increase actinide solubilities because they are soluble in aqueous solutions such as WIPP brines, and because they form complexes with dissolved actinides (Choppin 1988); and (3) of these 10 water-soluble organic ligands that form complexes with actinides, 4 (acetate, citrate, EDTA, and oxalate) were identified in the WIPP inventory (See the CCA, Appendix SOTERM, p. 96).

The effects of all four ligands (acetate, citrate, EDTA, and oxalate), as well as the Mg^{2+} and Ca^{2+} species present in brine, were addressed in the calculations of actinide solubility for GWB and ERDA-6 brine in the PABC calculations (Brush 2005). The stability constants for the complexes formed by the listed ligands with Ca^{2+} were assigned the same values as the stability complexes formed by these ligands with Mg^{2+} (Giambalvo 2003). Because of insufficient data these calculations did not include competition from the other dissolved metals such as Fe, V, Cr, Ni, copper (Cu), and Pb, all of which could be present at significant concentrations due to dissolution of steels and other metallic constituents of TRU waste (see Table SOTERM-19 and U.S. Department of Energy 2006). The FMT calculations (Brush 2005) demonstrate that the solubility of the III and IV actinides was not significantly enhanced by complexation with acetate, citrate, EDTA, and oxalate at their maximum potential concentrations (Table SOTERM-19). EDTA does, however, exert a strong influence on the speciation of the III actinides, in that it essentially forms a 1:1 complex with the actinide. In this context, higher levels of EDTA in the repository, should they exist, could overwhelm carbonate complexation and hydrolysis to dominate the speciation of the III actinides.

In the FMT calculations, all four ligands (acetate, citrate, EDTA, and oxalate) were present simultaneously in Salado or Castile brine at the concentrations calculated by Brush and Xiong (2005a). The results of the FMT calculations for the CRA-2004 PABC demonstrate that acetate, citrate, EDTA, and oxalate will not form complexes with the III and IV actinides to a significant extent under expected WIPP conditions, and thus will not significantly affect the III and IV actinide solubilities (Brush and Xiong 2003c; Downes 2003a and 2003b).

The importance and role of colloids in defining the concentration of actinide in the WIPP was discussed in Section SOTERM-3.8, and more extensive discussions of WIPP-related results were

Table SOTERM-19. Comparison of Actinide Solubility Calculations With and Without Organics

Property or Actinide Oxidation State	FMT Run 7 (GWB, hmag, with orgs)	FMT Run 8 (GWB, hmag, without orgs)	FMT Run 11 (ERDA-6, hmag, with orgs)	FMT Run 12 (ERDA-6, hmag, without orgs)
An(III), M	3.87×10^{-7}	2.26×10^{-7}	2.88×10^{-7}	8.67×10^{-8}
An(IV), M	5.64×10^{-8}	5.66×10^{-8}	6.79×10^{-8}	7.20×10^{-8}
An(V), M	3.55×10^{-7}	2.36×10^{-7}	8.24×10^{-7}	5.38×10^{-7}
I, m	7.66	7.54	6.80	6.72
log f_{CO_2}	-5.50	-5.50	-5.50	-5.50
ρ, kg/m^3	1230	1230	1220	1220
pH	8.69	8.69	8.94	9.02
RH, %	73.2	73.3	74.8	74.8

presented in the CRA-2004, Appendix PA, Attachment SOTERM. Results of the colloidal actinide investigation were used in the CRA-2004 PABC, the CRA-2004 PA, the CCA PA, and the 1997 PAVT to define the PA approach to accounting for colloidal enhancement of actinide concentrations. The four types of colloids identified as relevant to the WIPP are listed and described in Table SOTERM-20.

Table SOTERM-20. Classification of Four Colloid Types Considered by WIPP PA

Mineral Fragment Colloids	Hydrophobic, hard-sphere particles that are kinetically stabilized or destabilized by electrostatic forces and may consist of crystalline or amorphous solids. Mineral fragments may be made kinetically stable by coatings with steric stabilizers that prevent close contact. Mineral fragments may act as substrates for sorption of actinides, or they may consist of precipitated or coprecipitated actinide solids.
Intrinsic Actinide Colloids	Intrinsic actinide colloids (also known as true colloids, real colloids, Type I colloids, and Eigenkolloide) are macromolecules of actinides that, at least in some cases, may mature into a mineral-fragment type of colloidal particle. When immature, they are hydrophilic; when mature, they become hydrophobic.
Humic Colloids	Humic substances are hydrophilic, soft-sphere particles that are stabilized by solvation forces. They are often powerful substrates for uptake of metal cations and are relatively small (less than 100,000 atomic mass units).
Microbial Colloids	Microbes are relatively large colloidal particles stabilized by hydrophilic coatings on their surfaces, which behave as steric stabilizing compounds. They may act as substrates for extracellular actinide sorption or actively bioaccumulate actinides intracellularly.

SOTERM-4.7 Calculation of Colloidal Contribution to Actinide Solution Concentrations

Three types of parameter values were determined: (1) constant concentration values, (2) concentration values proportional to the dissolved actinide concentration, and (3) maximum concentration values. The parameter types are summarized below and were initially described in parameter record packages (Papenguth and Behl 1996a; Papenguth 1996a, 1996b, and 1996c)

and resummarized for the CRA-2004 PABC (Garner and Leigh 2005). For intrinsic actinide colloids and mineral-fragment colloids, associated actinide concentrations were described as constant values. Table SOTERM-21 summarizes the material and parameter names and descriptions.

Table SOTERM-21. Material and Property Names for Colloidal Parameters

Material	Property	Brief Description of Parameter
Th, U, Np, Pu, Am	CONCMIN	Concentration of actinide associated with mobile mineral fragment colloids
Th, U, Np, Pu, Am	CONCINT	Concentration of actinide associated with mobile intrinsic actinide colloids
Th, U, Np, Pu, Am	PROPMIC	Proportionality constant for concentration of actinides associated with mobile microbes
PHUMOX3 [a] PHUMOX4 PHUMOX5 PHUMOX6	PHUMCIM	Proportionality constant for concentration of actinides associated with mobile humic colloids; in Castile brine; actinide solubilities are inorganic only (complexes with man-made organic ligands are not important); solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite)
PHUMOX3 [a] PHUMOX4 PHUMOX5 PHUMOX6	PHUMSIM	Proportionality constant for concentration of actinides associated with mobile humic colloids; in Salado brine; actinide solubilities are inorganic only (complexes with man-made organic ligands are not important); solubilities were calculated assuming equilibrium with Mg-bearing minerals (brucite and magnesite)
Th, U, Np, Pu, Am	CAPMIC	Maximum (cap) concentration of actinide associated with mobile microbes
Th, U, Np, Pu, Am	CAPHUM	Maximum (cap) concentration of actinide associated with mobile humic colloids

[a] Proportionality constant for actinide concentrations associated with mobile humic substances for PHUMOX3, for actinide elements with oxidation state *III* (that is, Pu(III) and Am(III)); PHUMOX4, oxidation state IV (Th(IV), U(IV), Np(IV), and Pu(IV)); PHUMOX5, oxidation state V (Np(V)); and PHUMOX6, oxidation state VI (U(VI)).

Experiments conducted to quantify actinide concentrations associated with humic substances and microbes provided the basis for a more sophisticated representation, in which colloidal actinide concentrations were related to the dissolved actinide concentration by proportionality constants. For microbes, the proportionality relationship was made by element. For humic actinides, however, the relationship was made by oxidation state, rather than by element. For microbes and humic substances, the experiments also provided a basis to define upper limits of the actinide concentration that could be associated with each of those colloid types. For both humic and microbial actinides, the upper limit parameter was defined by element, rather than oxidation state, and is in units of molality. The use of the two upper limit parameters is slightly different, and is described in the sections below discussing humic substances and microbes.

The colloid concentration factors used in the CRA-2004 PABC are summarized in Table SOTERM-22. The general approach used to account for colloidal enhancement of actinide solubilities is described in detail by Garner and Leigh (2005). There were essentially no changes in the approach used from the CRA-2004 PA. The maximum concentrations of actinides predicted for the four types of WIPP colloids are tabulated in Table SOTERM-23. These data

Table SOTERM-22. Colloid Concentration Factors (The CRA-2004, Appendix PA, Attachment SOTERM)

Actinide	CONCMIN (Concentration on Mineral Fragments [a])	CONCINT (Concentration as Intrinsic Colloid [a])	PROPMIC (Proportion Sorbed on Microbes [b,c])	CAPMIC (Maximum Sorbed on Microbes[d])	Proportion Sorbed on Humics [b]		CAPHUM (Maximum Sorbed on Humics [a])
					PHUMSIM (Salado)	PHUMCIM (Castile)	
Th(IV)	2.6×10^{-8}	0.0	3.1	0.0019	6.3	6.3	1.1×10^{-5}
U(IV)	2.6×10^{-8}	0.0	0.0021	0.0021	6.3	6.3	1.1×10^{-5}
U(VI)	2.6×10^{-8}	0.0	0.0021	0.0021	0.12	0.51	1.1×10^{-5}
Np(IV)	2.6×10^{-8}	0.0	12.0	0.0027	6.3	6.3	1.1×10^{-5}
Np(V)	2.6×10^{-8}	0.0	12.0	0.0027	9.1×10^{-4}	7.4×10^{-3}	1.1×10^{-5}
Pu(III)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	0.19	1.37 [e]	1.1×10^{-5}
Pu(IV)	2.6×10^{-8}	1.0×10^{-9}	0.3	6.8×10^{-5}	6.3	6.3	1.1×10^{-5}
Am(III)	2.6×10^{-8}	0.0	3.6	1.0	0.19	1.37 [e]	1.1×10^{-5}

[a] In units of moles colloidal actinide per liter
[b] In units of moles colloidal actinide per mole dissolved actinide
[c] For the CRA-2004 PABC, all vectors were microbial
[d] In units of moles total mobile actinide per liter
[e] A cumulative distribution from 0.065 to 1.60 with a median value of 1.37 was used

NOTE: The colloidal source term is added to the dissolved source term to arrive at a total source term. Mineral fragments were provided with distributions, but the maximum was used as described in the CRA-2004, Appendix PA, Attachment SOTERM. Humic proportionality constants for the III, IV, and V states were provided with distributions, but only the Castile Am(III) and Pu(III) were sampled.

Table SOTERM-23. Actinide Concentration or Maximum Concentration Due to Colloidal Enhanced Solution Concentrations (Garner and Leigh 2005)

Actinide	CAPHUM Humic colloids	CAPMIC Microbial Colloids	CONCMIN Mineral Colloids	CONCINT Intrinsic Colloids	PROPMIC Microbial Colloids[a]
Am	1.1×10^{-5} M	1.0 M	2.6×10^{-8} M	0.0	1.0
Np	1.1×10^{-5} M	0.0027 M	2.6×10^{-8} M	0.0	2.7×10^{-3}
Pu	1.1×10^{-5} M	6.8×10^{-5} M	2.6×10^{-8} M	1.00×10^{-9} M	6.8×10^{-5}
Th	1.1×10^{-5} M	0.0019 M	2.6×10^{-8} M	0.0	1.9×10^{-3}
U	1.1×10^{-5} M	0.0021 M	2.6×10^{-8} M	0.0	2.1×10^{-3}

[a] In units of moles colloidal actinide per mole dissolved actinide

show that microbial colloids are likely to have the most significant effect on actinide concentrations, with a smaller but significant contribution from the humic colloidal fraction. Section SOTERM-5.0 provides more details on the PA implementation of these data.

SOTERM-5.0 Use of the Actinide Source Term in PA

The WIPP ASTP provided the parameters to construct the maximum dissolved and suspended colloidal actinide concentrations for use in modeling the mobilization and transport of actinides in the disposal system. In the WIPP PA, mobilization of radionuclides is represented by the PANEL code and transport of radionuclides within the repository and the Salado is represented by the Nuclide Transport System (NUTS) code (Appendix PA-2009, Section PA-4.4 and Section PA-4.3, respectively). A description of the simplifications, manipulations, and approach used in the PA to perform this modeling is discussed in this section.

SOTERM-5.1 Simplifications

The DOE has concentrated on those processes most likely to have a significant impact on system performance. Therefore, several simplifications were used in the modeling of radionuclide mobilization and transport in the CCA PA, the CCA PAVT, the CRA-2004 PA, the CRA-2004 PABC, and the CRA-2009 PA calculations. These include

- Using constant solubility parameters and constant colloidal parameters throughout the repository and regulatory period for a given realization
- Modeling only the isotopes most important to compliance
- Using the compositions of Castile and Salado brines (the end-member brines) to bracket the behavior of mixtures of these brines within the repository
- Sampling only the uncertain parameters with the most significant effect on repository performance
- Combining dissolved and colloidal species for transport within the disposal system, as modeled by NUTS and PANEL

SOTERM-5.1.1 Elements and Isotopes Modeled

Selection of isotopes for modeling mobilization and transport in the disposal system with NUTS and PANEL is described in Appendix PA-2009, Section PA-4.3.3. Runs of PANEL, the PA code that computes total mobilized radionuclide concentrations, include 29 radionuclides in the decay calculations (Garner and Leigh 2005, Table 7 and Table 12). Runs of NUTS, the PA code that computes radionuclide transport within the Salado, are based on five radionuclides: (^{230}Th, ^{234}U, ^{238}Pu, ^{239}Pu, and ^{241}Am) that represent groupings of radionuclides with similar decay and transport properties (Appendix PA-2009, Section PA-4.3.3). The number of radionuclides for transport calculations in NUTS has been reduced because calculations for the full WIPP inventory and decay chains would be very time consuming and because accurate results can be achieved with this limited set of radionuclides.

Transport calculations in the Culebra use a reduced set of four radionuclides: (^{230}Th, ^{234}U, ^{239}Pu, and ^{241}Am) for computational efficiency (Garner 1996). ^{238}Pu has been omitted from transport in

the Culebra because its short half-life (87.7 years) means that little ^{238}Pu will enter the Culebra via brine flows up a borehole.

SOTERM-5.1.2 Use of Brine End Members

The general scenarios described in Appendix PA-2009, Section PA-2.3.2 and Section PA-3.10 and considered in the source term calculations may be categorized into three groups: (1) undisturbed performance (BRAGFLO S1 scenario); (2) intrusion through the repository and into the Castile, intersecting a pressurized brine reservoir (BRAGFLO S2, S3, and S6 scenarios); and (3) intrusion through the repository, but not into a pressurized brine reservoir (BRAGFLO S4 and S5 scenarios). The specific scenarios and the associated type of borehole intrusion considered by the WIPP PA are listed in Table SOTERM-24.

Table SOTERM-24. WIPP PA Modeling Scenarios for the CRA-2004 PABC (Garner and Leigh 2005; Leigh et al. 2005)

BRAGFLO Scenario	Description	Brine Used in PA
S1	E0 (Undisturbed Repository)	Salado (GWB)
S2	E1 intrusion at 350 years penetrates the repository and a brine pocket	Castile (ERDA-6)
S3	E1 intrusion at 1000 years penetrates the repository and a brine pocket	Castile (ERDA-6)
S4	E2 intrusion at 350 years penetrates the repository (only)	Salado (GWB)
S5	E2 intrusion at 1000 years penetrates the repository (only)	Salado (GWB)
S6	E2 intrusion at 1000 years penetrates the repository (only); E1 intrusion at 2000 years penetrates the repository and a brine pocket	Castile (ERDA-6)

Brine may enter the repository from three sources, depending on the nature of the borehole intrusion. Under all scenarios, brine may flow from the surrounding Salado through the DRZ and into the repository in response to the difference between the hydraulic head in the repository and in the surrounding formation. For the BRAGFLO S2 through S6 scenarios, in which a borehole is drilled into the repository, brine may flow down the borehole from the Rustler and/or the Dewey Lake. For the BRAGFLO S2, S3, and S6 scenarios, in which a pressurized Castile brine reservoir is intercepted, brine from the Castile may flow up the borehole into the repository.

As mentioned in Section SOTERM-2.3.1, the brines in the Salado and Castile have different compositions and the actinides solubilities are somewhat different in each of these end-member compositions.

The composition of the more dilute groundwaters from the Rustler and Dewey Lake are expected to change rapidly upon entering the repository as a result of fast dissolution of host Salado minerals from the walls and floor of the repository. These minerals comprise about 90-95% halite and about 1-2% each of polyhalite, gypsum, anhydrite, and magnesite (Brush 1990). Calculations titrating Salado rock into dilute brines using EQ3/6 (Wolery 1992; Wolery and Daveler 1992) show that gypsum, anhydrite, and magnesite saturate before halite. When halite saturates, the brine composition is very similar to that of Castile brine. One hundred times as much polyhalite must be added to the system before the resulting brine has a composition similar to Salado brines. These calculations indicate that if dilute brines dissolve away only the surfaces of the repository, they will obtain Castile-like compositions, but if they circulate through the Salado after saturating with halite, they may obtain compositions similar to Salado brine. Similarly, if Castile brine circulates through enough host rock, it may also approach Salado brine composition. In either case, the actual brine within the repository may be described as a mixture of the two concentrated-brine end members: Salado and Castile. This mixture, however, is very hard to quantify, because it is both temporally and spatially variable. Only in the undisturbed scenario is the mixture well defined as 100% Salado brine over the 10,000-year regulatory period. In this context, the Salado (GWB) and Castile (ERDA-6) brines bracket the range of expected brine compositions.

For a panel intersected by a borehole, the BRAGFLO calculations show that in the 10% of the repository represented by the BRAGFLO panel computational cells, the ratio of brine inflow that enters through the borehole versus through inflow from the host rock varies in time and depends on the sampled parameter values and scenario considered. This ratio was the only measure of brine mixing available to the source term runs in the CCA PA, the CCA PAVT, the CRA-2004 PA, and the CRA-2004-PABC calculations. As an estimate, this ratio (1) does not account for compositional changes that occur when H_2O is consumed by corrosion reactions; (2) does not resolve the details of flow, diffusion, and brine interaction with internal pillars and the DRZ; and (3) is an average over one-tenth of the repository. It is expected that the fraction of Salado brine will be quite high in areas of the repository distant from the borehole and much lower near the borehole. Because radionuclide travel up the borehole can lead to significant release, the solubility of radionuclides near the borehole is important. Given these uncertainties, the DOE decided to use the Castile end-member composition to calculate radionuclide solubilities for scenarios where a borehole penetrates a brine reservoir, and to use the Salado end-member composition for scenarios where it does not (see Table SOTERM-24).

SOTERM-5.1.3 Sampling of Uncertain Parameters

The parameters to be sampled for the PA were selected based on the expected significance of their effect on repository performance. The following four parameters are sampled independently (Garner and Leigh 2005, Table 3 and Table 8):

- The solubility uncertainty for oxidation state III (see discussion below and Figure SOTERM-19).

- The solubility uncertainty for oxidation state IV (see discussion below and Figure SOTERM-20).

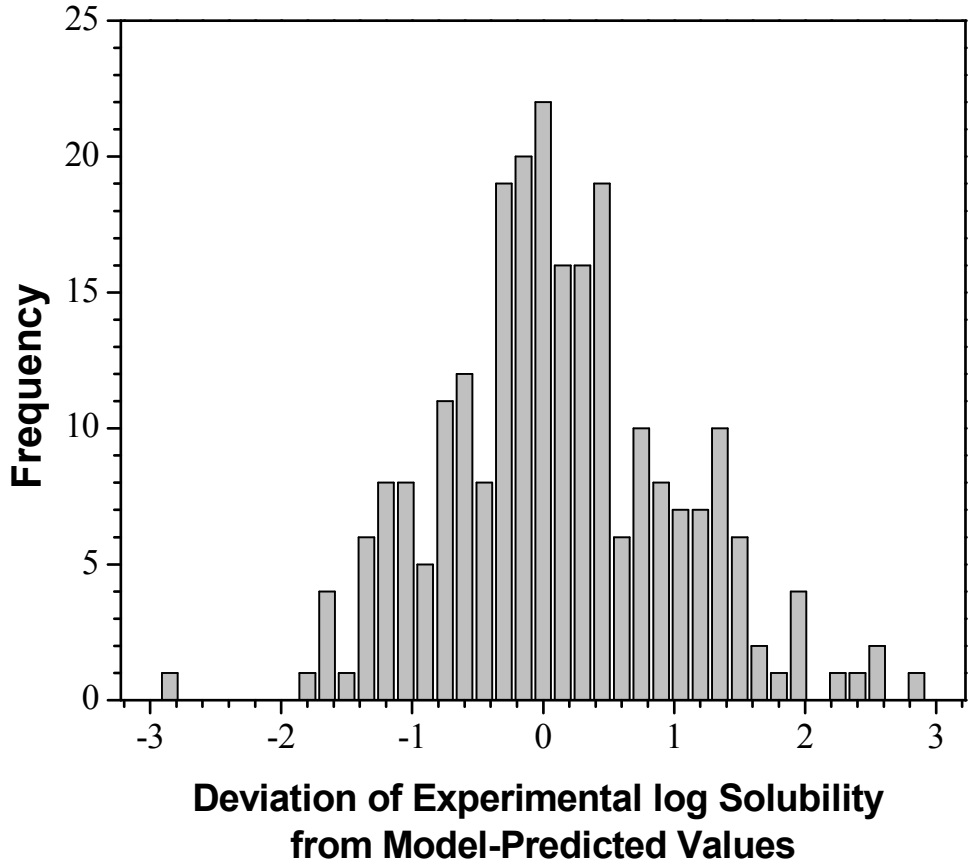


Figure SOTERM-19. Frequency Distribution of the Deviation of Experimental log Solubility from Model-Predicted Value for all An(III) Comparisons. A Total of 243 Measured and Predicted Solubilities were Compared (Xiong 2005).

- The oxidation state for Pu, Np, and U. The sampled value is a flag that is "low" 50% of the time and "high" 50% of the time. If the flag is set to "high," Pu is assumed to be in the IV oxidation state, Np is assumed to be in the V oxidation state, and U is assumed to be in the VI oxidation state. If the flag is set to "low," Pu is assumed to be in the III oxidation state and Np and U are assumed to be in the IV oxidation state.

- The humic-acid proportionality constant for the III oxidation state in Castile brine (see Table SOTERM-22 and Figure SOTERM-21).

As discussed by Garner and Leigh (2005, Section 2.3), the solubility uncertainty for oxidation state V is zero. The solubility uncertainty for oxidation state VI is zero because the EPA specified a fixed, maximum solubility of 1×10^{-3} mol/L for U(VI).

Actinide solubilities for a single realization in the PA depend on (1) the oxidation state; (2) the brine for that realization (see Table SOTERM-24); and (3) the solution concentration uncertainty, as shown in Equation (SOTERM.73).

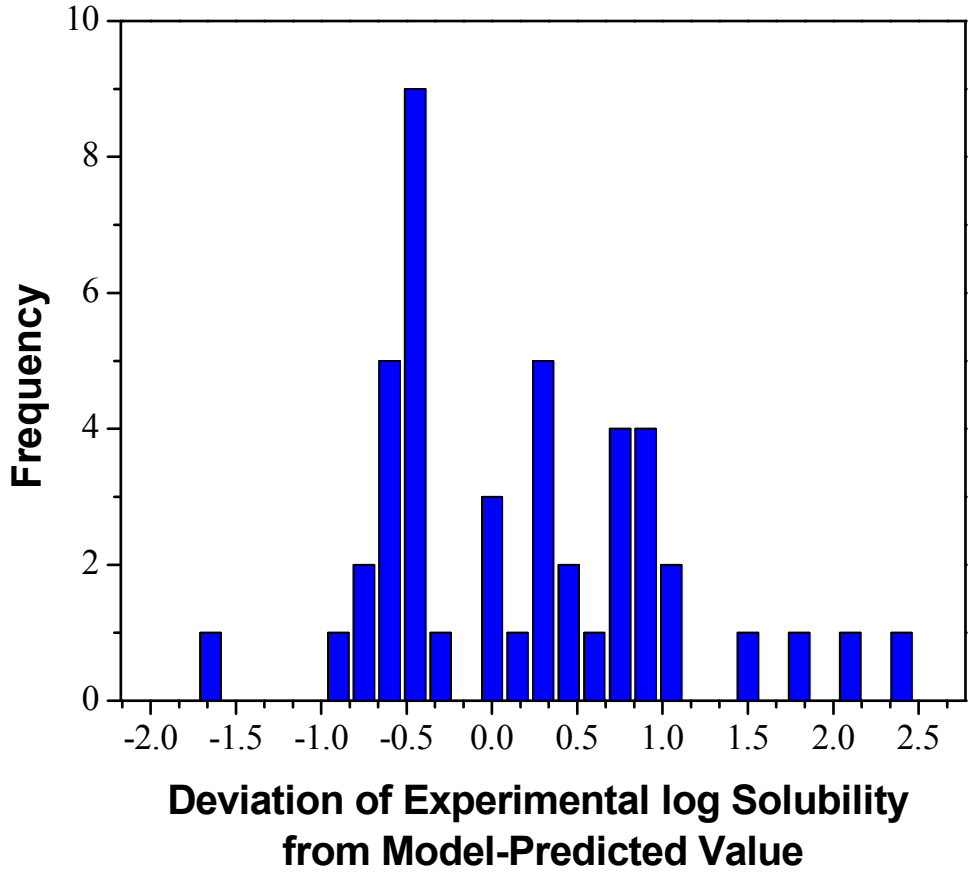


Figure SOTERM-20. Frequency Distribution of the Deviation of Experimental log Solubility from Model-Predicted Value for all An(IV) Comparisons. A Total of 45 Measured and Predicted Solubilities were Compared (Xiong 2005).

$$C_{i,b} = (S_{i,b}) \times (10^{SU_i}) \qquad \text{(SOTERM.73)}$$

$C_{i,b}$, used for every element in oxidation state i, is the concentration of oxidation state i and brine b. $S_{i,b}$ is the solubility calculated for oxidation state i in brine b with FMT (see Table SOTERM-17). SU_i is the solubility uncertainty sampled from a distribution unique to each oxidation state. Figure SOTERM-19 shows the distribution of SU values for oxidation state III. Figure SOTERM-20 shows the distribution of SU values for oxidation state IV. These distributions are calculated and documented in Xiong (2005).

Figure SOTERM-21 shows the cumulative distribution function for the humic-acid proportionality constant.

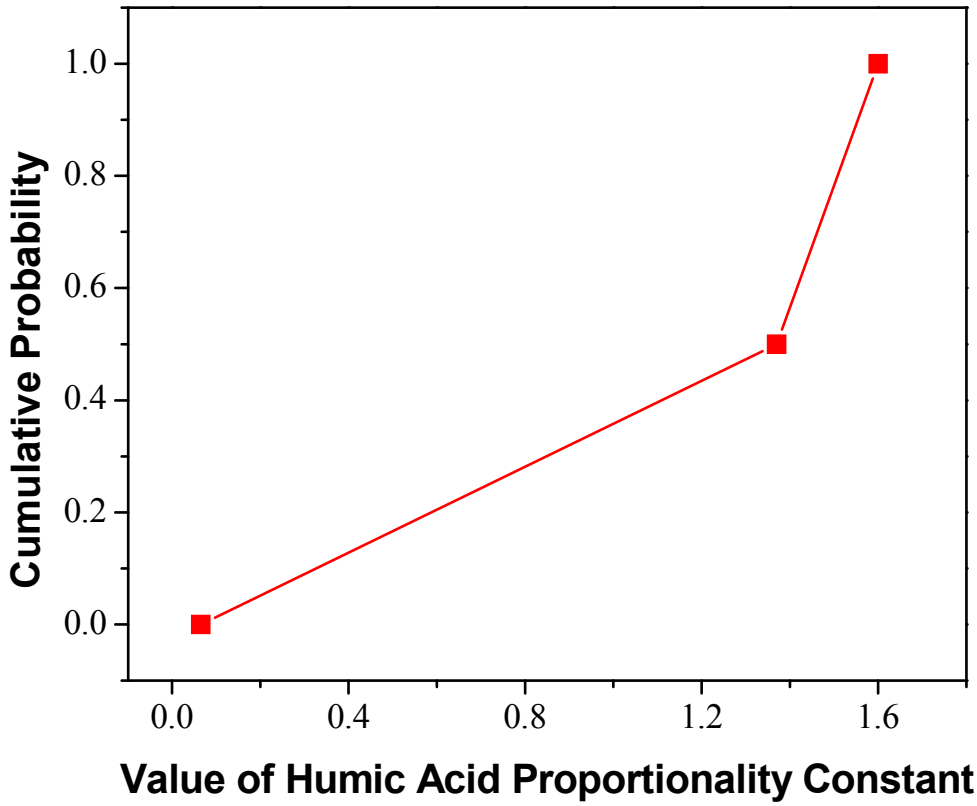


Figure SOTERM-21. Cumulative Distribution Function for the Humic-Acid Proportionality Constant

SOTERM-5.1.4 Combining the Transport of Dissolved and Colloidal Species in the Salado

Dissolved and colloidal species may transport differently because of different diffusion rates, sorption onto stationary materials, and size-exclusion effects (filtration and hydrodynamic chromatography). With maximum molecular diffusion coefficients of about 4×10^{-10} m^2/s, actinides are estimated to diffuse about 10 m in 10,000 years, a negligible distance. Sorption and filtration have beneficial but unquantified effects on performance. Hydrodynamic chromatography may increase colloidal transport over dissolved transport by, at most, a factor of two for theoretically perfect colloidal-transport conditions. In the WIPP, the expected increase is much lower. Given the small or beneficial nature of these effects, they were not included in the CCA PA, the CCA PAVT, the CRA-2004 PA, or the CRA-2004 PABC calculations of radionuclide transport in the repository.

SOTERM-5.2 Construction of the Source Term

Because there was no modeled mechanism in PA to differentiate dissolved from colloidal species, the DOE combined them for transport within the Salado. To model transport within the Culebra, however, this simplification was replaced by separating the mobilized actinides delivered to the Culebra by Salado transport codes into five components (dissolved, humic,

microbial, mineral-fragment, and intrinsic colloids) to account for differences in their transport behavior. This is important because transport within the repository occurs through, at most, hundreds of meters of poorly defined waste undergoing decomposition, whereas transport through the Culebra occurs over kilometers in a relatively homogeneous (compared to waste) fractured dolomite.

The parameters required to construct the source term were as follows:

1. Solubilities for four oxidation states in Salado and Castile brines, the two brine end members.
2. Uncertainty distributions to be applied to the median solubilities for oxidation states III and IV.
3. A scheme for assigning sampled oxidation states ("low" or "high").
4. Colloidal concentrations or proportionality constants for each actinide (Th, U, Np, Pu, and Am) and an associated oxidation state for each of four colloid types.
5. Caps on the actinide concentrations that may be applied to two types of colloids (microbial and humic).
6. Cm is assigned the source term calculated for Am.

Cm and Np are not explicitly transported in NUTS (see Section SOTERM-5.1.1) although they are implicitly lumped with other modeled isotopes. They are, however, included in the PANEL calculations for use with the DBR calculations in PA.

These parameters are combined into a single maximum concentration for each modeled actinide in the PA calculations. The term "total mobilized concentration" is used for the combined concentrations of dissolved and colloidal species. The combined concentrations are not necessarily the actual concentrations, because the concentration may be lower as a result of inventory limits. Both NUTS and PANEL assume that the actinide concentrations specified by the total mobilized concentrations are attained instantaneously as long as sufficient inventory is available. When the inventory is insufficient, the actual mobilized concentration will be lower and is said to be inventory limited. The calculation of the total mobilized concentration is performed by PANEL for each of 100 sampled vectors in a replicate. A similar methodology to generate the combined maximum concentrations was also used for the CCA PA, the CCA PAVT, the CRA-2004 PA, and the CRA-2004 PABC.

All of the source term parameters and their associated distributions are entered into the PA parameter database. For each sampled parameter, the Latin Hypercube Sampling code uses the distribution from the PA parameter database to create 100 sampled values. These values are combined with the parameters that have constant values and stored in computational databases for each of the 100 vectors (i.e., 100 realizations), which constitute one replicate. For each realization, PANEL uses both the constant and sampled values for all of the source term parameters, and constructs the source term for NUTS and PANEL, as shown below. This process is repeated for scenarios using the Salado end-member total mobilized concentration and for scenarios using the Castile end-member total mobilized concentration.

$$\text{Dissolved} = \text{Base Solubility} \times 10^{\text{Sampled from Solubility Distribution}} \quad \text{(SOTERM.74)}$$

IF (Dissolved × Proportionality Constant < Humic Cap),
THEN Humic = Dissolved × Proportionality Constant, (SOTERM.75)
ELSE Humic = Humic Cap

IF (Total Mobile < Microbial Cap),
THEN Microbial = Dissolved × Proportionality Constant, (SOTERM.76)
ELSE Microbial = Microbial Cap

Mineral = Database Concentration (a constant value) (SOTERM.77)

Intrinsic = Database Concentration (a constant value) (SOTERM.78)

Total Mobile = Dissolved + Humic + Microbial + Mineral + Intrinsic (SOTERM.79)

For actinides with more than one oxidation state, the oxidation state is specified by the oxidation-state parameter

IF (OXSTAT ≤ 0.5); THEN Lower Oxidation State,
ELSE Higher Oxidation State (SOTERM.80)

where OXSTAT is the oxidation-state parameter sampled from a uniform distribution between 0 and 1.

Similar solubility calculations are performed for Am, U, Th, and Np. The total mobilized concentration and mobile fractions for Cm are set equal to the values for Am. In addition, the PA groups radioisotopes with similar decay and transport properties for the NUTS and SECOTP2D (component radionuclide transport in fractures or granular acquifers) transport calculations, as explained in Section SOTERM-5.1.1. For example, the U solubility is decreased to account for the shared solubility with the low-activity ^{238}U, which is not explicitly modeled, enabling NUTS to properly represent the effect of the U isotopes on compliance using the single lumped isotope ^{234}U (the CRA-2004, Appendix PA, Section PA-4.3.3).

PANEL also calculates the fraction of each actinide mobilized by the five different mechanisms, as follows:

Fraction dissolved = Dissolved/Total Mobilized Concentration (Conc.) (SOTERM.81)

Fraction on humics = Humic/Total Mobilized Conc. (SOTERM.82)

Fraction in/on microbes = Microbe/Total Mobilized Conc. (SOTERM.83)

Fraction on mineral fragments = Mineral/Total Mobilized Conc. (SOTERM. 84)

Fraction as intrinsic colloid = Intrinsic/Total Mobilized Conc. (SOTERM.85)

SOTERM-5.3 Example Calculation of Actinide Solubility

For example, for one realization in Salado brine, the sampled value for OXSTAT was 0.9, so Pu would be present in the IV state. The sampled value of the solubility uncertainty distribution was 1.8 for the IV state, which has a median brine solubility of 5.64×10^{-8} M. The humic proportionality constant for the IV oxidation state in Salado brine is 6.3, the microbial proportionality constant for Pu is 0.3, the humic cap is 1.1×10^{-5} M, the microbe cap for Pu is 6.8×10^{-5} M, the concentration of the actinide on mineral fragments is 2.6×10^{-8} M, and the Pu intrinsic-colloid concentration is 1×10^{-9} M.

For this realization, the maximum dissolved concentration of Pu(IV) used by the PA would be

$$C_{Pu} = (5.64 \times 10^{-8}) \times (10^{1.8}) = 3.6 \times 10^{-6} \text{ M}. \quad \text{(SOTERM.86)}$$

(The calculations for this example have been rounded to two significant figures, although the PA would not round the intermediate or final values.) C_{Pu} is the maximum dissolved concentration of all combined isotopes of Pu.

The maximum humic-complexed Pu would be

$$(3.6 \times 10^{-6} \text{ M})(6.3 \text{ mol adsorbed per mol}) = 2.3 \times 10^{-5} \text{ M}. \quad \text{(SOTERM.87)}$$

This value, however, exceeds the cap for humic-mobilized Pu, 1.1×10^{-5} M. Therefore, in this case, the cap would be used for the maximum humic-mobilized actinide concentration. Note that the humic-mobilized concentration of Pu exceeds the maximum dissolved concentration of Pu, which is usually the case.

The maximum microbial-mobilized Pu would be

$$(3.6 \times 10^{-6} \text{ M})(0.3 \text{ mol bioaccumulated per mol}) = 1.1 \times 10^{-6} \text{ M}. \quad \text{(SOTERM.88)}$$

This value is less than the cap, 6.8×10^{-5} M, so the cap does not affect microbial-mobilized Pu for this realization.

The total mobilized concentration of Pu(IV) for this realization would then be the sum of the dissolved and colloidal contributions (see Equation [SOTERM.79]):

$$\begin{aligned} \text{Total Mobile} &= \text{Dissolved} + \text{Humic} + \text{Microbial} + \text{Mineral} + \text{Intrinsic}, \quad \text{(SOTERM.89)} \\ &= 3.6 \times 10^{-6} + 1.1 \times 10^{-5} + 1.1 \times 10^{-6} + 2.6 \times 10^{-8} + 1.0 \times 10^{-9}, \\ &= 1.6 \times 10^{-5} \text{ M}. \end{aligned}$$

SOTERM-5.4 Calculated Dissolved, Colloidal, and Total Actinide Solubilities

The output of the PANEL calculations is a computational database containing the source term and effective inventories. NUTS and PANEL both assume instantaneous dissolution and colloidal mobilization up to the solubility limits when sufficient inventory is present, as discussed in Appendix PA-2009, Section PA-4.3. Table SOTERM-25 shows the dissolved and

Table SOTERM-25. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values for the CCA PAVT and CRA-2004 PABC[a]

Actinide Oxidation State and Brine	PAVT	CRA-2004 PABC
Pu(III), dissolved, Salado brine	9.75×10^{-8}	3.61×10^{-7}
Pu(III), colloidal, Salado brine	7.48×10^{-8}	2.04×10^{-7}
Pu(III), total mobile, Salado brine	1.72×10^{-7}	5.64×10^{-7}
Pu(III), dissolved, Castile brine	1.06×10^{-8}	2.68×10^{-7}
Pu(III), colloidal, Castile brine	4.46×10^{-8}	4.75×10^{-7}
Pu(III), total mobile, Castile brine	5.52×10^{-8}	7.44×10^{-7}
Am(III), dissolved, Salado brine	9.75×10^{-8}	3.61×10^{-7}
Am(III), colloidal, Salado brine	3.96×10^{-7}	1.39×10^{-6}
Am(III), total mobile, Salado brine	4.93×10^{-7}	1.75×10^{-6}
Am(III), dissolved, Castile brine	1.06×10^{-8}	2.68×10^{-7}
Am(III), colloidal, Castile brine	7.78×10^{-8}	1.34×10^{-6}
Am(III), total mobile, Castile brine	8.83×10^{-8}	1.61×10^{-6}
Th(IV), dissolved, Salado brine	1.06×10^{-8}	6.70×10^{-8}
Th(IV), colloidal, Salado brine	1.25×10^{-7}	6.56×10^{-7}
Th(IV), total mobile, Salado brine	1.36×10^{-7}	7.23×10^{-7}
Th(IV), dissolved, Castile brine	3.33×10^{-8}	8.07×10^{-8}
Th(IV), colloidal, Castile brine	3.39×10^{-7}	7.85×10^{-7}
Th(IV), total mobile, Castile brine	3.73×10^{-7}	8.65×10^{-7}
U(IV), dissolved, Salado brine	1.06×10^{-8}	6.70×10^{-8}
U(IV), colloidal, Salado brine	9.26×10^{-8}	4.48×10^{-7}
U(IV), total mobile, Salado brine	1.03×10^{-7}	5.15×10^{-7}
U(IV), dissolved, Castile brine	3.33×10^{-8}	8.07×10^{-8}
U(IV), colloidal, Castile brine	2.36×10^{-7}	5.35×10^{-7}
U(IV), total mobile, Castile brine	2.69×10^{-7}	6.15×10^{-7}
Pu(IV), dissolved, Salado brine	1.06×10^{-8}	6.70×10^{-8}
Pu(IV), colloidal, Salado brine	9.67×10^{-8}	4.69×10^{-7}
Pu(IV), total mobile, Salado brine	1.07×10^{-7}	5.36×10^{-7}
Pu(IV), dissolved, Castile brine	3.33×10^{-8}	8.07×10^{-8}
Pu(IV), colloidal, Castile brine	2.47×10^{-7}	5.60×10^{-7}
Pu(IV), total mobile, Castile brine	2.80×10^{-7}	6.40×10^{-7}
U(VI), dissolved, Salado brine	7.07×10^{-6}	1.00×10^{-3}
U(VI), colloidal, Salado brine	8.89×10^{-7}	1.31×10^{-5}

[a] Values are calculated using data retrieved from the WIPP PA Database http://yardbirds.sandia.gov/pview/ and equations SOTERM.75 through SOTERM.79.

Table SOTERM-25. Concentrations (M) of Dissolved, Colloidal, and Total Mobile Actinides Obtained Using Median Parameter Values for the CCA PAVT and CRA-2004 PABC[a] (Continued)

Actinide Oxidation State and Brine	PAVT	CRA-2004 PABC
U(VI), total mobile, Salado brine	7.96×10^{-6}	1.01×10^{-3}
U(VI), dissolved, Castile brine	7.15×10^{-6}	1.00×10^{-3}
U(VI), colloidal, Castile brine	3.69×10^{-6}	1.31×10^{-5}
U(VI), total mobile, Castile brine	1.08×10^{-5}	1.01×10^{-3}

[a] Values are calculated using data retrieved from the WIPP PA Database http://yardbirds.sandia.gov/pview/ and equations SOTERM.75 through SOTERM.79.

colloidal components of the source term and the total mobile actinide concentrations obtained when median parameter values are used. The values from CRA-2004 PABC have been used as the source term in the PA for CRA-2009.

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Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix TFIELD-2009
Transmissivity Fields

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix TFIELD-2009
Transmissivity Fields

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Preface

Appendix TFIELD-2009 and the associated transmissivity fields for Compliance Recertification Application (CRA)-2009 were originally prepared for the CRA-2004 Performance Assessment Baseline Calculation. The only changes that have been made to the text are minor and editorial in nature, such as corrections of referencing errors and the addition of a missing reference. Although additional hydrogeologic investigations, described in Appendix HYDRO-2009, were performed after these transmissivity fields (T fields) were constructed, T fields incorporating the new data have not been completed.

Acronyms and Abbreviations

%	percent
AP	Analysis Plan
BLM	Bureau of Land Management
CCA	Compliance Certification Application
CDF	cumulative distribution function
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	feet
ft^2	square feet
GHz	gigahertz
GSLIB	Geostatistical Software Library
high-T	high-transmissivity
km	kilometer
LHS	Latin hypercube sampling
low-T	low-transmissivity
LWB	Land Withdrawal Boundary
m	meter
m^2	square meters
M/H	mudstone/halite
m^2/s	square meters per second
m^3/s	cubic meters per second
mi	mile
PA	performance assessment
PEST	Parameter ESTimation software
RMSE	root mean squared error
s	second
S	storativity
SNL	Sandia National Laboratories
SP	stress period
SSE	sum of squared errors

T field	transmissivity field
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WIPP	Waste Isolation Pilot Plant
WQSP	Water Quality Sampling Program

TFIELD-1.0 Overview of Transmissivity Field Development, Calibration, and Modification Process

Modeling the transport of radionuclides through the Culebra Dolomite Member of the Rustler Formation (hereafter referred to as the Culebra) is one component of the Performance Assessment (PA) performed for the Waste Isolation Pilot Plant (WIPP) Compliance Recertification Application (CRA). This transport modeling requires a model of groundwater flow through the Culebra. This Appendix describes the process used to develop and calibrate the transmissivity fields (T fields) for the Culebra, and then modify them for the possible effects of potash mining for use in flow modeling for the CRA-2004 (U.S. Department of Energy 2004).

The work described in this appendix was performed under two Sandia National Laboratories (SNL) Analysis Plans (APs): AP-088 (Beauheim 2002a) and AP-100 (Leigh, Beauheim, and Kanney 2003). AP-088 (Analysis Plan for the Evaluation of the Effects of Head Changes on Calibration of Culebra T Fields) dealt with the development, calibration, and modification for potash mining of the T fields. AP-100 (Analysis Plan for Calculations of Culebra Flow and Transport: Compliance Recertification Application) included the development of T-field acceptance criteria, as well as radionuclide-transport calculations not described herein.

The starting point in the T-field development process was to assemble information on geologic factors that might affect Culebra transmissivity (Section TFIELD-2.0). These factors include dissolution of the upper Salado Formation, the thickness of overburden above the Culebra, and the spatial distribution of halite in the Rustler Formation above and below the Culebra. Geologic information is available from hundreds of oil and gas wells and potash exploration holes in the vicinity of the WIPP site, while transmissivity values are available from only 46 well locations. Details of the geologic data compilation are given in Powers (2002a, 2002b, 2003) and summarized below in Section TFIELD-2.0.

A two-part "geologically based" approach was then used to generate Culebra base T fields. In the first part (Section TFIELD-3.0), a conceptual model for geologic controls on Culebra transmissivity was formalized, and the hypothesized geologic controls were regressed against Culebra transmissivity data to determine linear regression coefficients. The regression includes one continuously varying function, Culebra overburden thickness, and three indicator functions that assume values of 0 or 1 depending on the occurrence of open, interconnected fractures, Salado dissolution, and the presence or absence of halite in units bounding the Culebra.

In the second part (Section TFIELD-4.0), a method was developed for applying the linear regression model to predict Culebra transmissivity across the WIPP area. The regression model was combined with the maps of geologic factors to create 500 stochastically varying Culebra base T fields. Details about the development of the regression model and the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

By the nature of regression models, the base T fields do not honor the measured transmissivity values at the measurement locations. Therefore, before these base T fields could be used in a flow model, they had to be conditioned to the measured transmissivity values. This conditioning is described in McKenna and Hart (2003a, 2003b) and summarized in Section TFIELD-5.0. Section TFIELD-6.0 presents details on the modeling approach used to calibrate the T fields to

both steady-state heads and transient drawdown measurements. Heads measured in late 2000 were used to represent steady-state conditions in the Culebra, and drawdown responses in 40 wells to pumping in 7 wells were used to provide transient calibration data. Details on the heads and drawdown data used are described in Beauheim (2002b) and Beauheim and Fox (2003). Assumptions made in modeling, the definition of an initial head distribution, assignment of boundary conditions, discretization of the spatial and temporal domain, weighting of the observations, and the use of Parameter ESTimation software (PEST) (Doherty 2002) in combination with MODFLOW-2000 (Harbaugh et al. 2000) to calibrate the T fields using a pilot-point method are described in McKenna and Hart (2003a, 2003b) and summarized in Section TFIELD-6.0.

Section TFIELD-7.0 addresses the development and application of acceptance criteria for the T fields. Acceptance was based on a combination of objective fit to the calibration data and providing travel time results consistent with the cumulative distribution function (CDF) of travel times from the 23 best-calibrated T fields (Beauheim 2003). Of the 146 T fields that went through the calibration process, 121 T fields were judged adequate for further use, with the 100 best T fields selected for use in the CRA-2004 transport calculations.

Section TFIELD-8.0 provides summary statistics and other information for the 121 T fields that were judged to be acceptably calibrated. Particle tracks from a point above the center of the WIPP disposal panels to the Land Withdrawal Boundary (LWB) are shown, along with information on the model fits to steady-state heads, identification of the most sensitive pilot point locations, and characteristics of an ensemble average T field. This information is summarized from McKenna and Hart (2003b).

Section TFIELD-9.0 discusses the modification of the T fields to account for the effects of potash mining both within and outside the WIPP LWB. Mining-affected areas were delineated, random transmissivity multipliers were applied to transmissivities in those areas, and particle tracks and travel times were determined (Lowry 2003). The flow fields produced by these mining-affected T fields are input to SECOTP2D for the CRA-2004 radionuclide-transport calculations.

Section TFIELD-10.0 provides a brief summary of this appendix.

TFIELD-2.0 Development of Maps of Geologic Factors

Beauheim and Holt (1990), among others, suggested three geologic factors that might be related to the transmissivity of the Culebra in the vicinity of the WIPP site:

1. Thickness (or erosion) of overburden above the Culebra
2. Dissolution of the upper Salado
3. Spatial distribution of halite in the Rustler below and above the Culebra

Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra transmissivity leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity.

Maps were developed for each of these factors using drillhole data of different types. The general area for the geologic study comprised 12 townships, located in townships T21S to T24S, ranges R30 to 32E (the WIPP site lies in T22S, R31E). The original sources of geologic data for this analysis are mainly Powers and Holt (1995) and Holt and Powers (1988) and new information derived by log interpretation by Powers (2002a, 2002b, 2003). All of the data are either included or summarized in the references cited above, and can be independently checked; basic data reports are available for WIPP drillholes, geophysical logs for oil and gas wells are available commercially or at offices of the Oil Conservation Division (New Mexico) in Artesia and Hobbs, and potash drillhole information is in files that can be accessed for stratigraphic information at the Bureau of Land Management (BLM), Carlsbad, NM. No proprietary data are included.

Factor 1 is represented by a structure contour map of the elevation of the top of the Culebra (Figure TFIELD-1) that can be digitized and then subtracted from a digital elevation model of the land surface to obtain the thickness of overburden. Factor 2 is represented on a map as an approximate margin of the area beginning to be affected by dissolution of the upper Salado (Figure TFIELD-2). Factor 3 is delineated on a map by lines that represent as nearly as possible the boundaries of the occurrence of halite in the Los Medaños, Tamarisk, and Forty-niner Members of the Rustler in the study domain (Figure TFIELD-3).

With respect to Factor 2, the upper Salado has been dissolved, and presumably is still dissolving, along the eastern margin of Nash Draw. On the basis of limited core information, Holt and Powers (1988) suggested that formations overlying the dissolving upper Salado in Nash Draw are affected in proportion to the amount of Salado dissolution. The most direct way to estimate the spatial distribution of dissolution is to have cores of the upper Salado and basal Rustler and knowledge of the thickness to marker beds in the upper Salado. The upper Salado has not been cored frequently, but geophysical logs from oil and gas wells, and descriptive logs of cores or cuttings from potash drillholes, provide a considerable amount of evidence of the thickness of the lower Rustler and upper Salado, even though cores and cuttings are no longer available from potash industry drillholes.

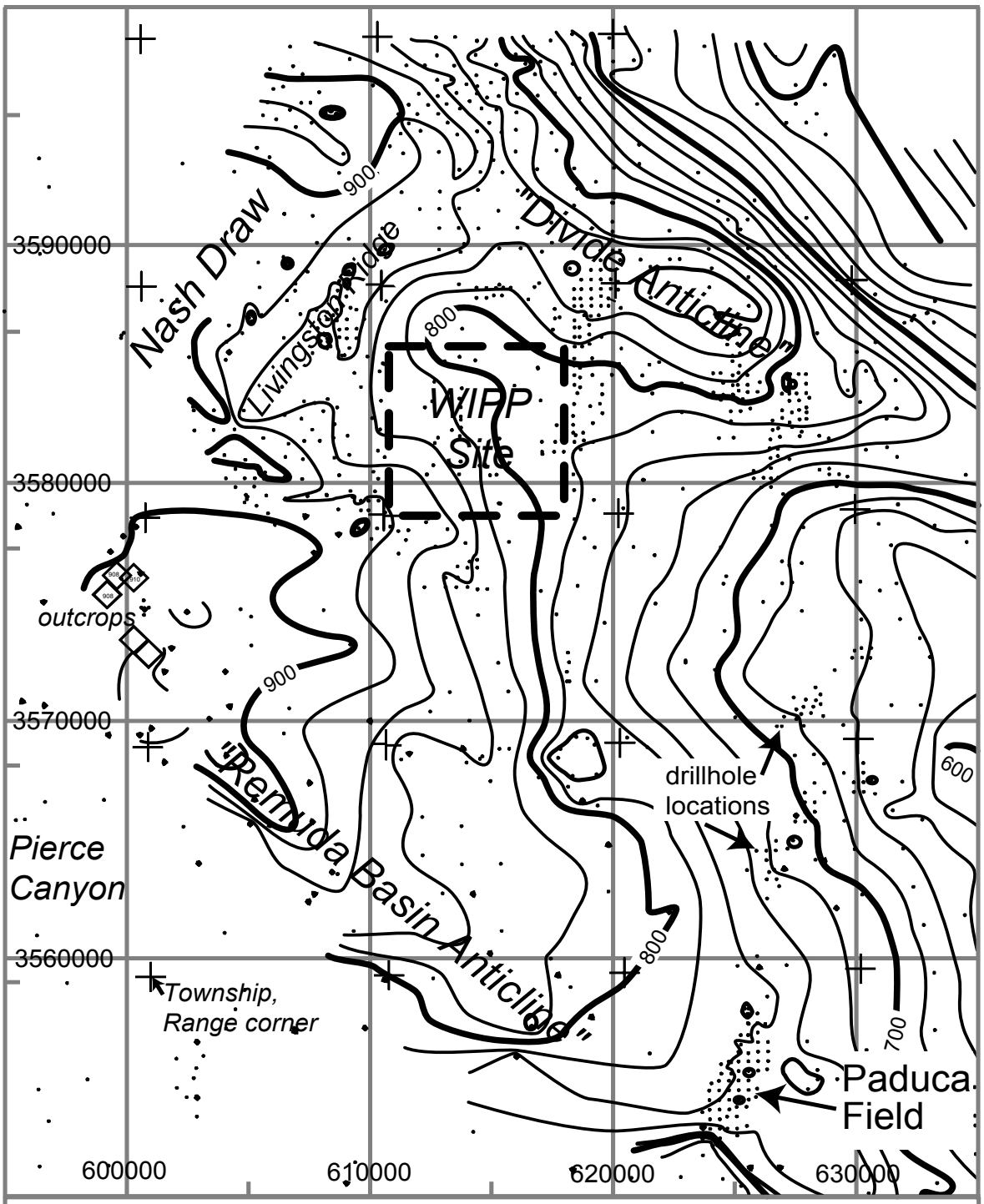


Figure TFIELD-1. Structure Contour Map for the Top of the Culebra

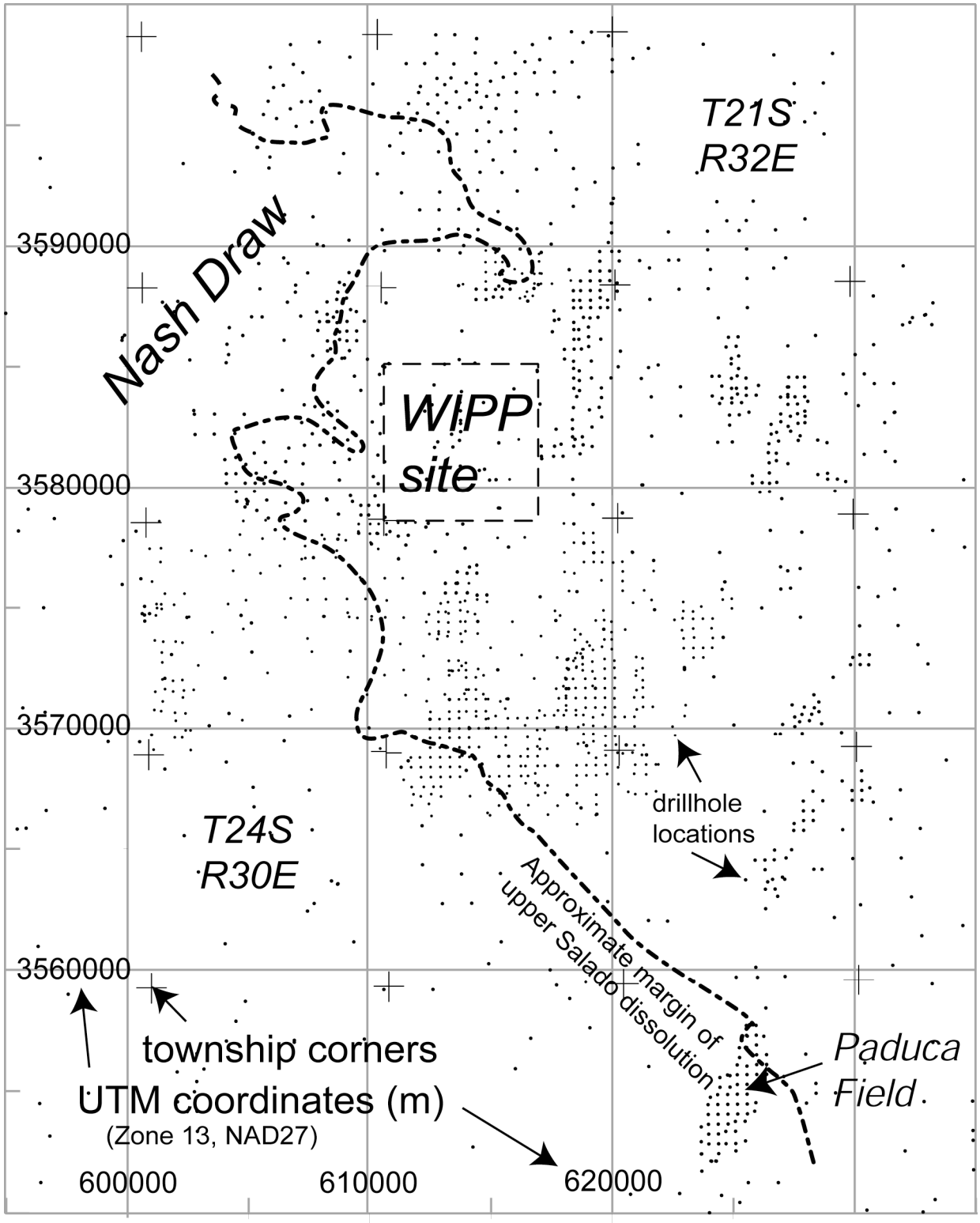
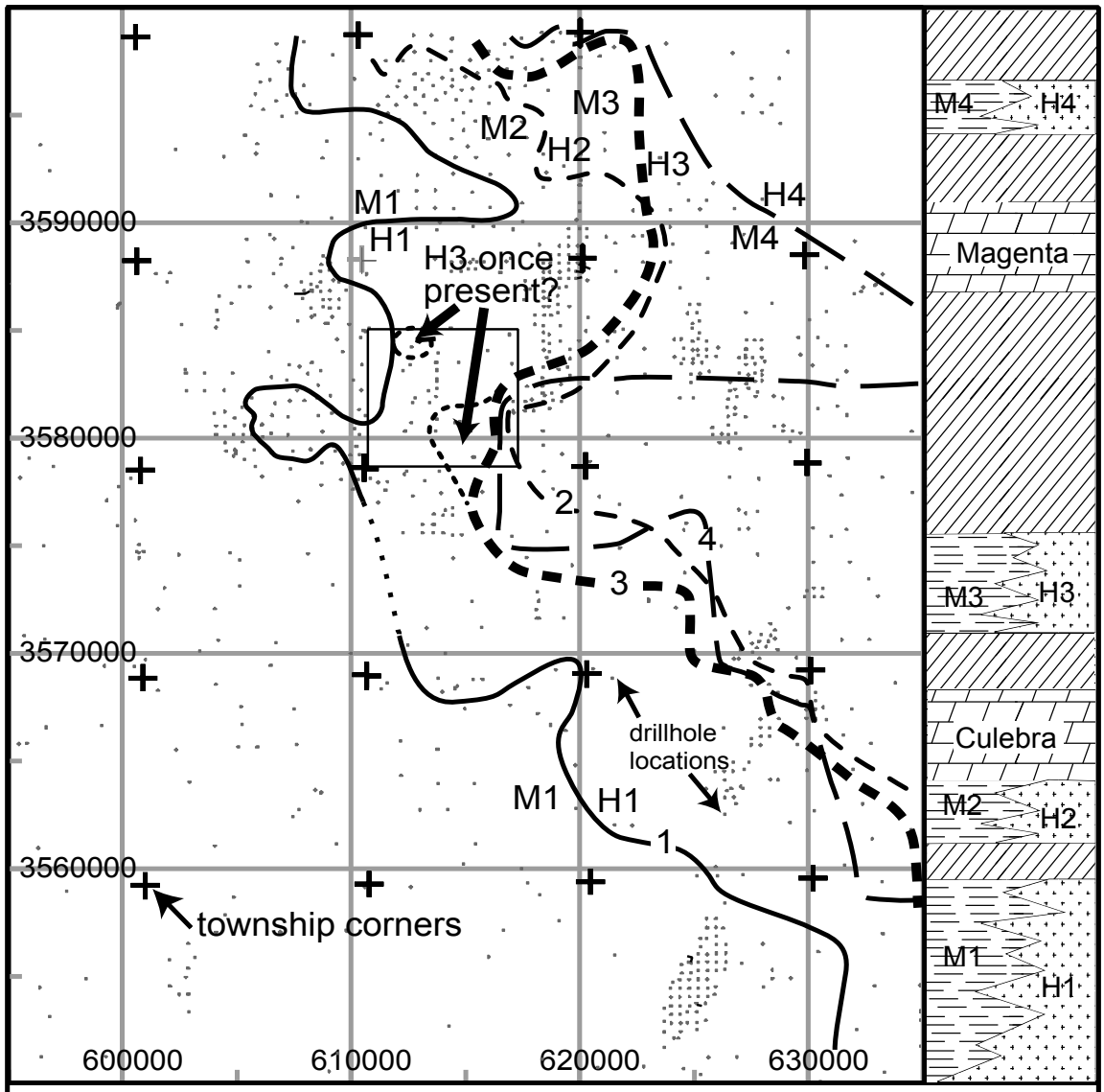


Figure TFIELD-2. Salado Dissolution Margin



Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure TFIELD-4).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬ ▬ ▬ ▪).

Figure TFIELD-3. Rustler Halite Margins. See Figure TFIELD-4 for Key to Stratigraphic Column.

Potash industry geological logs examined at the BLM in Carlsbad, NM, are quite variable in the quality of description and the stratigraphic interval described. Drillhole logs from the 1930s and 1950s typically are the most descriptive; recent drillhole logs are commonly useless for this project because no strata are described above portions of the McNutt potash zone of the Salado, near the middle of the formation.

The top of the Culebra and the base of the Vaca Triste Sandstone Member in the upper Salado are the most consistent stratigraphic markers spanning the upper Salado that are recognizable across various types of records. As a guide to the limits or bounds of upper Salado dissolution, a map of the thickness from the top of Culebra to the base of Vaca Triste was prepared (Powers 2003). In conjunction with previous work by Powers and Holt (1995) and the evidence of the structure of the top of Culebra (see Figure TFIELD-1), an approximate boundary of dissolution was drawn as shown in Figure TFIELD-2.

With respect to Factor 3, the boundaries of where halite is found in the three non-carbonate members of the Rustler have been drawn several times on the basis of different borehole data sets and different data types (e.g., core data and geophysical logs). For the most part, the different versions of the boundaries do not vary significantly. In the map shown in Figure TFIELD-3, the margins are based principally on the work of Powers and Holt (1995), which is a continuation of work reported by Holt and Powers (1988). As discussed in Powers and Holt (1995), the boundaries drawn here vary slightly from those drawn by Snyder (1985) based on core data for two reasons: (1) the Los Medaños Member (Powers and Holt 1999; formerly called the unnamed lower member) is here divided into two separate halite-bearing units (Powers and Holt 2000), and (2) geophysical log signatures are now used to identify halite in areas where cores are not available. Figure TFIELD-3 includes a stratigraphic sketch showing the relationship of halite-bearing strata to other strata in the Rustler. Following the convention established by Holt and Powers (1988), the mudstone/halite (M/H) strata are numbered consecutively starting at the base of the Rustler.

The margins for halite have now been drawn in the area north of the WIPP site around the northeastern arm of Nash Draw based on the descriptions of halite encounters in the Rustler Formation in potash drillholes. In addition, a few areas have been modified (from Powers and Holt 1995) to the south and west of the WIPP based on the records from potash drillholes as well as the records of drilling H-12 and H-17 for the WIPP.

In 12 potash drillholes, halite was reported above the upper contacts of the Culebra or Magenta Dolomite Members. The boundaries for M3/H3 and M4/H4 margins (i.e., the spatial limits of where halite is found in the mudstone intervals) have been drawn north of the WIPP based on these data. The depth below the Culebra at which halite was reported has also been used to draw the boundaries of the lower (M1/H1) or the upper (M2/H2) halite-bearing units of the Los Medaños in this area. Anhydrite A1 divides the M1/H1 (below) and M2/H2 (above) intervals. M2 (no halite) is about 3 meters (m) (10 feet [ft]) thick. If halite is reported within about 3 m (10 ft) of the base of Culebra or is clearly above A1, H2 is considered to be present. The M1/H1 interval is about 33–37 m (110–120 ft) thick at the WIPP site. In potash drillholes north of the WIPP site, where halite was reported less than 33 m (110 ft) below the Culebra, H1 is present. Within the zone for H1, other drillholes frequently reveal halite less than 33 m (110 ft) below the Culebra.

It should be noted that the report of "top of salt" or first salt in records for potash drillholes does not consistently mean the same thing and is frequently not the uppermost halite. It may instead mean the first halite that is encountered after coring begins or the first unit that is dominantly halite. Detailed inspection of logs sometimes shows halite described from cuttings, with a summary report of "top of salt" much deeper. In some cases, it appears "top of salt" is an estimate of where the Salado-Rustler contact should be.

Halite margins in the Rustler are interpreted as mainly due to depositional limits of saltpan environments and syndepositional removal of some halite exposed in saline mud flat deposits (Holt and Powers 1988). The halite margins are expected to be the locus of halite dissolution, if any, since the Rustler was deposited. Facies including halite beds or halite cements are expected to be less permeable than the equivalent mudstone facies. As a consequence, the margin is more likely to be attacked by advection and diffusion at the margin, from the mudstone facies side of the margin. In addition, removing halite along the margin as the saltpan margin fluctuates is likely to introduce some vertical and horizontal discontinuities that persist after lithification and are not created where the saltpan persisted. Water in adjacent units or in the mudstone unit likely has more pathways along these margins, increasing the likelihood that the margins will be the locus of dissolution. Recent findings of a narrow margin along which halite is dissolved from the upper Salado (Powers et al. 2003) are consistent with the expectation that halite margins in the Rustler would be the locus of dissolution.

Two areas have been identified where halite appears to have been dissolved from the M3/H3 interval after deposition of the Rustler. These areas are shown with the annotation "H3 once present?" on Figure TFIELD-3. In the vicinity of drillhole H-19b0 and south (the southern area shown), cores of several WIPP drillholes show brecciation of the upper Tamarisk Member anhydrite in response to dissolution. Another area of dissolution, previously discussed in Holt and Powers (1988), Powers and Holt (1995), and Beauheim and Holt (1990), is around WIPP-13 (the northern area shown), and may represent an outlier of salt left behind during syndepositional removal of halite from the M3 areas west of the WIPP site (Powers and Holt 2000). These areas have not been extended interpretively on Figure TFIELD-3 as was done in Beauheim and Holt (1990), but are limited to the vicinities of the locations at which evidence of dissolution has been directly observed.

Because of the position of M2/H2 directly beneath the Culebra, dissolution of H2 might be expected to have a strong influence on Culebra transmissivity. However, the H2 depositional margin is largely east of the WIPP site, barely crossing the southern portion of the eastern WIPP site boundary (Figure TFIELD-3). H2 dissolution does not appear to be a factor affecting Culebra transmissivity in any hydrology test well for WIPP, but there are no direct observations along the H2 margin.

TFIELD-3.0 Development of Model Relating Culebra Transmissivity to Geologic Factors

Holt and Powers (1988), Powers and Holt (1990), Beauheim and Holt (1990), and Holt (1997) have described the geology and geologic history of the Culebra. The following model is developed from their work and is consistent with their interpretations. It is important to note that this work follows Holt (1997) and assumes that variability in Culebra transmissivity is due strictly to post-depositional processes. Throughout the following discussion, the informal stratigraphic subdivisions of Holt and Powers (1988) are used to identify geologic units within the Rustler (Figure TFIELD-4).

The spatial distribution of Culebra transmissivity on a regional scale is a function of a series of deterministic geologic controls, including Culebra overburden thickness, dissolution of the upper Salado, and the occurrence of halite in units above or below the Culebra. Each of these geologic controls can be determined at any location using geological map data. In the region between the margin of upper Salado dissolution and the margin of halite occurrence above the Culebra, which includes the WIPP site, however, high-transmissivity (high-T) regions occur that cannot be predicted using geologic data. These high-T zones are treated stochastically, using what is termed a fracture-interconnectivity indicator.

In the following paragraphs, the fracture-interconnectivity indicator is defined, and then the specifics of each hypothesized control on Culebra transmissivity are outlined. Finally, a linear model relating these controls to Culebra transmissivity is presented that provides an excellent fit to the available data, is testable, and is consistent with our understanding of Culebra geology.

TFIELD-3.1 Fracture Interconnection

Culebra transmissivity data show a bimodal distribution (Figure TFIELD-5). Interpretations of hydraulic tests (e.g., Beauheim and Ruskauff 1998) and observations of the presence or absence of open fractures in core show the bimodal transmissivity distribution to be the result of hydraulically significant fractures. Some degree of fracturing is evident in all Culebra cores, but the fractures tend to be filled with gypsum at locations where the transmissivity inferred from hydraulic tests is less than approximately 4×10^{-6} square meters per second (m^2/s) ($\log_{10} = -5.4$). Where $\log_{10}$ transmissivity (m^2/s) is greater than –5.4, hydraulic tests show double-porosity responses and open fractures are observed in core. Therefore, a fracture-interconnectivity indicator is defined based on a cutoff of $\log_{10}$ transmissivity (m^2/s) = –5.4:

$$I_f = \begin{cases} 1, & \log_{10} T\left(\mathrm{m}^2/\mathrm{s}\right) > -5.4 \\ 0, & \log_{10} T\left(\mathrm{m}^2/\mathrm{s}\right) \le -5.4 \end{cases} \qquad \text{(TFIELD.1)}$$

Open, interconnected fractures and high transmissivities occur in regions affected by Salado dissolution (e.g., Nash Draw) and in areas west of the M3/H3 margin where gypsum fracture fillings are absent.

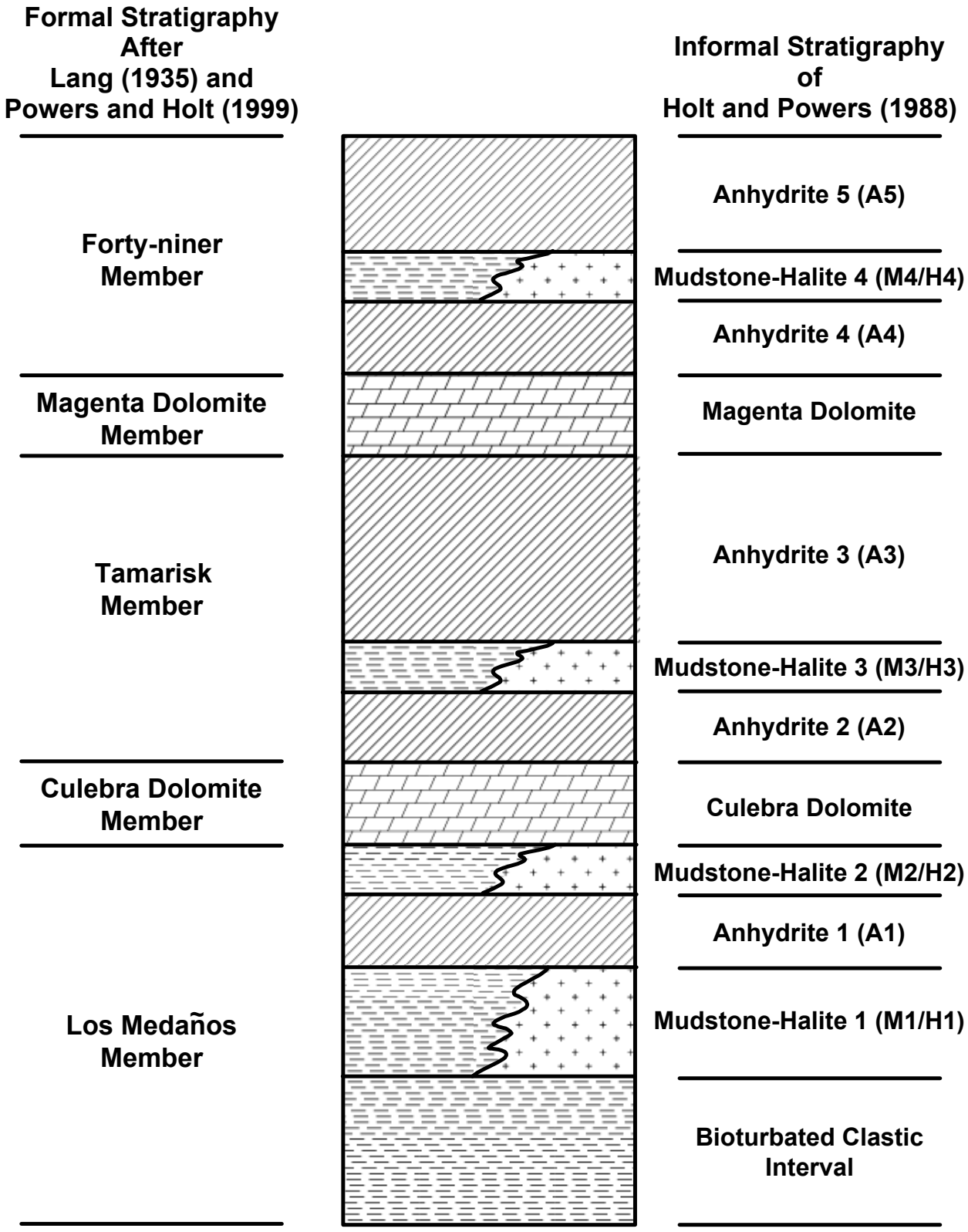


Figure TFIELD-4. Stratigraphic Subdivisions of the Rustler

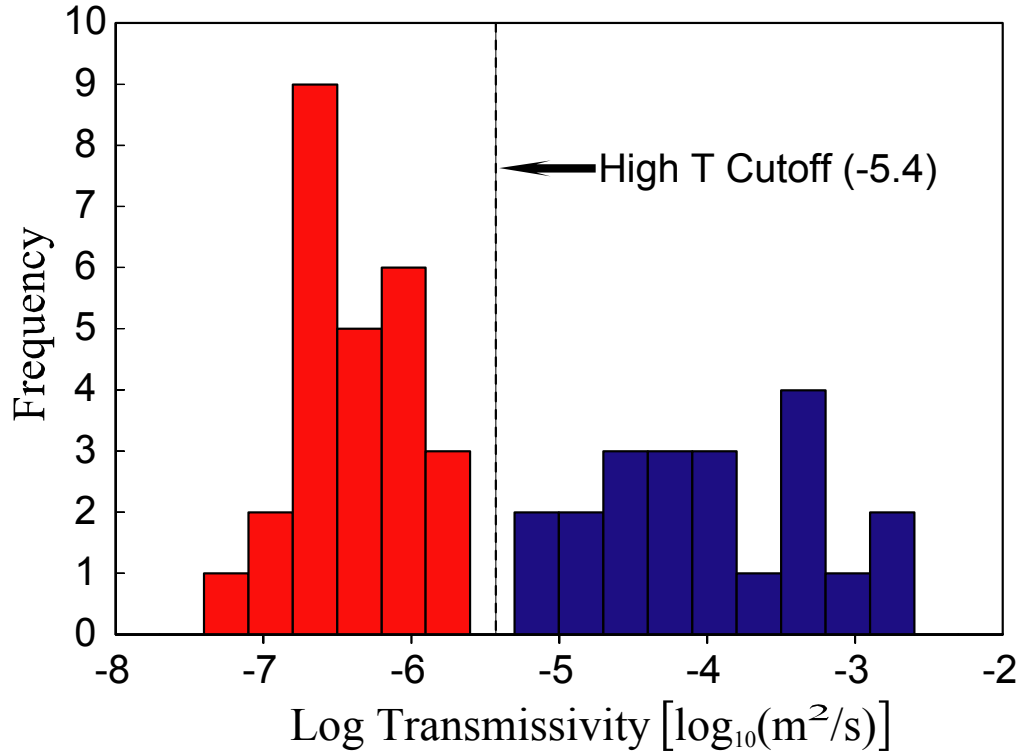


Figure TFIELD-5. Histogram of $\log_{10}$ Culebra Transmissivity. Data from U.S. Department of Energy (1996), Beauheim and Ruskauff (1998), and Beauheim (2002c).

TFIELD-3.2 Overburden Thickness

An inverse relationship exists between Culebra overburden thickness and transmissivity. At the WIPP wells for which transmissivity data are available, the Culebra overburden thickness ranges from 3.7 m (at WIPP-29) to 414.5 m (at H-10) (Mercer 1983), increasing from west to east. Overburden thickness is a metric for two different controls on Culebra transmissivity. First, fracture apertures are limited by overburden thickness (e.g., Currie and Nwachukwu 1974), which should lead to lower transmissivity where Culebra depths are great (Beauheim and Holt 1990, Holt 1997). Second, erosion of overburden leads to changes in stress fractures, and the amount of Culebra fracturing increases as the overburden thickness decreases (Holt 1997). Holt (1997) estimates that at least 350 m of overburden has been eroded at the center of the WIPP site (where the Culebra is at a depth of approximately 214 m) since the end of the Triassic, with more erosion occurring west of the site center where overburden (chiefly the Dewey Lake) is thinner and less erosion occurring to the east where Triassic deposits are thicker.

TFIELD-3.3 Salado Dissolution

In regions north, south, and west of the WIPP site, Cenozoic dissolution has affected the upper Salado Formation (Figure TFIELD-2). Where this dissolution has occurred, the rocks overlying the Salado, including the Culebra, are strained (leading to larger apertures in existing fractures), fractured, collapsed, and brecciated (e.g., Beauheim and Holt 1990, Holt 1997). All WIPP wells

within the upper-Salado-dissolution zone fall within the high-T population, and all regions affected by Salado dissolution are expected to have well-interconnected fractures and high-T.

TFIELD-3.4 Halite Overlying the Culebra

All wells (e.g., H-12 and H-17) located where halite occurs in the M3/H3 interval of the Tamarisk (Figure TFIELD-3) show low-transmissivity (low-T). Transmissivity data are limited in this region, but it is unlikely that halite would survive in M3/H3, only several meters from the Culebra, in regions of high-T where Culebra flow rates are relatively high. High-T zones, therefore, are assumed to not occur in regions where halite is present in the M3/H3 interval.

TFIELD-3.5 Halite Bounding the Culebra

In regions where halite is present in the M2/H2 interval directly below the Culebra, no reliable quantitative estimates of Culebra transmissivity are available. Beauheim (1987) estimates transmissivity at P-18, the only tested well at which halite is present in the M2/H2 interval, to be less (probably much less) than 4×10^{-9} m^2/s ($\log_{10} = -8.4$). In much of the area where halite is present in the M2/H2 interval (including the P-18 location), halite is also present in the M3/H3 interval. Based upon geologic observations of halite-bound units elsewhere within the WIPP area, Holt (1997) suggests that porosity within the Culebra may contain abundant halite cements in these areas. Beauheim and Holt (1990) and Holt (1997) indicate that Culebra porosity shows increasing amounts of pore-filling cement east of the WIPP site. Consequently, Culebra transmissivity is assumed to be much lower in the region where halite occurs both above (M3/H3 interval) and below (M2/H2 interval) the Culebra. Much lower-T is also assumed in the area northeast of the WIPP site where halite is present in the M2/H2 interval but absent in the M3/H3 interval (see Figure TFIELD-3).

TFIELD-3.6 High-Transmissivity Zones

In addition to the high-T that occurs everywhere dissolution of the upper Salado has occurred, high-T zones also occur in the Culebra in the region bounded by the limit of upper Salado dissolution to the west and by the margin of where halite is present in the M2/H2 and M3/H3 intervals to the east (see Figure TFIELD-2 and Figure TFIELD-3). Fracture openness and interconnectivity in these high-T zones are controlled by a complicated history of fracturing with several episodes of cement precipitation and dissolution (Beauheim and Holt 1990; Holt 1997). No geologic metric has yet been defined that allows prediction of where fractures are filled or open, hence our knowledge of this indicator east of the Salado dissolution margin is limited to the test well locations shown in Figure TFIELD-6. Consequently, the spatial location of high-T zones between the Salado dissolution margin and the M2/H2 and M3/H3 margins is treated stochastically.

TFIELD-3.7 Linear Transmissivity Model

Using the hypothesized geologic controls on Culebra transmissivity, the following linear model for $Y(x) = \log_{10} T(x)$ was constructed:

$$Y(x) = \beta_1 + \beta_2\, d(x) + \beta_3\, I_f(x) + \beta_4\, I_D(x) \qquad \text{(TFIELD.2)}$$

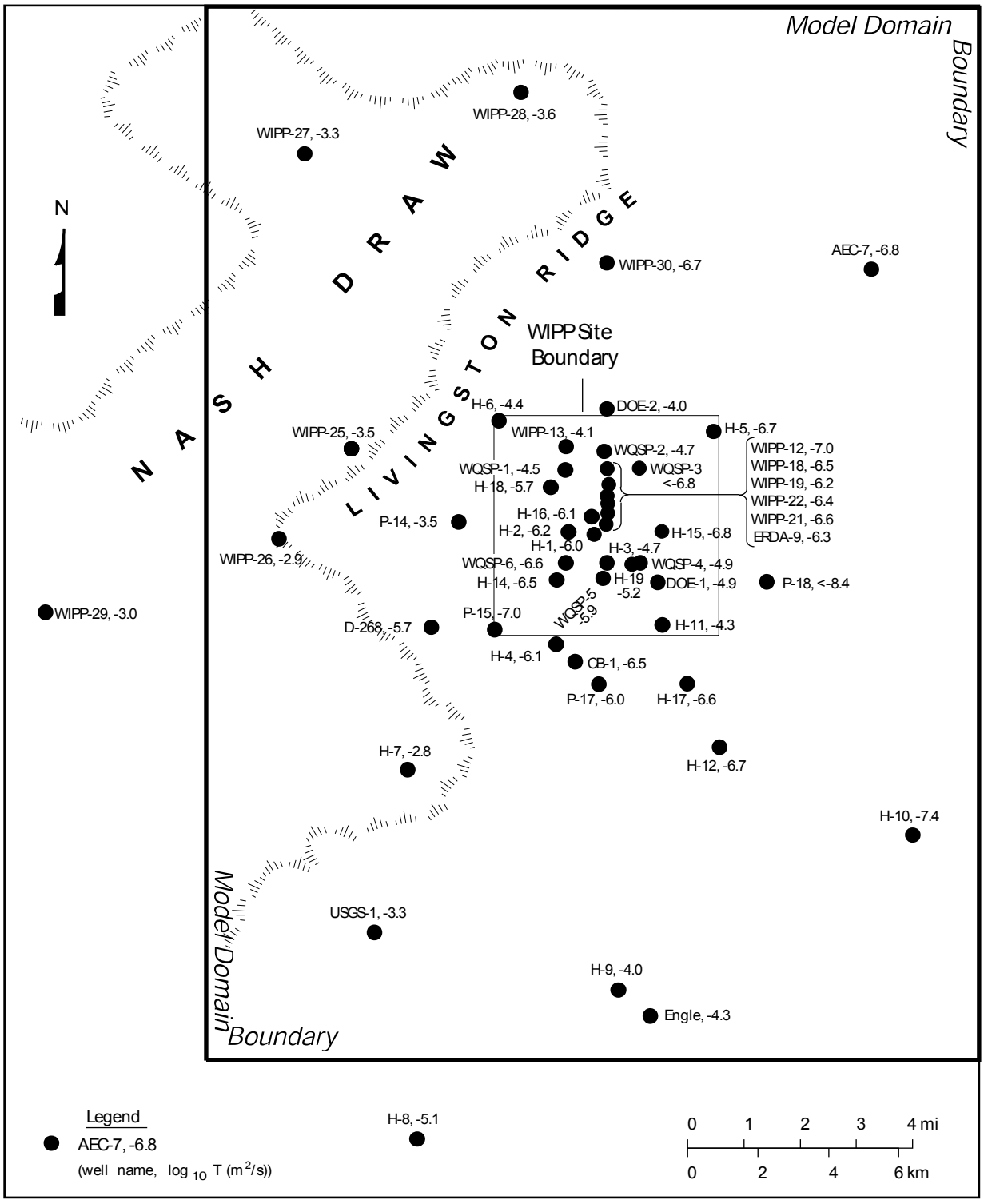


Figure TFIELD-6. Well Locations and $\log_{10}$ Culebra Transmissivities

where β_i (i = 1, 2, 3, 4) are regression coefficients, x is a two-dimensional location vector consisting of Universal Transverse Mercator (UTM) X and UTM Y coordinates, d(x) is the overburden thickness, $I_f(x)$ is the fracture-interconnectivity indicator given in Equation (TFIELD.1) that assumes the value of 1 if fracturing and high-T have been observed at point x and 0 otherwise, and $I_D(x)$ is a dissolution indicator function that assumes the value of 1 if Salado dissolution has occurred at point x and 0 otherwise. In this model, regression coefficient β_1 is the intercept value for the linear model. Coefficient β_2 is the slope of Y(x)/d(x). Coefficients β_3 and β_4 represent adjustments to the intercept for the occurrence of interconnected fractures and Salado dissolution, respectively. Although other types of linear models could be developed, this model is consistent with the conceptual model relating transmissivity to geologic controls and can be tested using published WIPP geologic and transmissivity data. Note that the regression model does not explicitly contain terms relating Culebra transmissivity to zones where the Culebra is bounded by halite in both the M2/H2 and M3/H3 intervals because of lack of data from these areas. Therefore, it cannot be used to predict transmissivity east of the M2/H2 margin.

TFIELD-3.8 Linear-Regression Analysis

A linear-regression model was written using the Windows®-based program MATHCAD™ 7 Professional specifically for this application. Although other variables are input, this model requires only $\log_{10}$ transmissivity data from tested wells, the depth of the Culebra at those wells, and an estimate of whether dissolution of the upper Salado has or has not occurred at each location. The fracture interconnectivity indicator is defined from the $\log_{10}$ transmissivity data, and a Salado dissolution indicator is defined using the Salado dissolution data. These data are then used in a standard linear regression algorithm to determine the regression coefficients for Equation (TFIELD.2).

The regression coefficients for Equation (TFIELD.2) derived from this analysis are presented in Table TFIELD-1. The regression has a multiple correlation coefficient (R^2) of 0.941 and a regression ANOVA F statistic of 222. The number of degrees of freedom about the regression (n) equals the number of observations (46) minus the number of parameters (4). The number of degrees of freedom due to the regression (m) equals the number of parameters (4) minus 1. With n = 42 and m = 3, the regression is significant above the 0.999 level. Residuals show no anomalous behavior. Accordingly, the regression model provides an accurate and reasonable description of the data. The fit of the regression to the $\log_{10}$ transmissivity data is shown in Figure TFIELD-7.

Table TFIELD-1. Regression Coefficients for Equations (TFIELD.2) and (TFIELD.3)

β_1	β_2	β_3	β_4
–5.441	-4.636×10^{-3}	1.926	0.678

The regression model does not predict transmissivity in the regions where the Culebra is underlain by halite in the M2/H2 interval because no quantitative data were available from these regions to be used in deriving the regression. In these regions, the following modified version of the regression model of Equation (TFIELD.2) is applied:

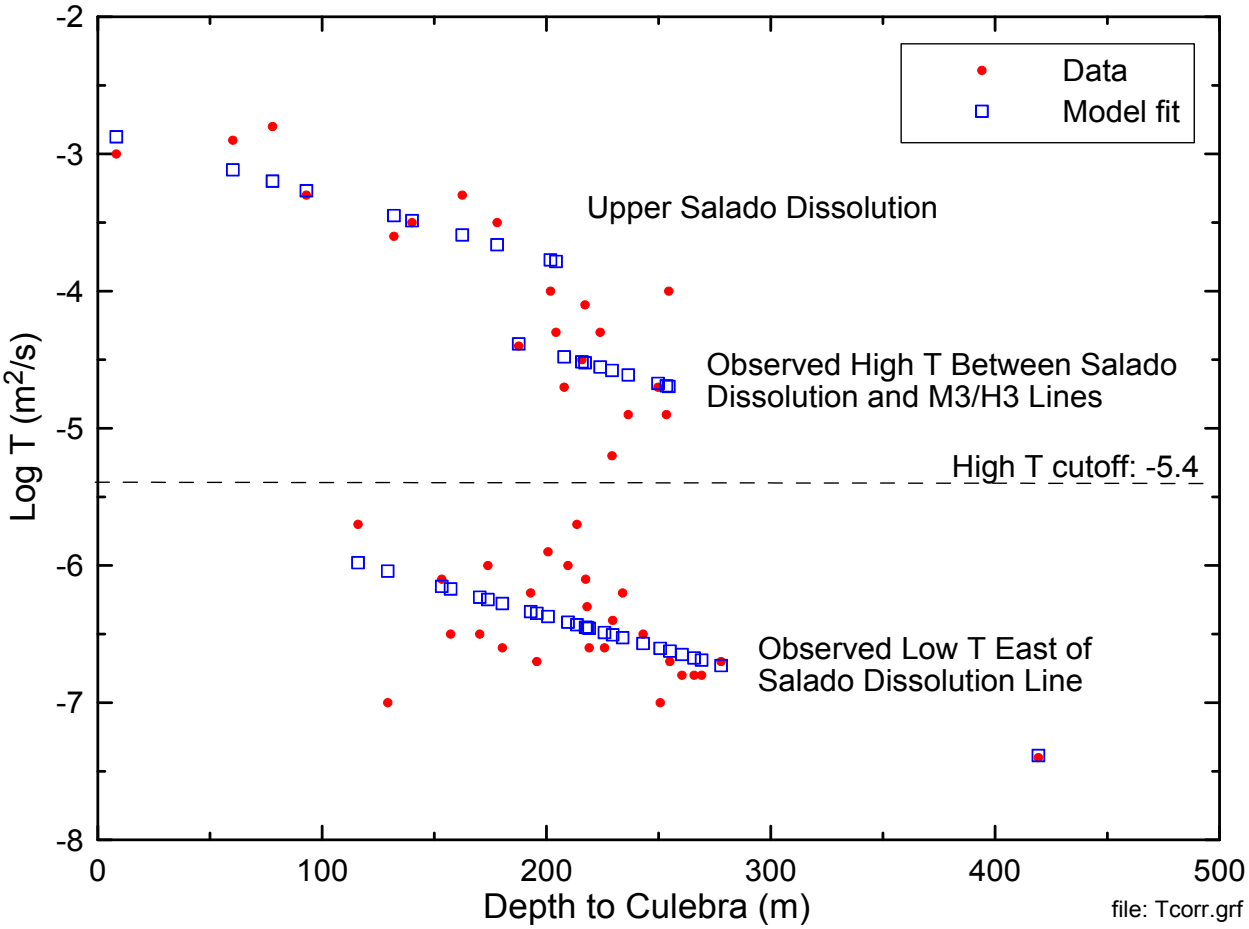


Figure TFIELD-7. Regression Fit to Observed Culebra $\log_{10}$ T Data

$$Y(x) = \beta_1 + \beta_2\, d(x) + \beta_3\, I_f(x) + \beta_4\, I_D(x) + \beta_5\, I_H(x) \qquad \text{(TFIELD.3)}$$

where $I_H(x)$ is a halite indicator function. This indicator is assigned a value of 1 in locations where halite occurs in the M2/H2 interval and 0 otherwise. The coefficient β_5 is set equal to –1 so that Equation (TFIELD.3) reduces the predicted transmissivity values by one order of magnitude where halite occurs in the M2/H2 interval, to accord qualitatively with the expected transmissivity reduction discussed in Section TFIELD-3.5 of this appendix. With knowledge (or stochastic estimations) of the values of the geologic controls (e.g., Culebra depth, fracture-interconnectivity indicator, dissolution indicator, and halite indicator), Culebra transmissivity values can be predicted at unobserved locations in the WIPP Culebra model domain using Equation (TFIELD.3).

TFIELD-4.0 Calculation of Base T Fields

In this section, a method is developed for applying the linear regression model from Section TFIELD-3.0 of this appendix to predict Culebra transmissivity across a model domain encompassing the WIPP area. Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra can be deterministically evaluated across the WIPP region using maps constructed from subsurface data (Section TFIELD-2.0). The presence of open, interconnected fractures, however, cannot be deterministically assessed across the WIPP area using maps. A geostatistical approach, conditional indicator simulation, is used to generate 500 equiprobable realizations of zones with hydraulically significant fractures in the WIPP region. These simulations are parameterized using the frequency of occurrence of WIPP wells with hydraulically significant fractures and a fit to a variogram constructed using data from those same wells. The regression model is then applied to the entire WIPP area by:

1. Overlaying the geologic map data for Culebra overburden thickness, Salado dissolution, and the presence or absence of halite in units bounding the Culebra with each of the 500 equiprobable realizations of zones containing open, interconnected fractures
2. Sampling each grid point within the model domain to determine the overburden thickness and the indicator values for Salado dissolution, overlying or underlying halite, and fracture interconnectivity
3. Using the sampled data at each grid point with the regression model coefficients to estimate Culebra transmissivity

When applied to the 500 equiprobable realizations of zones containing open, interconnected fractures, this procedure generates 500 stochastically varying Culebra base T fields. Details about the creation of the base T fields are given in Holt and Yarbrough (2002, 2003a, 2003b).

TFIELD-4.1 Definition of Model Domain

Two principal factors were considered in selecting the boundaries for the Culebra model domain. First, model boundaries should coincide with natural groundwater divides where feasible, or be far enough from the southern portion of the WIPP site, where transport will be modeled, to have minimal influence in that area. Second, the model domain should encompass known features with the potential to affect Culebra water levels at the WIPP site (e.g., potash tailings ponds). The modeling domain selected is 22.4 kilometers (km) (13.9 miles [mi]) east-west by 30.7 km (19.1 mi) north-south, aligned with the compass directions (Figure TFIELD-6). This is the same as the domain used by LaVenue, Cauffman, and Pickens (1990) except that the current domain extends 1 km (0.62 mi) farther to the west than the 1990 domain. The modeling domain is discretized into 68,768 uniform 100 m (328 ft) by 100 m (328 ft) cells. The northern model boundary is slightly north of the northern end of Nash Draw, 12 km (7.5 mi) north of the northern WIPP site boundary and about 1 km (0.62 mi) north of Mississippi Potash Incorporated's east tailings pile. The eastern boundary lies in a low-T region that contributes little flow to the modeling domain. The southern boundary lies 12.2 km (7.6 mi) south of the southern WIPP site boundary, 1.7 km (1.5 mi) south of our southernmost well (H-9) and far enough from the WIPP site to have little effect on transport rates on the site. The western model boundary passes through the IMC tailings pond (Laguna Uno of Hunter [1985]) due west of the WIPP site in Nash Draw. Boundary conditions assigned for the model are discussed in Section

TFIELD-6.2. The coordinates of each corner of the domain are given in Table TFIELD-2, in North American Datum 27 UTM coordinates.

Table TFIELD-2. Coordinates of the Numerical Model Domain Corners

Domain Corner	UTM X Coordinate (m)	UTM Y Coordinate (m)
Northeast	624,050	3,597,150
Northwest	601,650	3,597,150
Southeast	624,050	3,566,450
Southwest	601,650	3,566,450

TFIELD-4.2 Reduction of Geologic Map Data

To create useable data sets for conditional simulation of high-T zones and prediction of Culebra transmissivity, the geological maps described above in Section TFIELD-2.0 were imported into a geographic information systems environment and digitized. A uniform 100-m (328-ft) grid was then created over the Culebra model domain. Using the Culebra structure contour map data (Figure TFIELD-1) and surface elevation data obtained from the United States Geological Survey (USGS) National Elevation Dataset (U.S. Geological Survey 2002), an isopach map of the Culebra overburden on the 100-m (328-ft) model grid was created.

Using maps showing occurrence of halite in the units above and below the Culebra and well locations, soft data files were created for conditional indicator simulations. Transmissivity within 120 m (374 ft) of each well is assumed to be from the same population (e.g., high- or low-T reflecting open, interconnected fractures or filled (poorly interconnected) fractures, respectively), and regions where the Culebra is overlain by halite in M3/H3 or underlain by halite in M2/H2 are assumed to be low-T regions.

Using maps of Salado dissolution and the occurrence of halite in the units above and below the Culebra, 100-m (328-ft) indicator grids were created over the model domain. These indicator grids were created for regions affected by Salado dissolution, regions where the Culebra is underlain by halite in the M2/H2 interval, and a middle zone in which the Culebra is neither overlain nor underlain by halite where high-T zones occur stochastically (Figure TFIELD-8).

TFIELD-4.3 Indicator Variography

Excluding data where Salado dissolution occurs, Culebra transmissivity data are indicator transformed (1 for $\log_{10}$ transmissivity (m^2/s) > −5.4, 0 otherwise). A high-T indicator variogram is then constructed for the indicator data in the region not affected by Salado dissolution using the Geostatistical Software Library (GSLIB) program GAMV (Deutsch and Journel 1998). The lag spacing for this variogram is selected to maximize variogram resolution. The resulting indicator variogram is then fit with an isotropic spherical variogram model:

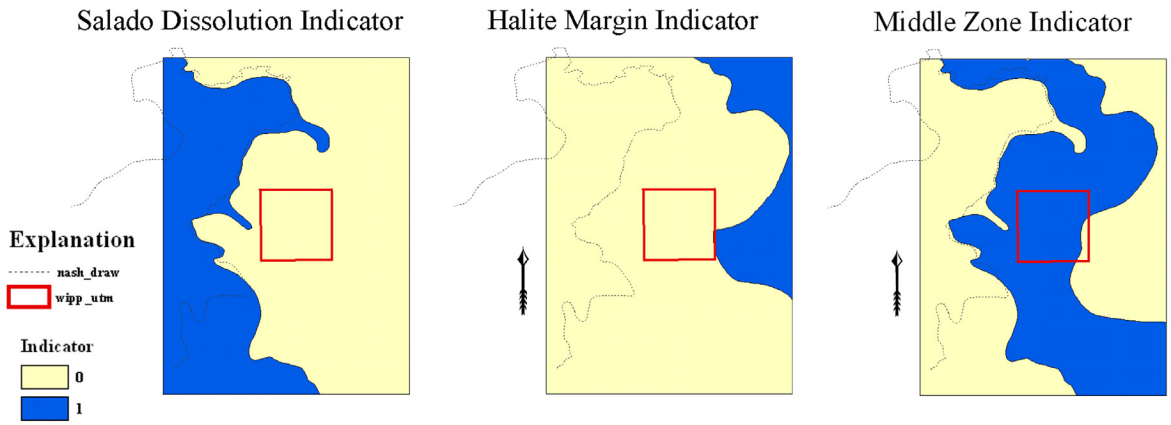


Figure TFIELD-8. Zones for Indicator Grids

$$\gamma(h) = \begin{cases} s[1.5(h/\lambda) - 0.5(h/\lambda)^3] & \text{if } h \le \lambda \\ s & \text{if } h \ge \lambda \end{cases} \qquad \text{(TFIELD.4)}$$

where γ(h) is the variogram as a function of lag spacing h, s is the sill value of the indicator variogram, and λ is the correlation length. This variogram model minimizes the mean squared error between the experimental and modeled variogram. The sill value was determined using:

$$s = P[\log_{10} T\ (m^2/s) > -5.4] - \{P[\log_{10} T\ (m^2/s) > -5.4]\}^2 \qquad \text{(TFIELD.5)}$$

where P[·] is a cumulative distribution function. For the Culebra data set, excluding wells where dissolution has occurred, s = 0.201. The correlation length λ was estimated to be 1,790 m (5,873 ft). No nugget effect was included in the variogram model (Figure TFIELD-9). Variogram model parameters were then used in conditional indicator simulations of Culebra high-T zones.

TFIELD-4.4 Conditional Indicator Simulation

"Soft" indicator data were created for the indicator simulations. To ensure that no high-T regions develop in areas where halite occurs in M2/H2 or M3/H3, soft data points, indicating low-T, were placed on a 200-m (656-ft) grid east of the M2/H2 and M3/H3 salt margins. This 200-m (656-ft) grid used the original 100-m (328-ft) grid excluding every other node to assure the 200-m (656-ft) soft data grid spatially overlay the 100-m (328-ft) grid. Soft data were also specified for every 100-m (328-ft) node along the combined lines of the M2/H2 and M3/H3 salt margins.

Additional soft data were created near well locations establishing a 120-m (394-ft) buffer around each well (Figure TFIELD-10). All 100-m (328-ft) grid nodes lying within the 120-m (394-ft) buffer were selected and assigned the transmissivity attribute of the well. Because all the nodes within 120 m (394 ft) of the well and the node corresponding to the block containing the well were selected as soft data, there was duplication in the input files. Only one data point can occupy a 100-m (328-ft) grid space during a realization. Therefore, the node closest to the well was eliminated from the soft data file.

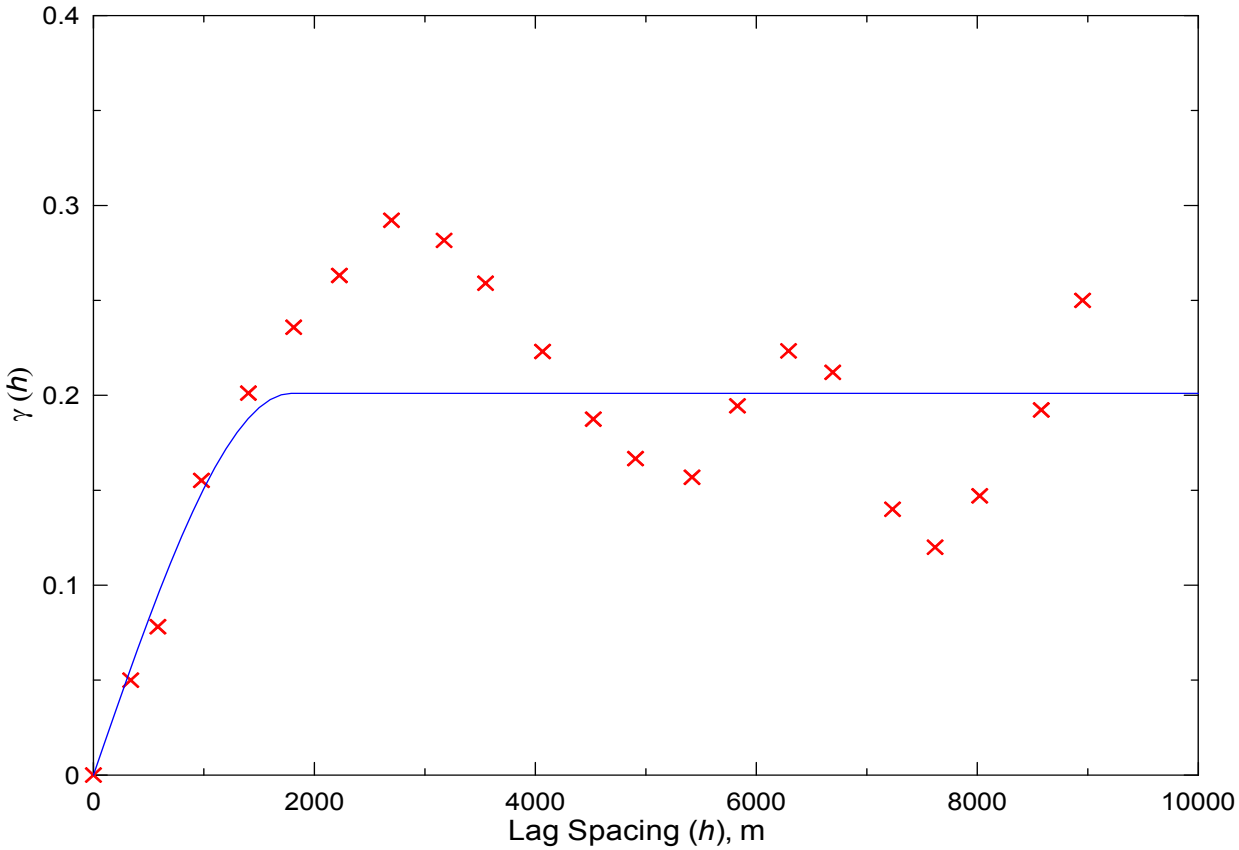


Figure TFIELD-9. High-T Indicator Model and Experimental Variograms

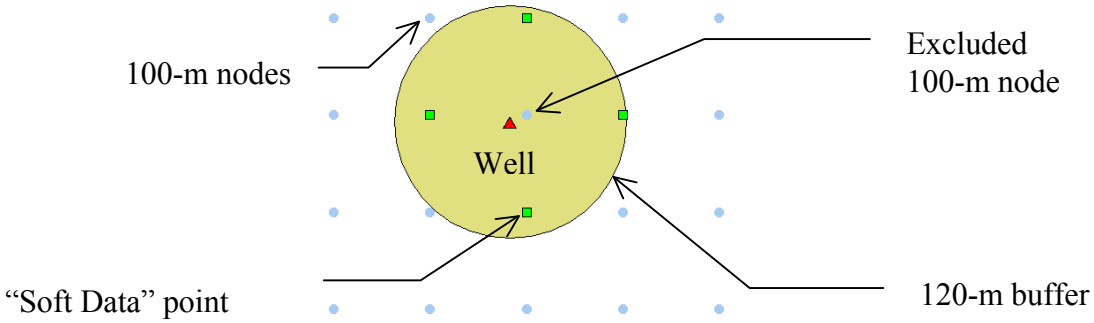


Figure TFIELD-10. Soft Data Around Wells

Five hundred conditional indicator simulations were generated on the 100-m (328-ft) model grid using the GSLIB program SISIM (Deutsch and Journel 1998) with Culebra high-T indicator data, soft data for regions around wells and regions where halite underlies and overlies the Culebra, and the variogram parameters. The resulting indicator simulations were used in the construction of base T fields.

TFIELD-4.5 Construction of Base Transmissivity Fields

The linear predictor (Equation (TFIELD.3) was used to generate 500 equally probable realizations of the transmissivity distribution in the Culebra model domain. This calculation

required the regression coefficients discussed in Section TFIELD-3.8, Culebra depth data (Section TFIELD-3.2), a Salado dissolution indicator function, an indicator for where halite occurs in M2/H2, and the 500 realizations of high-T indicators discussed in Section TFIELD-4.4.

The 500 base T fields were created in five sets. Each set consists of 10 groups of 10 realizations given d##r## designations. The "d" counter ranges from 01 to 50, while the "r" counter ranges from 01 to 10. An example base T field is shown in Figure TFIELD-11. Stochastically located patches of relatively high-T (yellowish-green) can be clearly seen in the middle zone of the model domain. (Note: On black and white copy, these patches appear as the lightest shade of gray.)

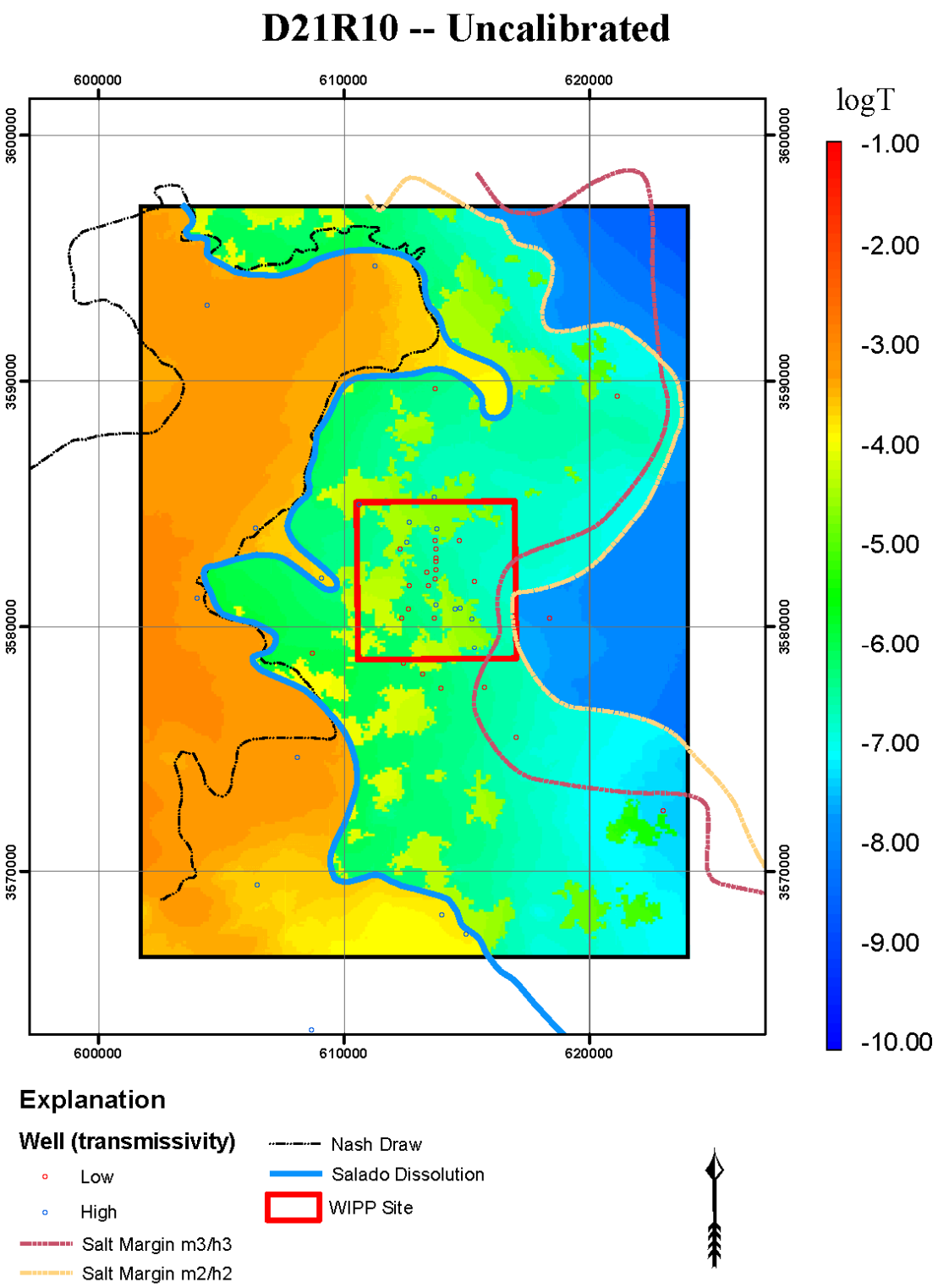


Figure TFIELD-11. Example Base T Field

TFIELD-5.0 Construction of Seed Realizations

The base T fields described in Section TFIELD-4.5 rely on a regression model to estimate transmissivity at every location. By the nature of regression models, the estimated transmissivity values will not honor the measured transmissivity values at the measurement locations. Therefore, before using these base T fields in a flow model, they must be conditioned to the measured transmissivity values. This conditioning is performed with a Gaussian geostatistical simulation algorithm to generate a series of 500 spatially correlated residual fields where each field has a mean value of zero. These fields are conditional such that the residual value at each measurement location, when added to the value provided by the regression model (which is the same for all 500 fields), provides the known transmissivity value at that location. The result of adding the simulated residual field to the base T field is the "seed" realization.

This process is shown conceptually along a west-to-east cross section of the Culebra in Figure TFIELD-12. The upper image shows the value of the residuals at five transmissivity measurement locations across the cross section. These residuals are calculated as the observed (measured) transmissivity value minus the base field transmissivity value at the same locations. Positive residuals are where the measured transmissivity value is greater than that of the base T field. To create a T field from these residuals, there needs to be a way to tie the base field to the measured transmissivity values. This tie is accomplished by creating a spatial simulation of the residual values, a "residual field." The middle image of Figure TFIELD-12 is an example residual field as a (red) dashed line along the cross section. This residual field is constructed through geostatistical simulation using a variogram model fit to the residual data. The residual field honors the measured residuals at their measurement locations and returns to a mean value of zero at distances far away from the measurement locations. Finally, this residual field is added to the base T field to create the seed T field. The base T field is represented by the solid (blue) line in the bottom image of Figure TFIELD-12 and the seed T field is shown by the dotted line. The seed T field corresponds to the base T field except at those locations where it must deviate to match the measured transmissivity data. The large discontinuity shown in the base T field at the bottom of Figure TFIELD-12 is due to the stochastic simulation of high-T zones within the Culebra.

A total of 46 measured transmissivity values and corresponding residual data, both in units of $\log_{10}$ (m^2/s), are available (Table TFIELD-3). For each pair of $\log_{10}$ transmissivity and residual data, the well name and the easting (X) and northing (Y) UTM coordinates are also given (for multiwell hydropads, a single well's coordinates were used).

The process of creating the residual fields is to use the residual data to generate variograms in the VarioWin software package and to then create conditional stochastic Gaussian geostatistical simulations of the residual field within the GSLIB program SGSIM (Deutsch and Journel 1998).

To use the data in a Gaussian simulation algorithm, it is first necessary to transform the distribution of the raw residual data to a standard normal distribution. This is accomplished through a process called the "normal-score transform," where each transformed residual value is the normal score of each original datum. The normal-score transform is a relatively simple two-step process. First the cumulative frequency of each original residual value, cdf(i), is determined as:

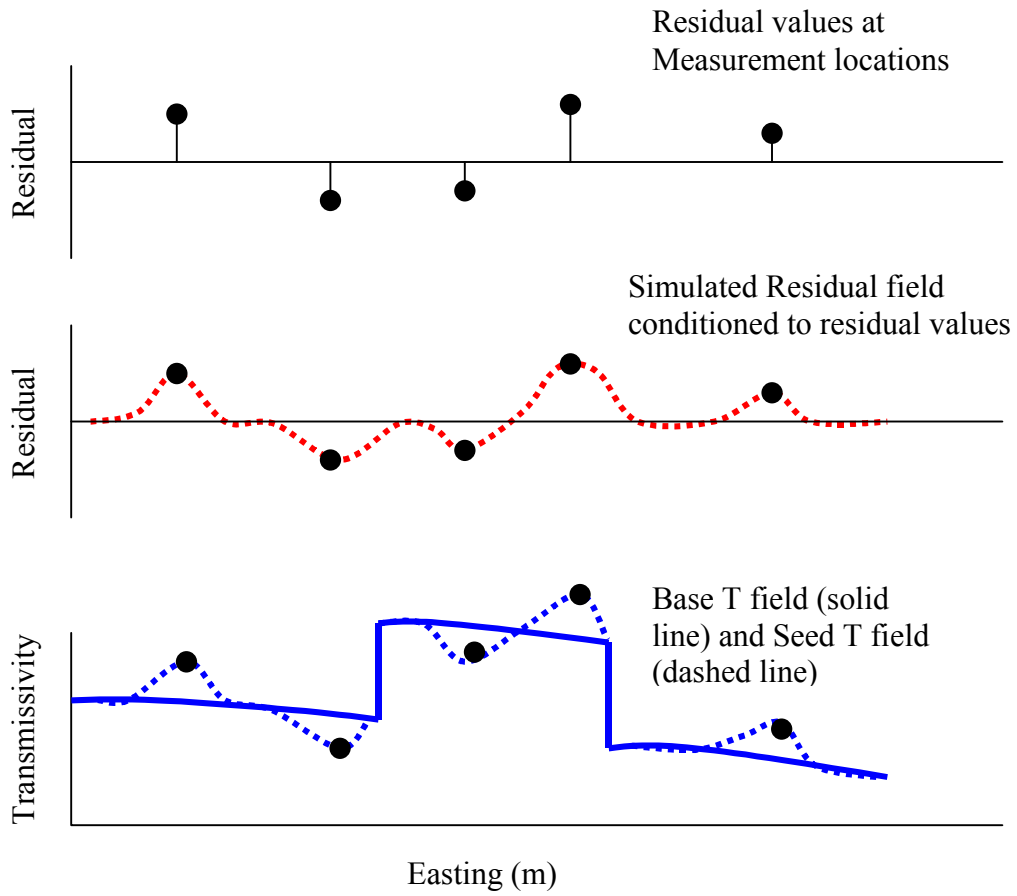


Figure TFIELD-12. Conceptual Cross Section Showing the Updating of the Residual Field and the Base T Field into the Seed T Field

$$cdf(i) = \frac{R(i) - 0.5}{N} \qquad \text{(TFIELD.6)}$$

where $R(i)$ is the rank (smallest to largest) of the ith residual value and N is the total number of data (46 in this case). Then for each cumulative frequency value, the corresponding normal-score value is calculated from the inverse of the standard normal distribution. By definition, the standard normal distribution has a mean of 0.0 and a standard deviation of 1.0. Further details of the normal-score transform process can be found in Deutsch and Journel (1998).

The two-step normal-score transformation process is conducted in Microsoft® Excel® (see details in McKenna and Hart 2003b). The resulting normal-score values are the distance from the mean as measured in standard deviations. The parameters describing the residual and normal-score transformed distributions are presented in Table TFIELD-4.

Table TFIELD-3. $\log_{10}$ Transmissivity Data Used in Inverse Calibrations

Well ID	Easting (UTM, m)	Northing (UTM, m)	$\log_{10}$ T (m^2/s)	$\log_{10}$ T Residual (m^2/s)
AEC-7	621126	3589381	–6.8	–0.11078
CB-1	613191	3578049	–6.5	–0.32943
D-268	608702	3578877	–5.7	0.27914
DOE-1	615203	3580333	–4.9	–0.21004
DOE-2	613683	3585294	–4.0	0.69492
Engle	614953	3567454	–4.3	–0.51632
ERDA-9	613696	3581958	–6.3	0.15250
H-1	613423	3581684	–6.0	0.41295
H-2c	612666	3581668	–6.2	0.13594
H-3b1	613729	3580895	–4.7	–0.22131
H-4c	612406	3578499	–6.1	0.05221
H-5c	616903	3584802	–6.7	0.02946
H-6c	610610	3584983	–4.4	–0.01524
H-7c	608095	3574640	–2.8	0.39794
H-9c	613974	3568234	–4.0	–0.22763
H-10b	622975	3572473	–7.4	–0.01484
H-11b4	615301	3579131	–4.3	0.25314
H-12	617023	3575452	–6.7	–0.07647
H-14	612341	3580354	–6.5	–0.26934
H-15	615315	3581859	–6.8	–0.12631
H-16	613369	3582212	–6.1	0.34962
H-17	615718	3577513	–6.6	–0.14310
H-18	612264	3583166	–5.7	0.73159
H-19b0	614514	3580716	–5.2	–0.62242
P-14	609084	3581976	–3.5	0.16212
P-15	610624	3578747	–7.0	–0.95938
P-17	613926	3577466	–6.0	0.24762
USGS-1	606462	3569459	–3.3	0.28998
WIPP-12	613710	3583524	–7.0	–0.39627
WIPP-13	612644	3584247	–4.1	0.42180
WIPP-18	613735	3583179	–6.5	0.06840
WIPP-19	613739	3582782	–6.2	0.32598
WIPP-21	613743	3582319	–6.6	–0.11148
WIPP-22	613739	3582653	–6.4	0.10549

Table TFIELD-3. log_{10} Transmissivity Data Used in Inverse Calibrations (Continued)

Well ID	Easting (UTM, m)	Northing (UTM, m)	log_{10} T (m^2/s)	log_{10} T Residual (m^2/s)
WIPP-25	606385	3584028	–3.5	–0.01378
WIPP-26	604014	3581162	–2.9	0.21598
WIPP-27	604426	3593079	–3.3	–0.03209
WIPP-28	611266	3594680	–3.6	–0.15124
WIPP-29	596981	3578694	–3.0	–0.12497
WIPP-30	613721	3589701	–6.7	–0.35131
WQSP-1	612561	3583427	–4.5	0.01540
WQSP-2	613776	3583973	–4.7	–0.02729
WQSP-3	614686	3583518	–6.8	–0.15139
WQSP-4	614728	3580766	–4.9	–0.28895
WQSP-5	613668	3580353	–5.9	0.47178
WQSP-6	612605	3580736	–6.6	–0.32261

Table TFIELD-4. Statistical Parameters Describing the Distributions of the Raw and Normal-Score Transformed Residual Data

Parameter	Raw Residual	Normal-Score Transformed Residual Data
Mean	0.000	0.000
Median	–0.015	0.000
Standard Deviation	0.330	0.997
Minimum	–0.959	–2.295
Maximum	0.732	2.295

The omnidirectional variogram is calculated with a 250-m (820-ft) lag spacing. The experimental variogram is shown in Figure TFIELD-13. The model fit to this experimental variogram is Gaussian with a nugget of 0.2, a sill of 0.8, and a range of 1,050 m (3,445 ft). The sum of the nugget and sill values is constrained to equal the theoretical variance of 1.0 by the sgsim software that is used to create the spatially correlated residual fields.

The variogram parameters for the normal-score transformed residuals are used directly in the sgsim program to create 500 conditional realizations of the residual field. Each of these 500 residual fields is used as an initial residual field and each one is assigned to an individual base T field. An example of a realization of the residual field and its combination with a base T field is shown in Figure TFIELD-14. From Figure TFIELD-14, the effect of the residual field on the base T field can be seen. The residual field perturbs the transmissivities to match the measured transmissivities at the well locations. The discrete features that are part of the original base

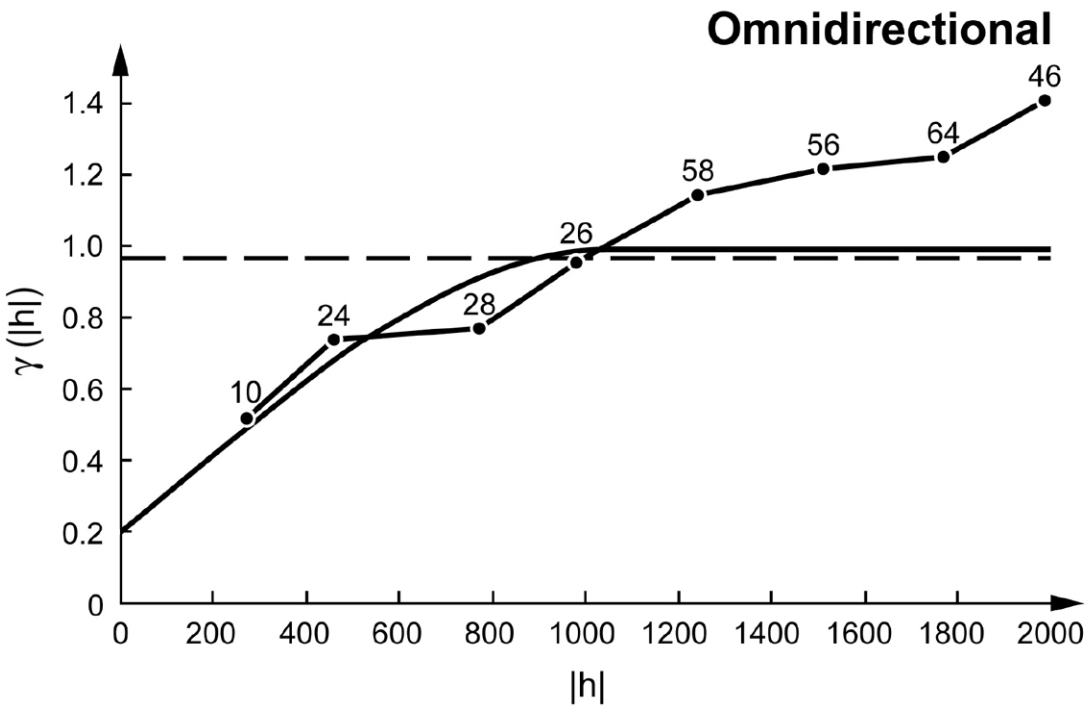


Figure TFIELD-13. Omnidirectional Variogram Model Fit to the Experimental Variogram of the Transmissivity Residuals

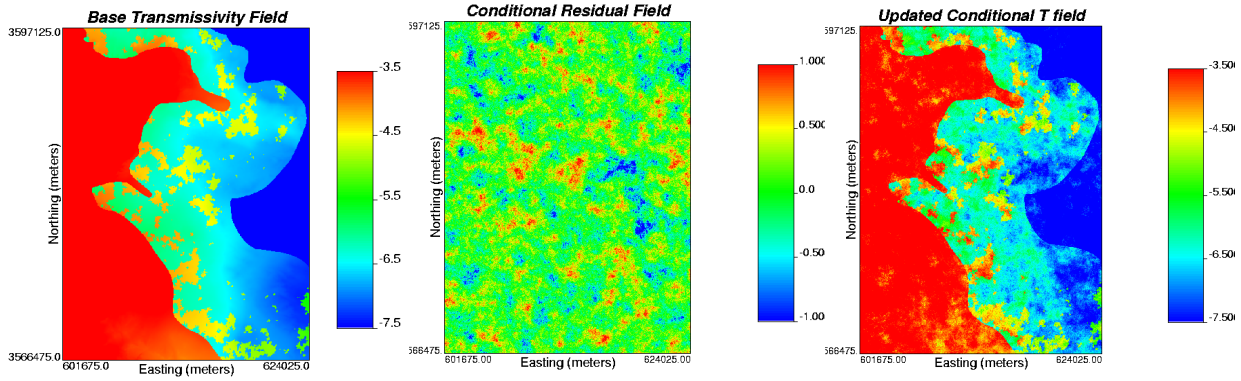


Figure TFIELD-14. An Example of the Creation of a Seed T Field. The Base T Field (Left Image) is Combined with the Initial Residual Field Created Through Geostatistical Simulation (Center Image) to Produce the Seed T Field (Right Image). That Field is Then Used as the Initial Field for the First Iteration of the Inverse Calibration Procedure. All Three Color Scales Denote the $\log_{10}$ Transmissivity (m^2/s) Value.

T field (e.g., high-T zones in the middle of the domain) are retained when the residual field is added to the base field, although transmissivity values within those features may be altered to a degree.

A number of distributed locations within the modeling domain are selected and designated as "pilot points." PEST adjusts the transmissivity value at each of these pilot points to achieve a better match between the groundwater flow model results and the observed steady-state and transient head data. The adjustments in transmissivity at each pilot point cannot be made independently of surrounding transmissivity values and, therefore, these surrounding transmissivity values must be updated in a manner consistent with the change made at the pilot point. This updating is done by applying a change at each of the surrounding points that is a weighted fraction of the change made at the pilot point. The weights are calculated from the residual variogram.

These updates are necessary to create a final T field that honors all observed transmissivity measurements and matches the observed heads when used as input to a groundwater flow model. Therefore, it is also necessary to calculate and model a variogram on the raw, not normal-score transformed residuals for use in this kriging process.

This variogram was also calculated with a 250-m (820-ft) lag and is omnidirectional. A doubly nested spherical variogram model was fit to the experimental variogram. The variogram parameters are a nugget of 0.008, a first sill and range of 0.033 and 500 m (1,640 ft), respectively, and a second sill and range of 0.067 and 1,500 m (4,921 ft), respectively (Figure TFIELD-15).

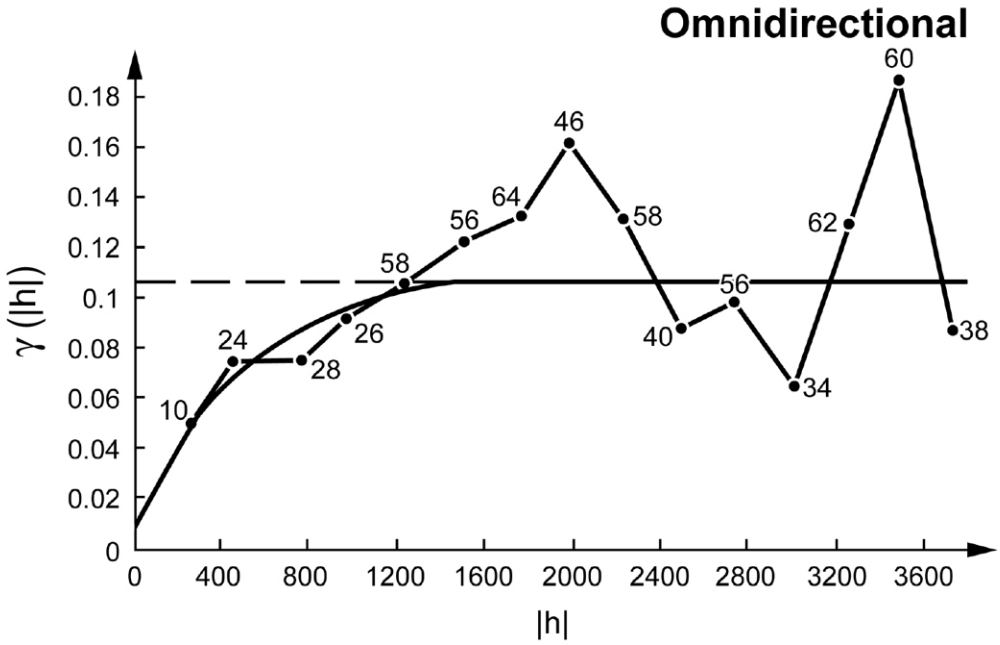


Figure TFIELD-15. Experimental and Model Variograms for the Raw-Space (Not Normal-Score Transformed) Transmissivity Residual Data

TFIELD-6.0 T-Field Calibration to Steady-State and Transient Heads

This section presents details on the modeling approach used to calibrate the T fields to both the 2000 steady-state heads and 1,332 transient drawdown measurements. This section is divided into the following subsections:

1. Assumptions made in the modeling and the implications of these assumptions are provided. (Section TFIELD-6.1)
2. The initial heads used for each calibration are estimated at each location in the domain using the heads measured in 2000 using kriging and accounting for the regional trend in the head values. (Section TFIELD-6.2)
3. The initial heads are used to assign fixed-head boundaries to three sides of the model. The fourth side, the western edge, is set as a no-flow boundary for the model. (Section TFIELD-6.3)
4. The transient head observations for each hydraulic test and each observation well are selected from the database. These heads are shown as a function of time for each hydraulic test. (Section TFIELD-6.4)
5. The spatial and temporal discretization of the model domain are presented. (Section TFIELD-6.5 and Section TFIELD-6.6)
6. The transient head observations are given relative weights based on the inverse of the maximum observed drawdown in each hydraulic test. The relative weights assigned to the steady-state observations are also discussed. (Section TFIELD-6.7)
7. The locations of the adjustable pilot points are determined using a combination of approaches. (Section TFIELD-6.8)

All of these steps can be considered as preprocessing aspects of the stochastic inverse calibration procedure. The actual calibrations are done using an iterative coupling of the MODFLOW-2000 and PEST codes. The details of this process are covered in McKenna and Hart (2003a, 2003b), and are briefly summarized in Section TFIELD-6.9.

TFIELD-6.1 Modeling Assumptions

The major assumptions that apply to this set of model calculations are as follows.

1. The boundary conditions along the model domain boundary are known and do not change over the time frame of the model. This assumption applies to both the no-flow boundary along the western edge of the domain as well as to the fixed-head boundaries that were created to be consistent with the 2000 head measurements in the model domain. Implicit in this assumption is that the fixed-head boundary conditions do not have a significant impact on the transient tests that were simulated in the interior of the model at times other than the 2000 period.
2. The fracture permeability of the Culebra can be adequately modeled as a continuum at the 100-m (328-ft) × 100-m (328-ft) grid block scale and the measured transmissivity values used to condition the model are representative of the transmissivity in the 100-m (328-ft) × 100-m (328-ft) grid block in which the well test was performed. Implicit in this assumption

is the prior assumption that the hydraulic test interpretations were done correctly and used the correct conceptual model.

3. Variable fluid densities in the Culebra can be adequately represented by casting the numerical solution in terms of freshwater head. Davies (1989) investigated the effects of variable fluid density on the directions of flow calculated in the Culebra using a freshwater-head approach. As the Culebra flow system was conceptualized and modeled by Davies, most of the water flowing in the Culebra in the vicinity of the WIPP site ultimately discharged to the Pecos River southwest of WIPP. When variable fluid density was taken into account, the only locations within the model domain where the flow direction changed by more than 10 degrees were regions 1.1 to 14.3 km (0.7 to 8.9 mi) south of the WIPP site, where the flow direction shifted as much as 70 degrees to the east toward a more downdip direction (but still primarily to the south) (Davies, 1989, Figure 35 and Figure 36). As currently conceptualized, flow in the Culebra in the vicinity of WIPP does not discharge to the Pecos to the southwest, but instead goes to the southsoutheast toward the Paduca oilfield where extensive dissolution of the Salado and collapse of the Culebra has occurred (see Figure TFIELD-1). Hence, taking variable fluid density into account would have little effect on the flow direction.

TFIELD-6.2 Initial Heads

A set of initial head values was estimated across the flow model domain based on water-level measurements made in late 2000 (Beauheim 2002b). The water-level measurements were converted to freshwater heads using fluid-density data collected from pressure-density surveys performed in the wells and/or from water-quality sampling. The head values estimated at the cells in the interior of the domain were used as initial values of the heads and were subsequently updated by the groundwater flow model until the final solution was achieved. The head values estimated for the fixed-head cells along the north, east, and south boundaries of the model domain remained constant for the groundwater flow calculation. The estimation of the initial and boundary heads was done by kriging. Observed heads both within and outside of the flow model domain (Figure TFIELD-16) were used in the kriging process.

Kriging is a geostatistical estimation technique that uses a variogram model to estimate values of a sampled property at unsampled locations. Kriging is designed for the estimation of stationary fields (see Goovaerts 1997); however, the available head data show a significant trend (nonstationary behavior) from high head in the northern part of the domain to low head in the southern part of the domain. This behavior is typical of groundwater head values measured across a large area with a head gradient. To use kriging with this type of nonstationary data, a Gaussian polynomial function is fit to the data, and the differences between the polynomial and the measured data (the "residuals") are calculated and a variogram of the residuals is constructed. This variogram and a kriging algorithm are then used to estimate the value of the residual at all locations within a domain. The final step in the process is to add the trend from the previously defined polynomial to the estimated residuals to get the final head estimates. This head estimation process is similar to that used in the Culebra calculations done for the Compliance Certification Application (CCA, U.S. Department of Energy 1996) (Lavenue 1996).

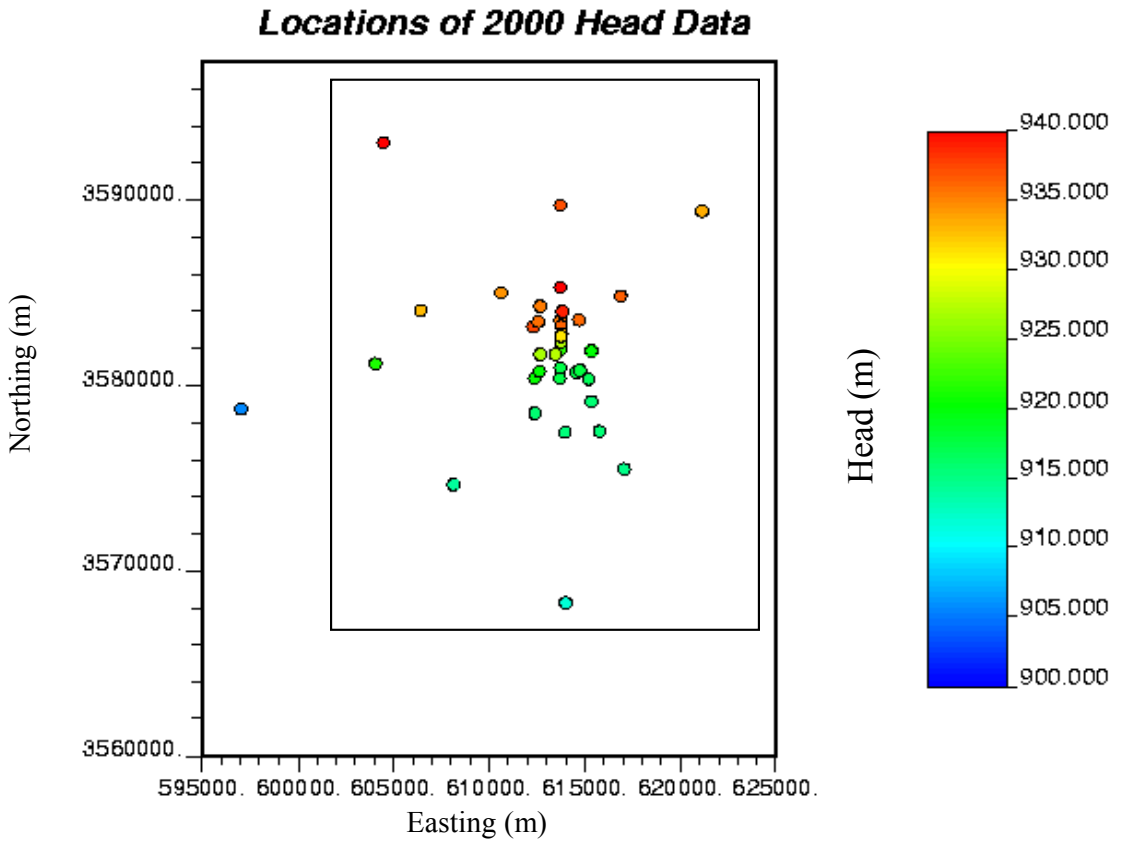


Figure TFIELD-16. Locations and Values of the 2000 Head Measurements Considered in the Steady-State Calibrations. The Approximate Extent of the Numerical Model Domain is Shown by the Black Rectangle in the Image.

The available head data from late 2000, comprising 37 measurements, are listed in Table TFIELD-5. In general, these head measurements show a trend from high head in the north to low head in the south. The trend was modeled with a bivariate Gaussian function. The use of this Gaussian function with five estimated parameters allows considerable flexibility in the shape of the trend that can be fit through the observed data. The value of the Gaussian function, Z, is:

$$Z = a \exp\left[-\frac{1}{2}\left(\left(\frac{X - X_0}{b} \right)^2 + \left(\frac{Y - Y_0}{c} \right)^2 \right) \right] \qquad \text{(TFIELD.7)}$$

where X_0 and Y_0 are the coordinates of the center of the function and b and c are the standard deviations of the function in the X (east-west) and Y (north-south) directions, respectively. The parameter a controls the height of the function. The Gaussian function was fit to the data using the regression wizard tool in the SigmaPlot® 2001 graphing software. The parameters estimated for the Gaussian function are presented in Table TFIELD-6. The fit of the Gaussian trend surface to the 2000 heads is shown in Figure TFIELD-17. The locations and values of the residuals (observed value–trend surface estimate) are shown in Figure TFIELD-18.

Table TFIELD-5. Well Names and Locations of the 37 Head Measurements Obtained in Late 2000 Used to Define Boundary and Initial Heads

Well	UTM X (Easting) (m)	UTM Y (Northing) (m)	2000 Freshwater Head (m amsl)
AEC-7	621126	3589381	933.19
DOE-1	615203	3580333	916.55
DOE-2	613683	3585294	940.03
ERDA-9	613696	3581958	921.59
H-1	613423	3581684	927.19
H-2b2	612661	3581649	926.62
H-3b2	613701	3580906	917.16
H-4b	612380	3578483	915.55
H-5b	616872	3584801	936.26
H-6b	610594	3585008	934.20
H-7b1	608124	3574648	913.86
H-9b	613989	3568261	911.57
H-11b4	615301	3579131	915.47
H-12	617023	3575452	914.66
H-14	612341	3580354	920.24
H-15	615315	3581859	919.87
H-17	615718	3577513	915.37
H-18	612264	3583166	937.22
H-19b0	614514	3580716	917.13
P-17	613926	3577466	915.20
WIPP-12	613710	3583524	935.30
WIPP-13	612644	3584247	935.17
WIPP-18	613735	3583179	936.08
WIPP-19	613739	3582782	932.66
WIPP-21	613743	3582319	927.00
WIPP-22	613739	3582653	930.96
WIPP-25	606385	3584028	932.70
WIPP-26	604014	3581162	921.06
WIPP-27	604426	3593079	941.01
WIPP-29	596981	3578701	905.36
WIPP-30	613721	3589701	936.88
WQSP-1	612561	3583427	935.64
WQSP-2	613776	3583973	938.82
WQSP-3	614686	3583518	935.89
WQSP-4	614728	3580766	917.49
WQSP-5	613668	3580353	917.22
WQSP-6	612605	3580736	920.02

Table TFIELD-6. Parameters for the Gaussian Trend Surface Model Fit to the 2000 Heads

Trend Surface Parameters	Value
X_0	611011.89
Y_0	3780891.50
a	1134.61
b	73559.35
c	313474.40

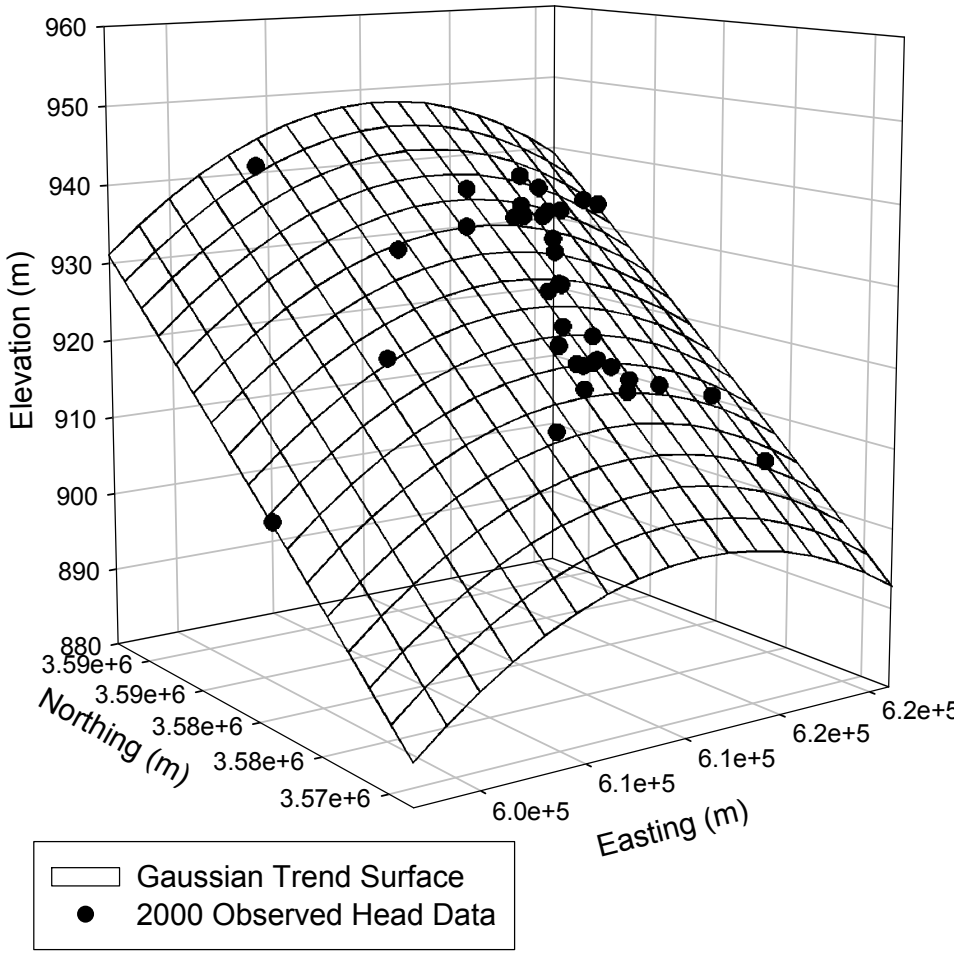


Figure TFIELD-17. Gaussian Trend Surface Fit to the 2000 Observed Heads

The next step in estimating the initial head values is to calculate an experimental variogram for each set of residuals and then fit a variogram model to each experimental variogram. Due to the rather limited number of data points, anisotropy in the spatial correlation of the residuals was not examined and an omnidirectional variogram was calculated. These calculations were done using the VARIOWIN (version 2.21) software (Pannatier 1996). The Gaussian variogram model is:

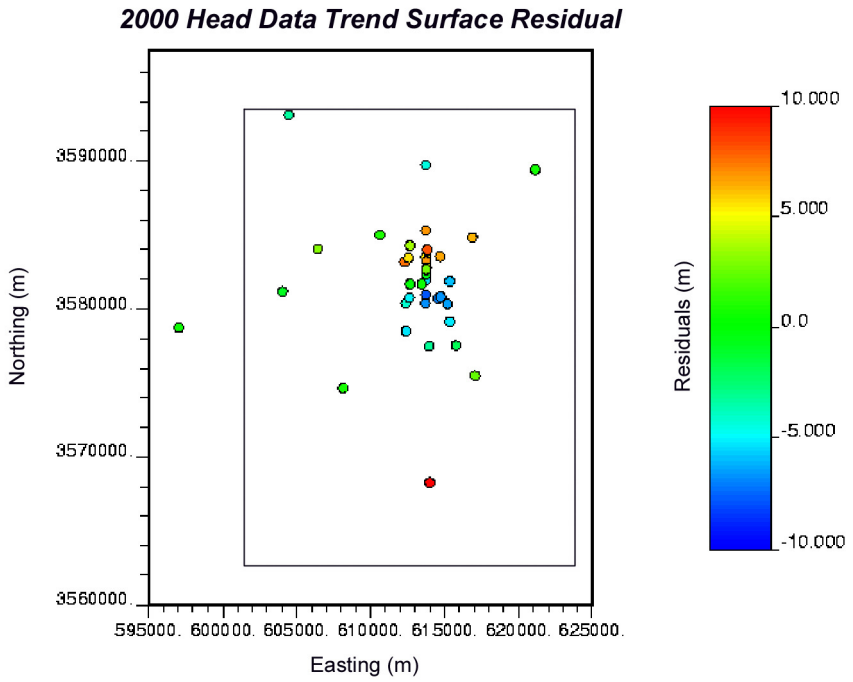


Figure TFIELD-18. Locations and Values of the Residuals Between the Gaussian Trend Surface Model and the Observed Head Data. The Approximate Boundary of the Flow Model is Shown as a Black Rectangle in the Image.

$$\gamma(h) = C\left[1 - e^{\left(\frac{3h^2}{a^2}\right)}\right] \text{ for } h > 0 \qquad \text{(TFIELD.8)}$$

where C is the sill of the variogram, h is the distance between any two samples, or the lag spacing, and a is the practical range of the variogram, or the distance at which the model reaches 95 percent (%) of the value of C. In addition to the sill and range, the variogram model may also have a nonzero intercept with the gamma (Y) axis of the variogram plot known as the nugget. Due to numerical instabilities in the kriging process associated with the Gaussian model without a nugget value, a small nugget was used in fitting each of the variogram models. The model variogram was fit to the experimental data (Figure TFIELD-19) and the parameters of this model are given in Table TFIELD-7.

The experimental variogram calculated on the 2000 data in Figure TFIELD-19 shows a number of points between lags 2,000 and 7,000 m (1.25 and 4.25 mi) that are above the variance of the data set (the horizontal dashed line). This behavior indicates that the Gaussian trend surface model used to calculate the residuals from the measured data did not remove the entire trend inherent in the observed data. A higher order trend surface model could be applied to these data to remove more of the trend, but the Gaussian trend surface model provides a reasonable estimate of the trend in the data.

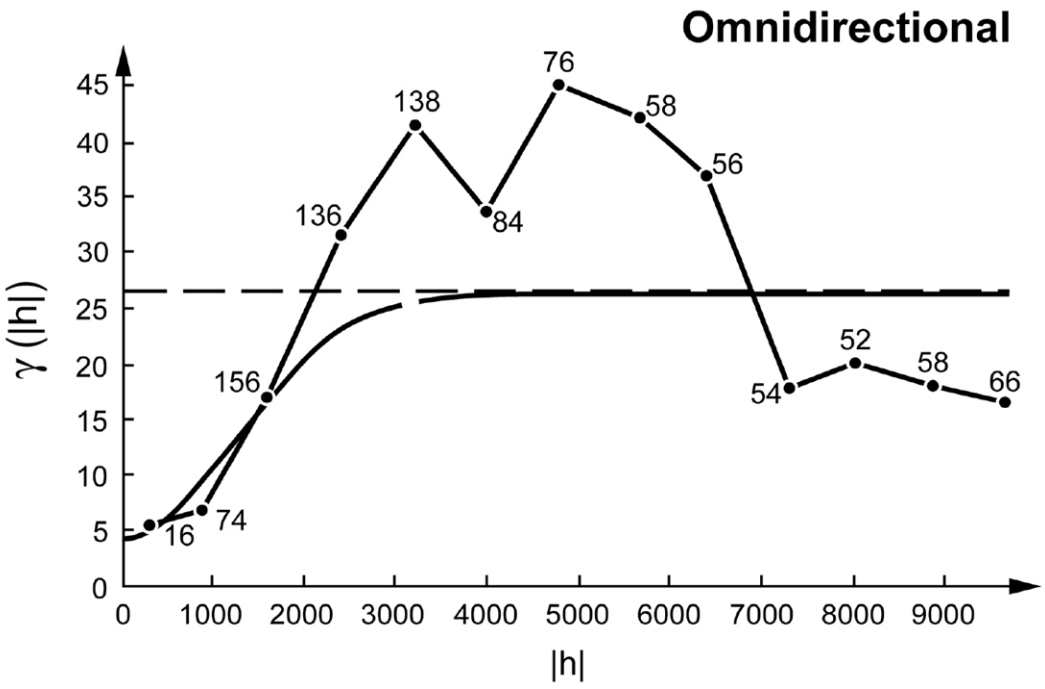


Figure TFIELD-19. Omnidirectional Experimental (Straight-Line Segments) and Model Variograms of the Head Residuals (Curves) for the 2000 Heads. The Numbers Indicate the Number of Pairs of Values That Were Used to Calculate Each Point and the Horizontal Dashed Line Denotes the Variance of the Residual Data Set.

Table TFIELD-7. Model Variogram Parameters for the Head Residuals

Parameter	Value
Sill	22
Range (meters)	3000
Nugget	4.5
Number of Data	37

The GSLIB kriging program KT3D (Deutsch and Journel 1998) was used to estimate the residual values at all points on the grid within the model domain. The Gaussian trend surface was then added to the estimated residual values to produce the final estimates of the initial head field.

TFIELD-6.3 Boundary Conditions

Two types of boundary conditions were specified in MODFLOW-2000: constant-head and no-flow. Constant-head conditions were assigned along the eastern boundary of the model domain, and along the central and eastern portions of the northern and southern boundaries. Values of these heads were obtained from the kriged initial head field. The western model boundary passes through the Mosaic Potash Carlsbad tailings pond (Laguna Uno) due west of the WIPP site in Nash Draw. A no-flow boundary (a flow line) is specified in the model from this tailings pond

up the axis of Nash Draw to the northeast, reflecting the concept that groundwater flows down the axis of Nash Draw, forming a groundwater divide. Similarly, another no-flow boundary is specified from the tailings pond down the axis of the southeastern arm of Nash Draw to the southern model boundary, coinciding with a flow line in the regional modeling of Corbet and Knupp (1996). Thus, the northwestern and southwestern corners of the modeling domain are specified as inactive cells in MODFLOW-2000. The initial (starting) head field is shown in Figure TFIELD-20 and the head values along each boundary of the model domain are shown in Figure TFIELD-21 and Figure TFIELD-22.

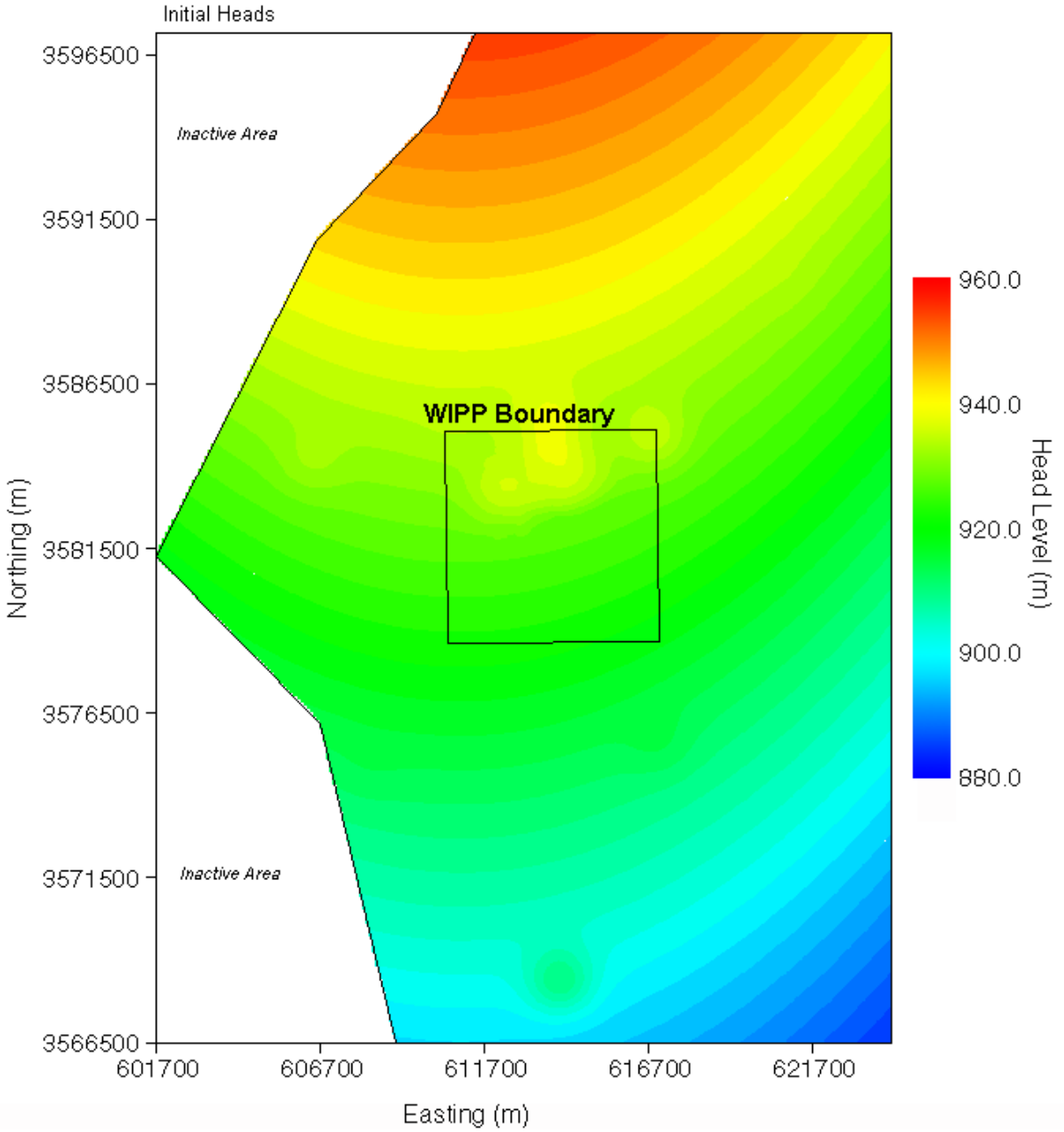


Figure TFIELD-20. Map of Initial Heads Created Through Kriging and Used to Assign Fixed-Head Boundary Conditions

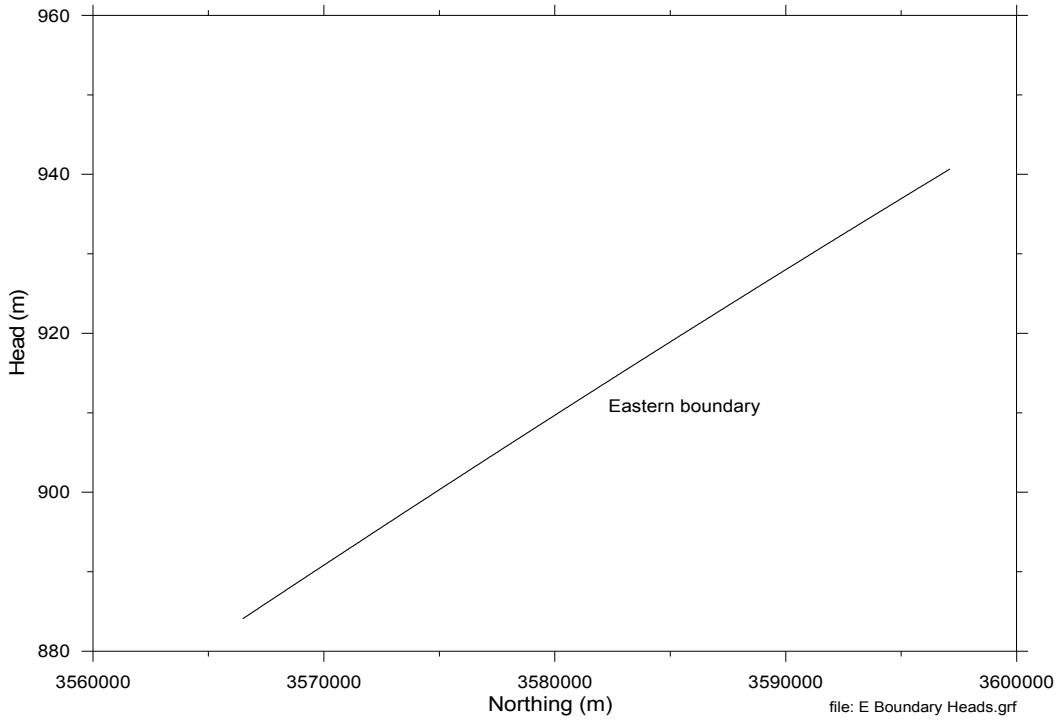


Figure TFIELD-21. Values of Fixed Heads Along the Eastern Boundary of the Model Domain

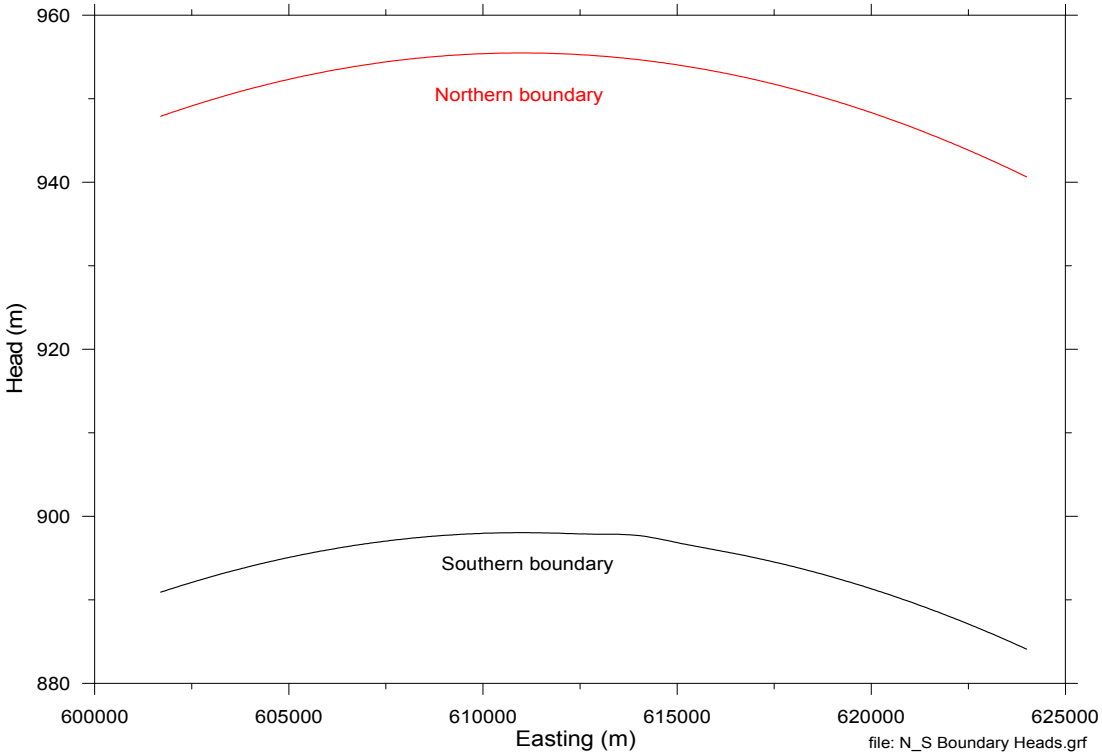


Figure TFIELD-22. Values of Fixed Heads Along the Northern and Southern Boundaries of the Model Domain. Note That Not All Locations Along the Boundaries are Active Cells.

TFIELD-6.4 Observed Steady-State and Transient Head Data Used in Model Calibration

In addition to being used to generate an initial head distribution, the water-level measurements made in 35 wells within the model domain during late 2000 were also used in steady-state model calibration. (Note that Table TFIELD-5 includes data from two wells–WIPP-27 and WIPP-29–that were used to define model boundary conditions but are outside the area of calibration).

The transient observation data used for the transient calibrations were taken from a number of different sources listed in Beauheim and Fox (2003). Responses to seven different hydraulic tests were employed in the transient portion of the calibration (Table TFIELD-8). Hydraulic responses for each of the 7 tests were monitored in 3 to 10 different observation wells depending on the hydraulic test.

A major change in the calibration data set from the CCA calculations is the exclusion of the hydraulic responses to the excavation of the exploratory (now salt) and ventilation (now waste) shafts in the current calibration. The responses to the shaft excavations were excluded because:

1. Only two wells (H-1 and H-3) responded directly to the shaft excavations and the areas between the shafts and these wells are stressed by other hydraulic tests that are included in the calibration data set (H-3b2, WIPP-13, and H-19b0).
2. It was difficult to model both the flux and pressure changes accurately during the excavation of the shafts with MODFLOW-2000. This difficulty is due to both the finite-difference discretization of MODFLOW-2000 that requires each shaft to be modeled as a complete model cell and some limitations of the data set.
3. The long-term effects of the shafts on site-wide water levels were important for the CCA modeling because that modeling sought to replicate heads over time. In the current CRA 2004 calibration effort, shaft effects are not important because drawdowns resulting from specific hydraulic tests are used as the calibration targets and shaft effects can be considered as second-order compared to the effects of the hydraulic tests that are simulated.

A small amount of processing of the observed data was necessary prior to using it in the calibration process. This processing included selecting the data values that would be used in the calibration procedure from the often voluminous measurements of head. These data were chosen to provide an adequate description of the transient observations at each observation well across the response time without making the modeling too computationally burdensome in terms of the temporal discretization necessary to model responses to these observations. Scientific judgment was used in selecting these data points. This selection process resulted in a total of 1,332 observations for use in the transient calibration.

Additionally, the modeling of the pressure data is done here in terms of drawdown. Therefore, the value of drawdown at the start of any transient test must be zero. A separate Perl script was written to normalize each set of observed heads to a zero value reference at the start of the test with the exception of the H-3 test that is only preceded by the steady-state simulation. The calculations are such that the resulting drawdown values are positive.

Table TFIELD-8. Transient Hydraulic Test and Observation Wells for the Drawdown Data

Stress Point	Observation Well	Observation Start	Observation End	Observation Type
H-3b2	DOE-1	10/15/1985	3/18/1986	Drawdown
	H-1	10/15/1985	4/14/1986	Drawdown
	H-2b2	10/15/1985	4/2/1986	Drawdown
	H-11b1	10/15/1985	4/21/1986	Drawdown
WIPP-13	DOE-2	1/12/1987	5/15/1987	Drawdown
	H-2b2	1/12/1987	5/15/1987	Drawdown
	H-6b	1/12/1987	5/15/1987	Drawdown
	P-14	1/12/1987	5/15/1987	Drawdown
	WIPP-12	1/12/1987	5/15/1987	Drawdown
	WIPP-18	1/12/1987	5/15/1987	Drawdown
	WIPP-19	1/12/1987	5/15/1987	Drawdown
	WIPP-25	1/12/1987	4/2/1987	Drawdown
	WIPP-30	1/12/1987	5/15/1987	Drawdown
P-14	D-268	2/14/1989	3/7/1989	Drawdown
	H-6b	2/14/1989	3/10/1989	Drawdown
	H-18	2/14/1989	3/10/1989	Drawdown
	WIPP-25	2/14/1989	3/7/1989	Drawdown
	WIPP-26	2/14/1989	3/7/1989	Drawdown
H-11b1	H-4b	2/7/1996	12/11/1996	Drawdown
	H-12	2/6/1996	12/10/1996	Drawdown
	H-17	2/6/1996	12/10/1996	Drawdown
	P-17	2/7/1996	12/10/1996	Drawdown
H-19b0	DOE-1	12/15/1995	12/10/1996	Drawdown
	ERDA-9	12/15/1995	12/10/1996	Drawdown
	H-1	12/15/1995	12/10/1996	Drawdown
	H-14	2/7/1995	12/10/1996	Drawdown
	H-15	12/12/1995	12/10/1996	Drawdown
	H-2b2	2/7/1996	12/10/1996	Drawdown
	H-3b2	12/15/1995	12/10/1996	Drawdown
	WIPP-21	1/18/1996	12/9/1996	Drawdown
	WQSP-4	1/1/1996	12/10/1996	Drawdown
	WQSP-5	1/18/1995	12/10/1996	Drawdown
WQSP-1	H-18	1/25/1996	2/20/1996	Drawdown
	WIPP-13	1/25/1996	2/20/1996	Drawdown
	WQSP-3	1/15/1996	2/20/1996	Zero Response
WQSP-2	DOE-2	2/20/1996	3/28/1996	Drawdown
	H-18	2/20/1996	3/28/1996	Drawdown
	WIPP-13	2/20/1996	3/28/1996	Drawdown
	WQSP-1	2/20/1996	3/24/1996	Drawdown
	WQSP-3	2/20/1996	3/24/1996	Zero Response

In addition to normalizing the measured head data, some of the tests produced negative drawdown values when normalized. These negative results are due to some of the observations having heads greater than the reference value. This occurs due to some hydraulic tests that were conducted at earlier times in the Culebra but were not included in the numerical model. If the drawdowns from one of these previous tests are still recovering to zero at the start of a

simulation, they can cause negative drawdowns in the simulation as the recovery continues. Most of these effects were addressed through trend removal in initial data processing (Beauheim and Fox 2003) but some residual effects remain.

The resultant transient calibration points are shown in Figure TFIELD-23 through Figure TFIELD-36. These sets of figures show the location of each hydraulic test and the locations of the observation wells for that test within the model domain and the time series of drawdown values for each observation well. The values of drawdown are in meters where a positive drawdown indicates a decrease in the pressure within the well relative to the pressure before the start of the pumping (negative drawdown values indicate rises in the water level). For the Water Quality Sampling Program (WQSP)-1 and WQSP-2 tests, well WQSP-3 showed no response. These results are used in the calibration process by setting the observed drawdown values to zero for WQSP-3. The maps in Figure TFIELD-23 through Figure TFIELD-35 also show the locations of the pilot points used in the calibration (these are discussed later).

TFIELD-6.5 Spatial Discretization

The flow model was discretized into 68,768 regular, orthogonal cells each of which represents 100 m (328 ft) × 100 m (328 ft). A constant Culebra thickness of 7.75 m (25.4 ft) was used (the CCA, Appendix TFIELD). The 100-m (328-ft) grid discretization was selected to make the finite-difference grid cell sizes considerably finer, on average, than those used in the CCA calculations, but still computationally tractable. In the CCA calculations, a telescoping finite-difference grid was used with the smallest cell being 100 m (328 ft) × 100 m (328 ft) near the center of the domain. The largest cells in the CCA flow model grid were 800 m (2,625 ft) × 800 m (2,625 ft) near the edges of the domain (Lavenue 1996).

The cells in the model domain were assigned elevations based on the digitized version of Figure TFIELD-1. Of the 68,768 cells (224 east-west by 307 north-south), 14,999 (21.8%) lie to the west of the no-flow boundary, so the total number of active cells in the model is 53,769. This number is nearly a factor of five larger than the 10,800 (108 × 100) cells used in the CCA calculations.

TFIELD-6.6 Temporal Discretization

The time period of nearly 11 years and 2 months covered by the transient modeling began October 15, 1985, and ended December 11, 1996. Additionally, a single steady-state calculation was run prior to the transient modeling. The length of this steady-state time period and the date at which it occurs were arbitrarily set to one day (86,400 s) occurring from October 14, 1985, to October 15, 1985. These steady-state heads were measured in the year 2000 and were only set to these October dates to provide a steady-state solution prior to the start of any transient hydraulic events. The responses to the transient events were defined by the amount of drawdown relative to the initial steady-state solution. The discretization of this time interval was dictated by the pumping history of the different wells used in the hydraulic testing and consideration of the additional computational burden required for increasingly fine time discretization.

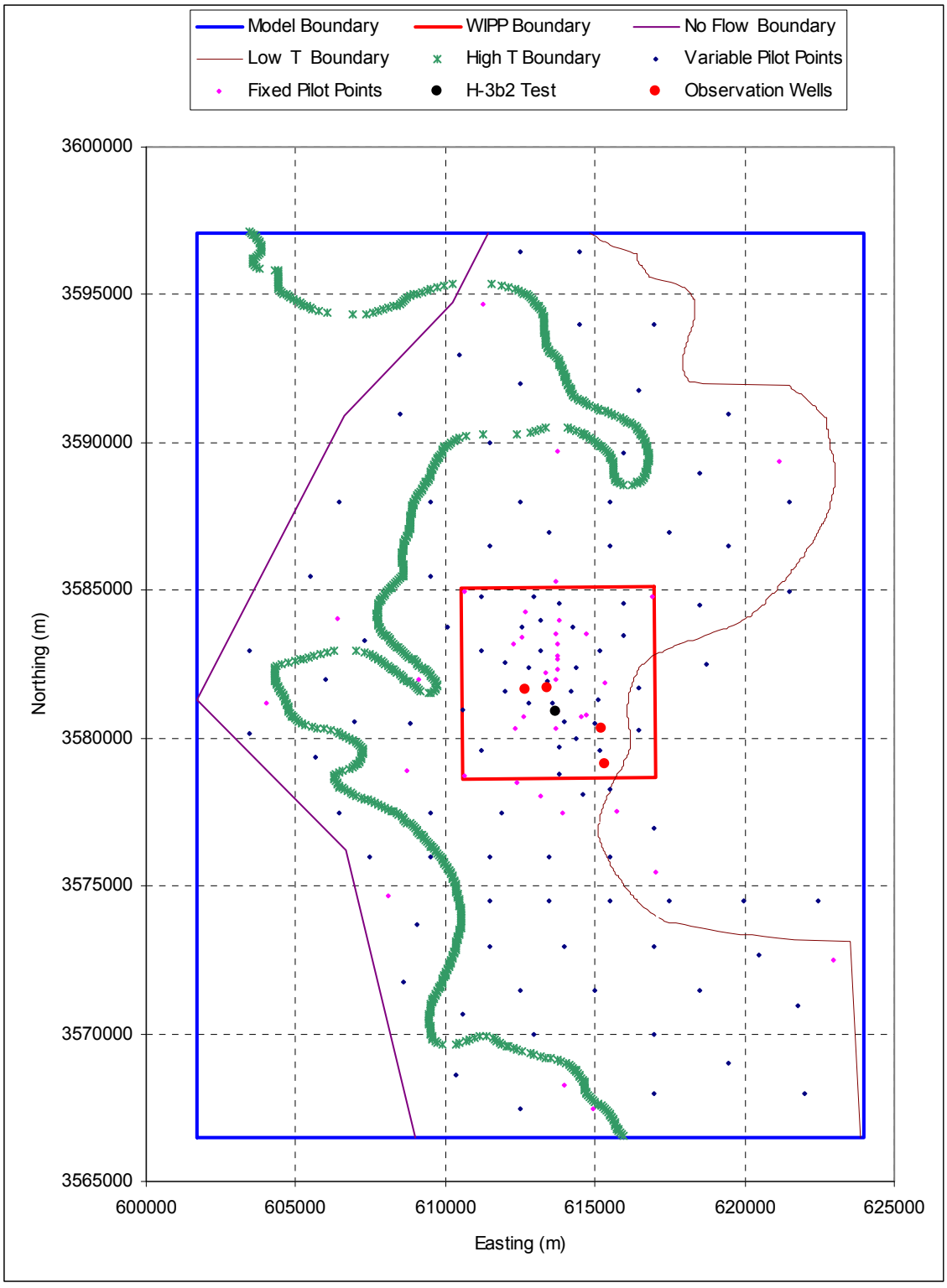


Figure TFIELD-23. Locations of the H-3b2 Hydraulic Test Well and Observation Wells

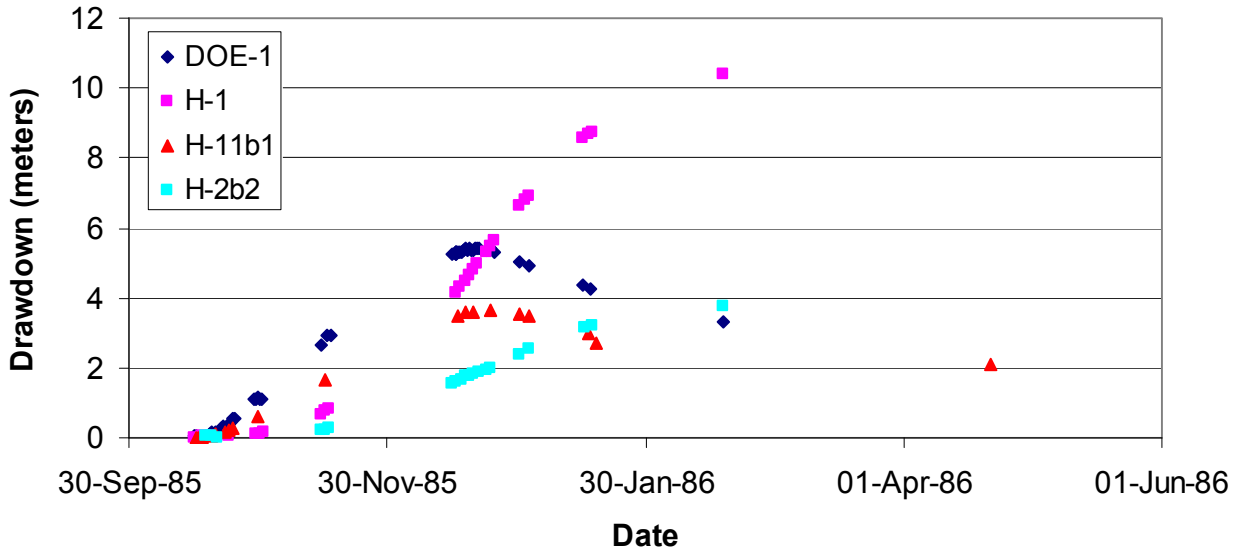


Figure TFIELD-24. Observed Drawdowns for the H-3b2 Hydraulic Test

The groundwater flow model, MODFLOW-2000, allows for the discretization of time into both "stress periods" and "time steps." A stress period is a length of time over which the boundary conditions and internal stresses on the system are constant. Even though these stresses are constant, this does not mean that the flow system is necessarily at steady state during the stress period. A time step is a subdivision of a stress period. System information such as the head or drawdown values is only calculated at the specified time steps. Each stress period must contain at least one time step. MODFLOW-2000 allows for the specification of the stress period length, the number of time steps in the stress period, and a time step multiplier. The time step multiplier increases the time between successive time steps geometrically. This geometric progression provides a nearly ideal time discretization for the start of a pumping or recovery period. To save on computational costs associated with calculating head/drawdown at each time step and with writing out the heads/drawdowns, the number of time steps in the model was kept to the minimum number possible that still adequately simulated the hydraulic tests. The time discretization in MODFLOW-2000 resulted in modeled heads calculated at times that sometimes differed from the observation times. For this situation, the PEST utility *mod2obs* was used to interpolate the head, or drawdown, values in time from the simulation times to the observation times.

A summary of the time discretization is given in Table TFIELD-9. There are five separate MODFLOW-2000 simulations for each complete forward simulation of the transient events. Each separate call to MODFLOW-2000 has its own set of input and output files. In Table TFIELD-9, each call to MODFLOW-2000 is separated by a horizontal black line. The first call is the steady-state simulation. The second, third, and fourth calls to MODFLOW-2000 (H-3, WIPP-13, and P-14) are all similar in that a single well was pumped. For the H-3 and WIPP-13 calls, there were a total of three stress periods. In the first stress period, the well was pumping at a constant rate; in the second stress period, the pumped well was inactive and heads were recovering after the cessation of pumping; and the final stress period was simply a long time of no pumping activity used to advance the simulation time to be consistent with the calendar time. The first two stress periods were discretized using eight time steps and the final stress period with no pumping activity was discretized using the minimum possible number of time steps—one.

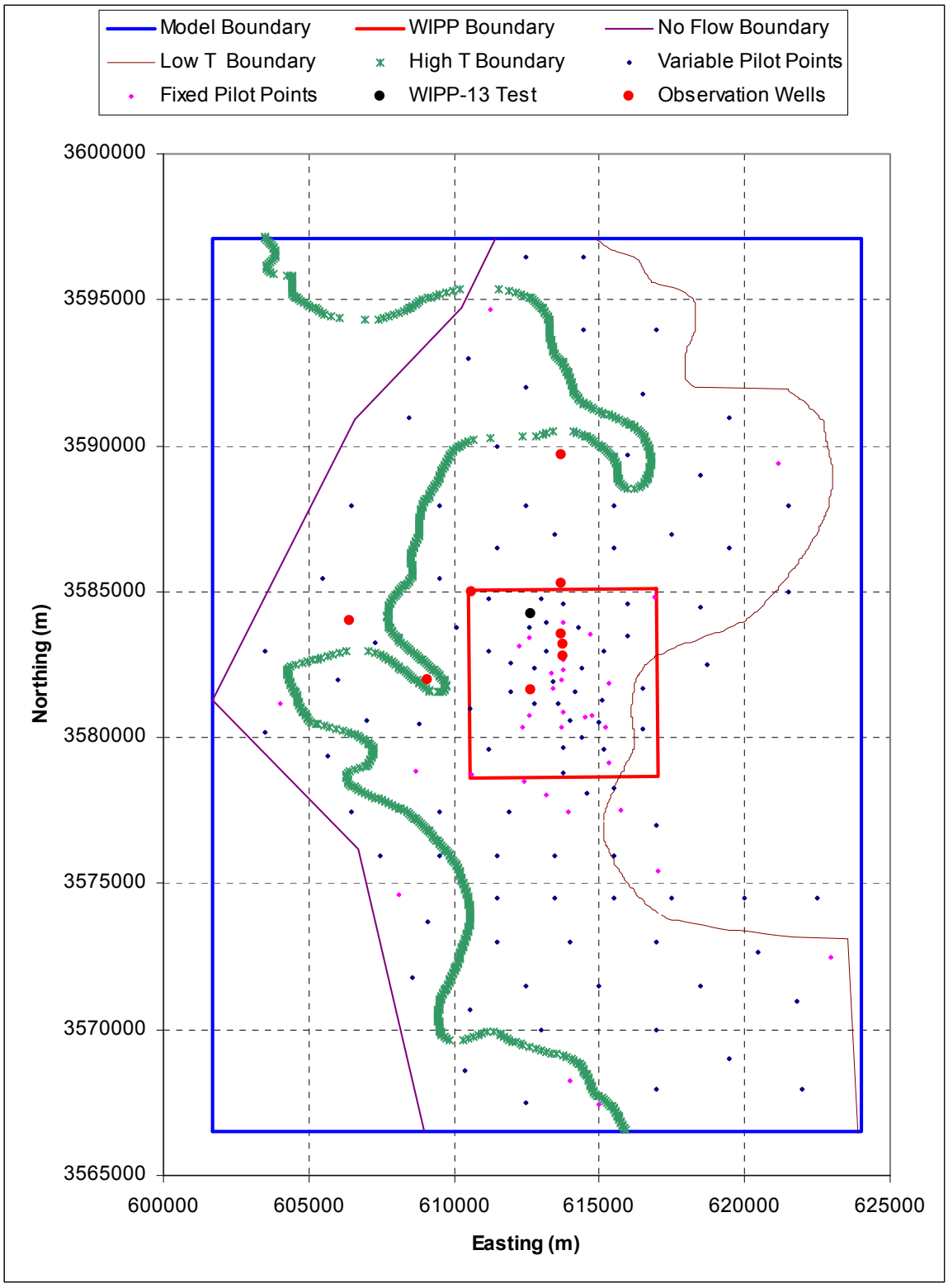


Figure TFIELD-25. Locations of the WIPP-13 Hydraulic Test Well and Observation Wells

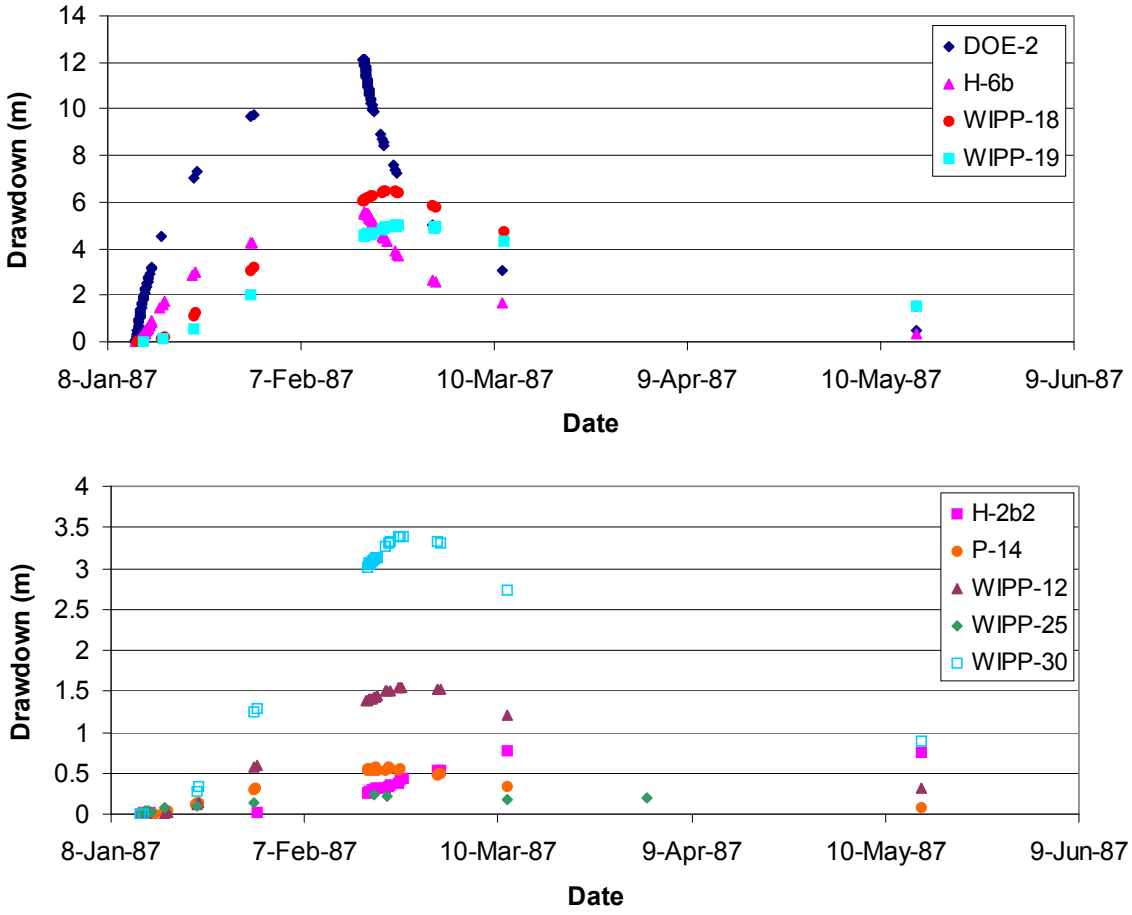


Figure TFIELD-26. Observed Drawdowns for the WIPP-13 Hydraulic Test. Note the Change in the Scale of the Y-Axis from the Upper to the Lower Image.

The final MODFLOW-2000 call, the H-19 call, was considerably more complicated than the earlier calls to MODFLOW-2000 and simulated the hydraulic conditions during the H-11, H-19, WQSP-1, and WQSP-2 hydraulic tests. This final call contained 17 stress periods with as many as 3 different wells pumping during any single stress period. The pumping rates of the different wells in this call to MODFLOW-2000 and the stress periods are shown as a function of time in Figure TFIELD-37. The first six stress periods in this call simulated pumping in the H-19 and H-11 wells without any observations (Table TFIELD-9). These pumping periods were added to the model solely to account for the effects of these tests in observations of later hydraulic tests and, therefore, these tests could be modeled with a single time step. The pumping rates shown in Figure TFIELD-37 are given as negative values to indicate the removal of water from the Culebra following the convention used in MODFLOW-2000.

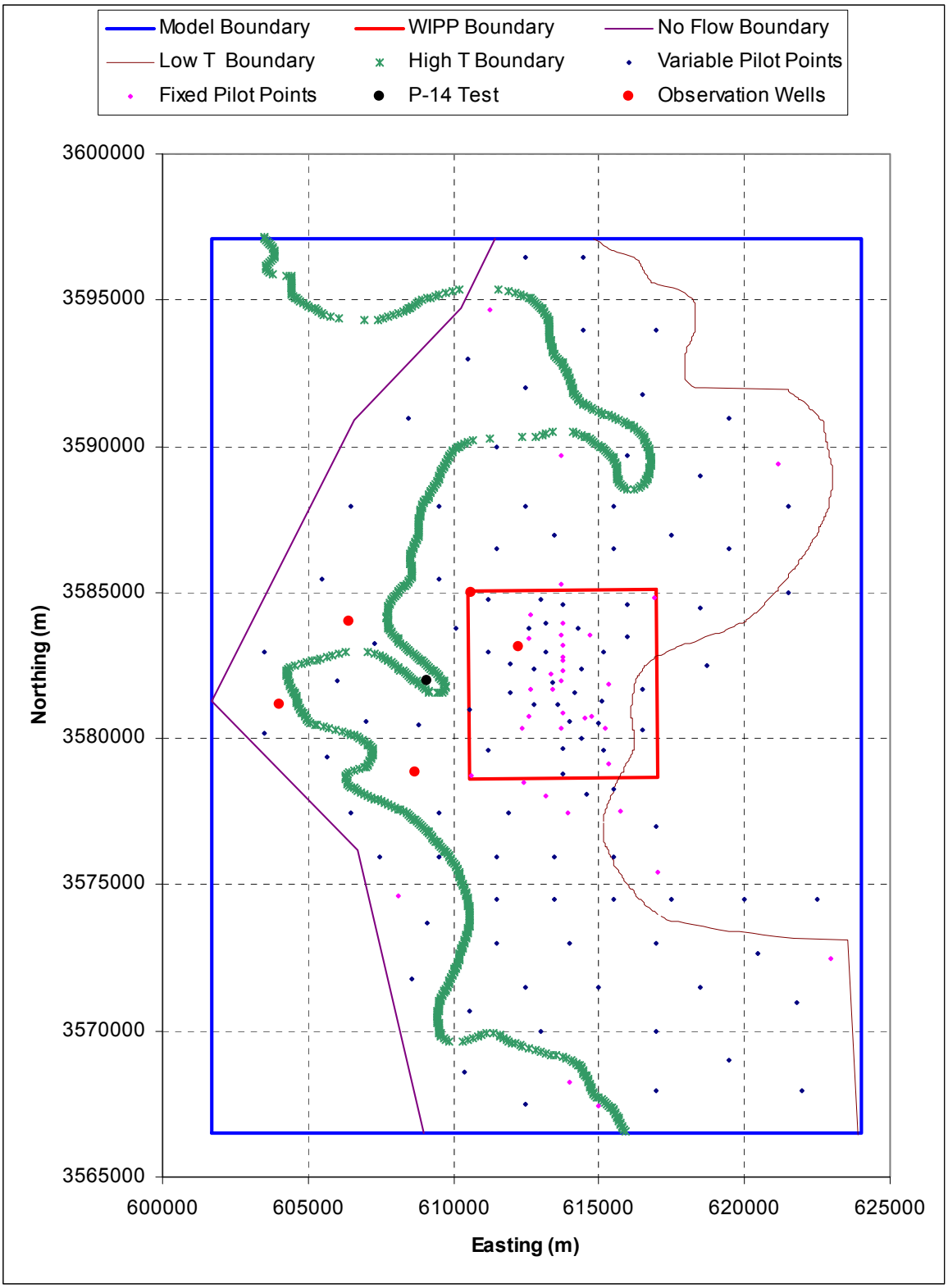


Figure TFIELD-27. Locations of the P-14 Hydraulic Test Well and Observation Wells

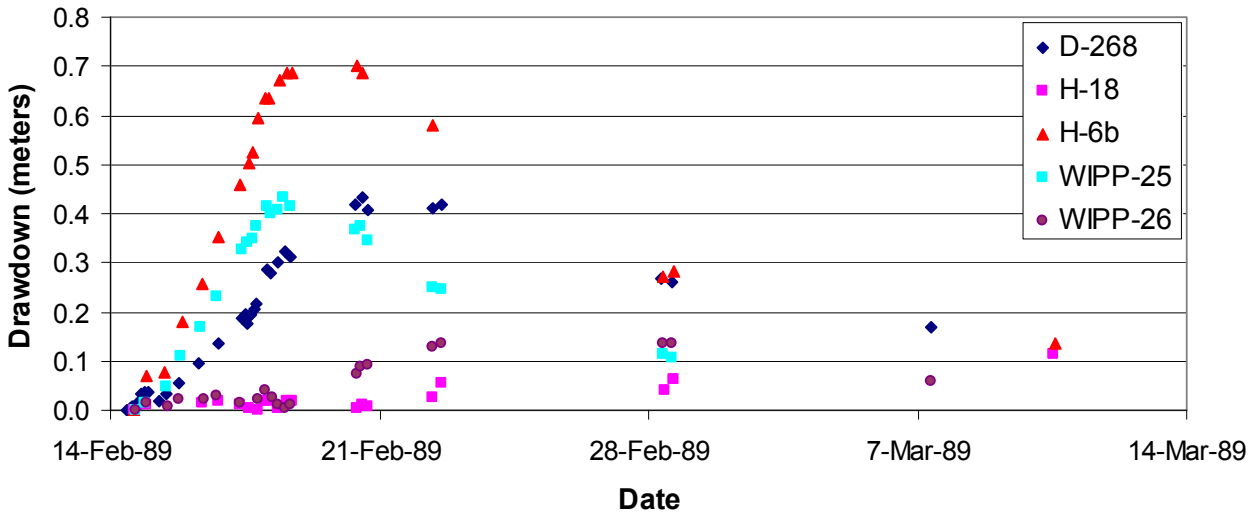


Figure TFIELD-28. Observed Drawdowns for the P-14 Hydraulic Test

The MODFLOW-2000 simulations could be done using a single call to MODFLOW-2000, but five separate calls were used here. Each of the five calls created separate binary output files of drawdown and head that were much smaller and easier to manage than a single output file would have been. Additionally, the simulated drawdowns at the start of each transient test must be zero (no drawdown prior to pumping). Because MODFLOW-2000 uses the resulting drawdowns and heads from the previous stress period as input to the next stress period, a single simulation would not necessarily start each transient test with zero drawdowns. Calling MODFLOW-2000 five times allowed the initial drawdowns to be reset to zero each time using shell scripts. The heads simulated at the end of the final time step in each MODFLOW-2000 call were used as the initial heads for the next call. The results of all five calls were combined to produce the 1332 model predictions prior to comparing them to the 1332 selected observation data, thus ensuring that all steady-state and transient data were used simultaneously in the inverse calibration procedure.

TFIELD-6.7 Weighting of Observation Data

The observed data for each response to each transient hydraulic test are weighted to take into account the differences in the responses across the different tests. The weights are calculated as the inverse of the maximum observed drawdown for each hydraulic test. This weighting scheme applies relatively less weight to tests with large drawdowns and relatively more weight to tests with smaller responses. This weighting scheme was used so that the overall calibration was not dominated by trying to reduce the very large residuals that may occur at a few of the observation locations with very large drawdowns. Under this weighting scheme, two tests that are both fit by the model to within 50% of the observed drawdown values would be given equal consideration in the calculation of the overall objective function even though one test may have an observed maximum drawdown of 10 m (33 ft) and the other a maximum observed drawdown of 0.10 m (0.33 ft).

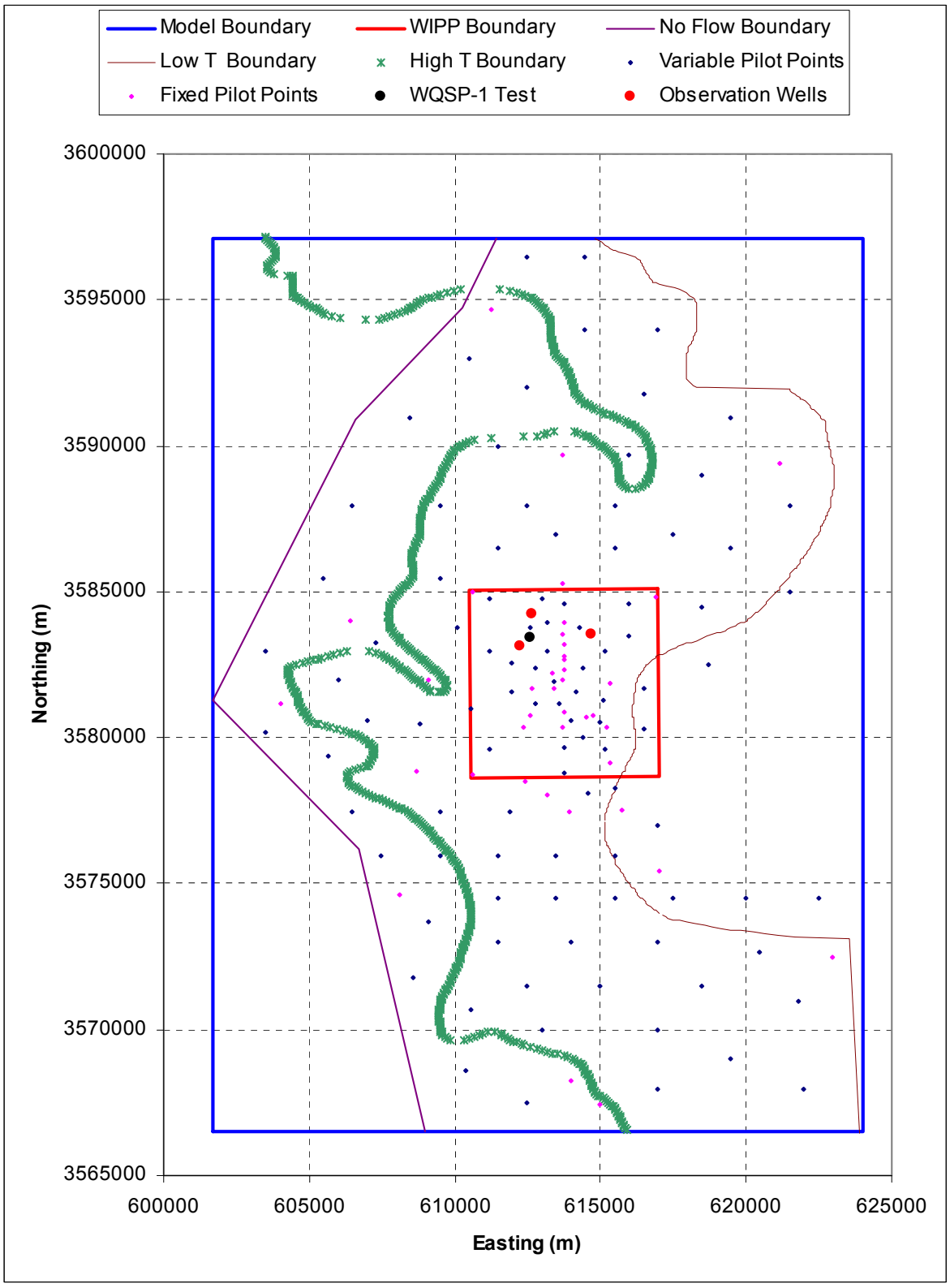


Figure TFIELD-29. Locations of the WQSP-1 Hydraulic Test Well and Observation Wells

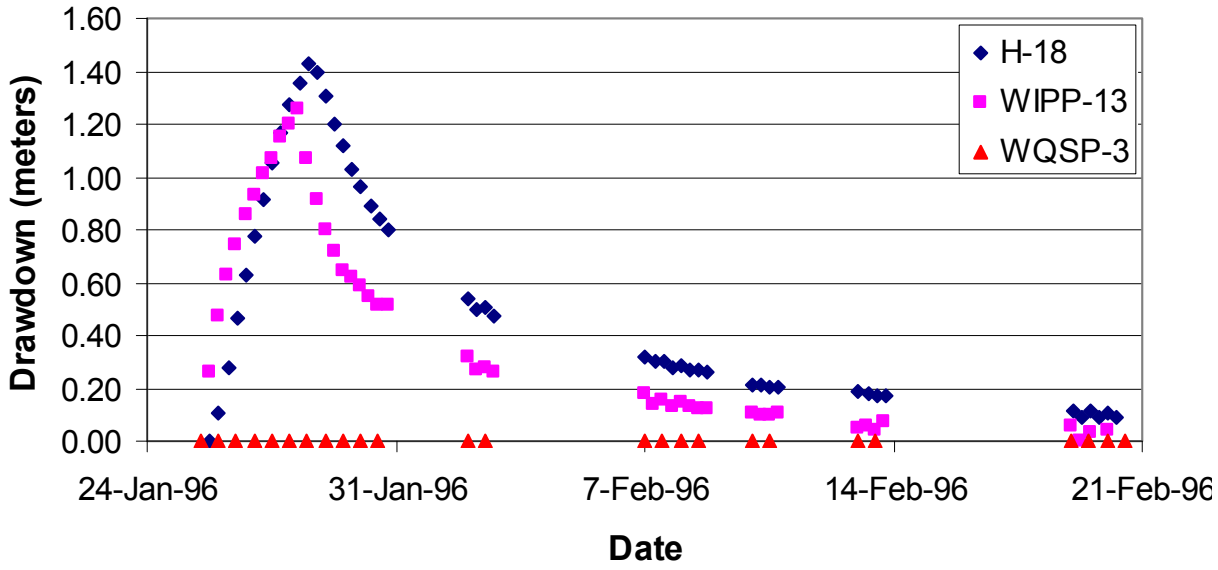


Figure TFIELD-30. Observed Drawdowns for the WQSP-1 Hydraulic Test

The weights assigned in this manner ranged from 0.052 to 20.19. The observed absence of a hydraulic response at WQSP-3 to pumping at WQSP-1 and WQSP-2 was also included in the calibration process by inserting measurements of zero drawdown that were given an arbitrarily high weight of 20. Through trial and error using the root mean squared error (RMSE) criterion of how well the modeled steady-state heads fit the observed steady-state heads, a weight of 2.273 was assigned to the 35 steady-state observations. This weight is near that of the average of all the weights assigned to the transient events and was found to be adequate to provide acceptable steady-state matches. It is noted that the steady-state data provide measurements of head while all of the transient events provide measurements of drawdown. However, the weights were applied to the residuals between the observed and modeled aquifer responses and because both heads and drawdowns are measured in meters, there was no need to adjust the weights to account for different measurement units.

The number of measurements used for calibrations that were made at individual wells during individual tests ranged from 6 to 104, and the number of measurements used for calibration that were made at all wells during a single test ranged from 64 to 410. This means that different well responses and different tests carried different cumulative weights. The spatially broadest sampling of transient data possible was used in an effort to get transient coverage of as much of the modeling domain as possible. In those areas where no transient data are available, the calibration is dominated by fitting the model to the steady-state measurements. The greatest coverage of transient data is within the boundaries of the WIPP site, which is also the area of most significance for radionuclide transport.

The maximum observed drawdown, the weight assigned to all the observed test values for each test, and the total number of observations for each observation well are given in Table TFIELD-10. In a few cases, weights were increased to obtain better fits, or decreased due to high degrees of noise in the data.

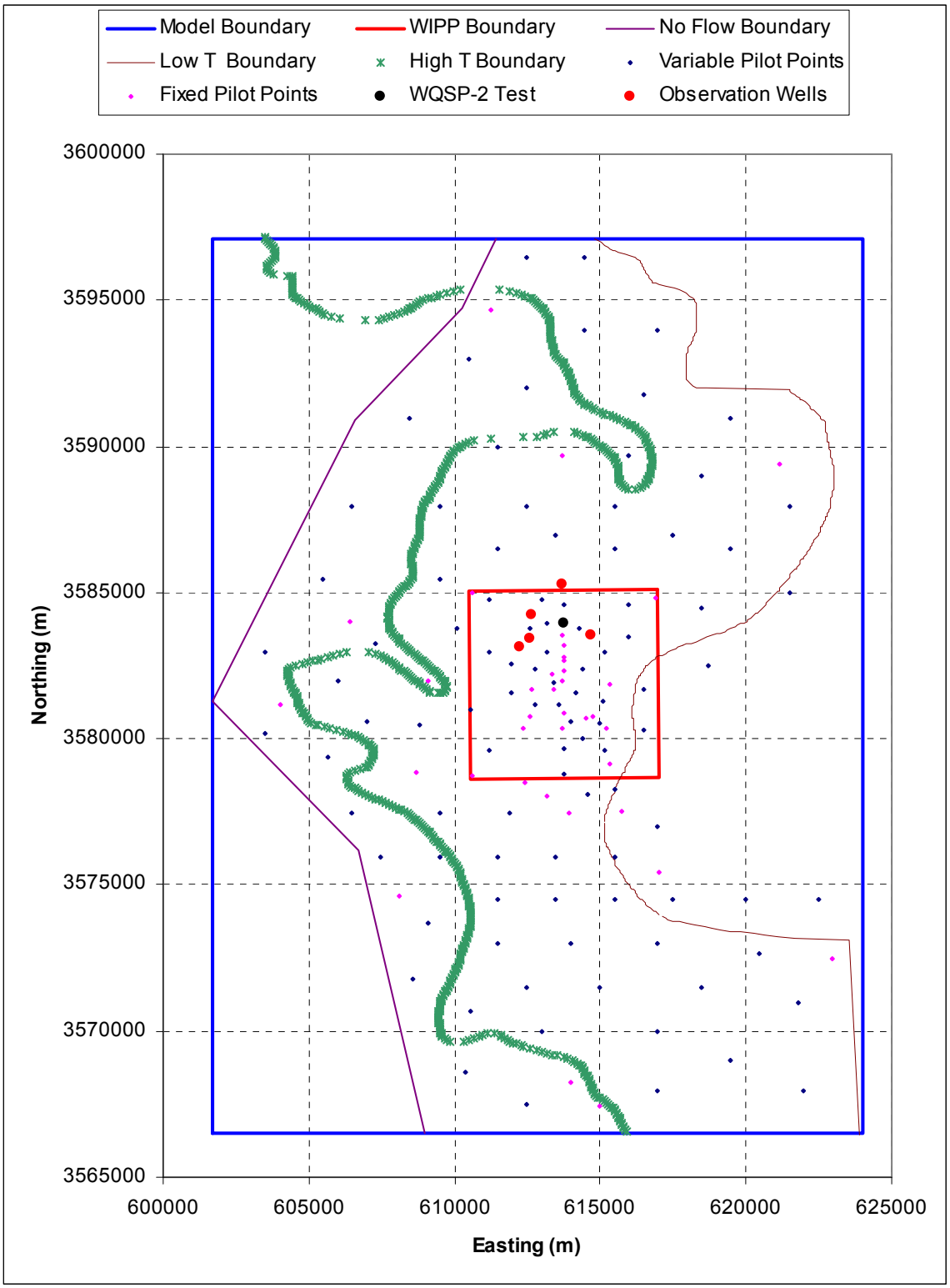


Figure TFIELD-31. Locations of the WQSP-2 Hydraulic Test Well and Observation Wells

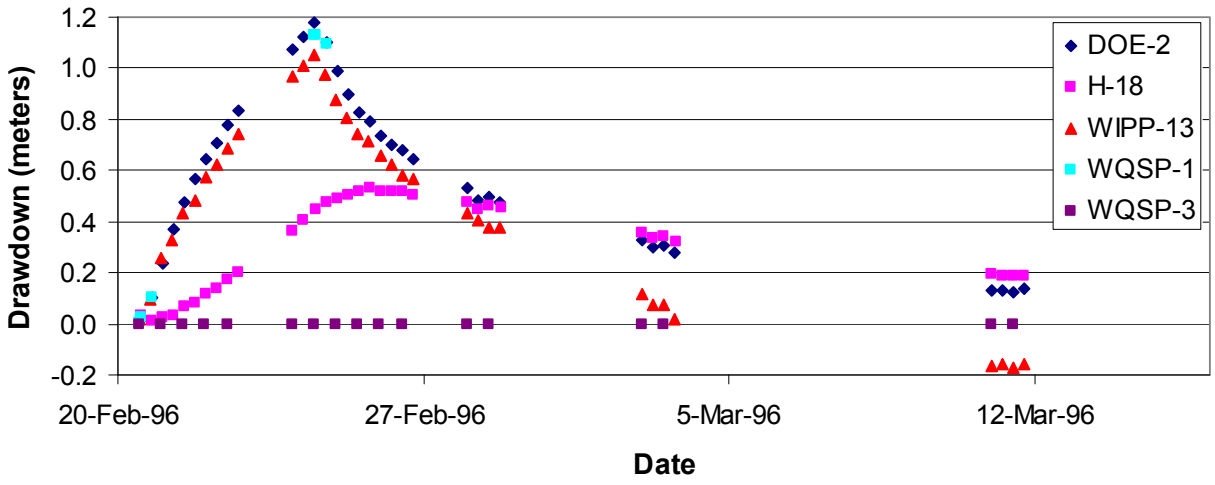


Figure TFIELD-32. Observed Drawdowns from the WQSP-2 Hydraulic Test

TFIELD-6.8 Assignment of Pilot Point Geometry

A major development in the field of stochastic inverse modeling that has occurred since the T fields were constructed for the CCA in 1996 is that inverse techniques are now capable of simultaneously determining optimal transmissivity values at a large number of pilot points. In the T fields constructed for the CCA, pilot points were added one at a time and each point was calibrated prior to the addition of the next pilot point. Furthermore, the total number of pilot points was limited to less than or equal to the total number of transmissivity observations to avoid numerical instabilities in the solution of the inverse problem. With the techniques now available and implemented in PEST, it is possible to use many more pilot points than there are transmissivity observations and to calibrate these pilot points simultaneously.

The pilot-point locations were chosen using a combination of a regular grid approach and deviations from that grid to accommodate specific pumping- and observation-well locations (Figure TFIELD-38). The goal in these deviations from the regular grid was to put at least one pilot point between each pumping well and each of its observation wells. Details of the pilot-point locations relative to the pumping and observation wells in the WIPP site area are shown in Figure TFIELD-39. This combined approach of a regular grid with specific deviations from that grid follows the guidelines for pilot-point placement put forth by John Doherty (the author of PEST 2003) (Doherty 2002) as Appendix 1 in the work of McKenna and Hart (2003a). Pilot points located at the transmissivity measurement locations were held as fixed values during the optimization (fixed pilot points shown as magenta squares in Figure TFIELD-38). The variable pilot points (dark blue diamonds in Figure TFIELD-38) are those where the transmissivity value was adjusted during the calibration procedure. A total of 43 fixed and 100 variable pilot points was used in the T-field calibration process. The zone option in PEST was employed to limit the influence of pilot points in any one zone (e.g., high-T or low-T) to adjusting only locations that are in the same zone.

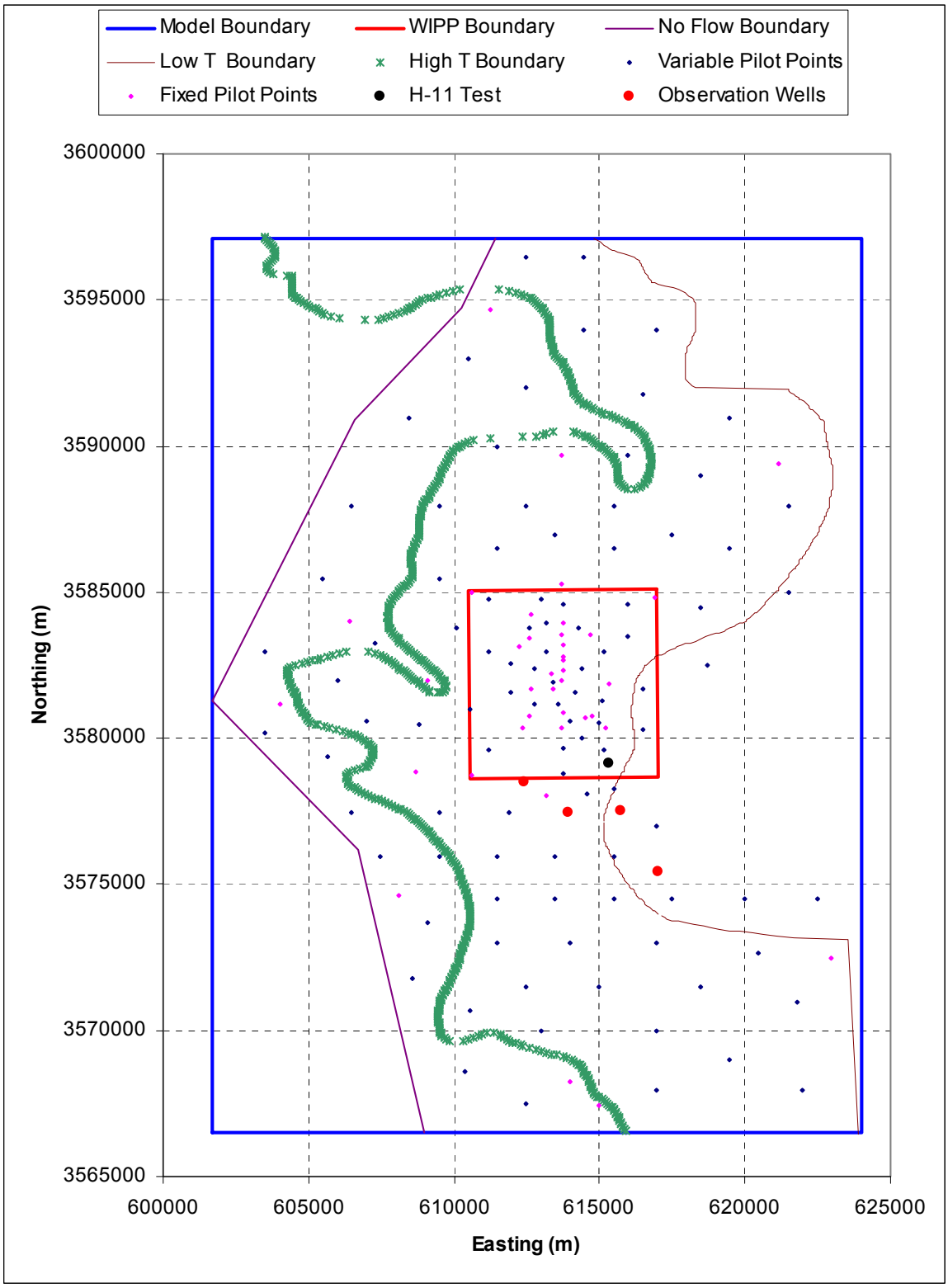


Figure TFIELD-33. Locations of the H-11 Hydraulic Test Well and Observation Wells

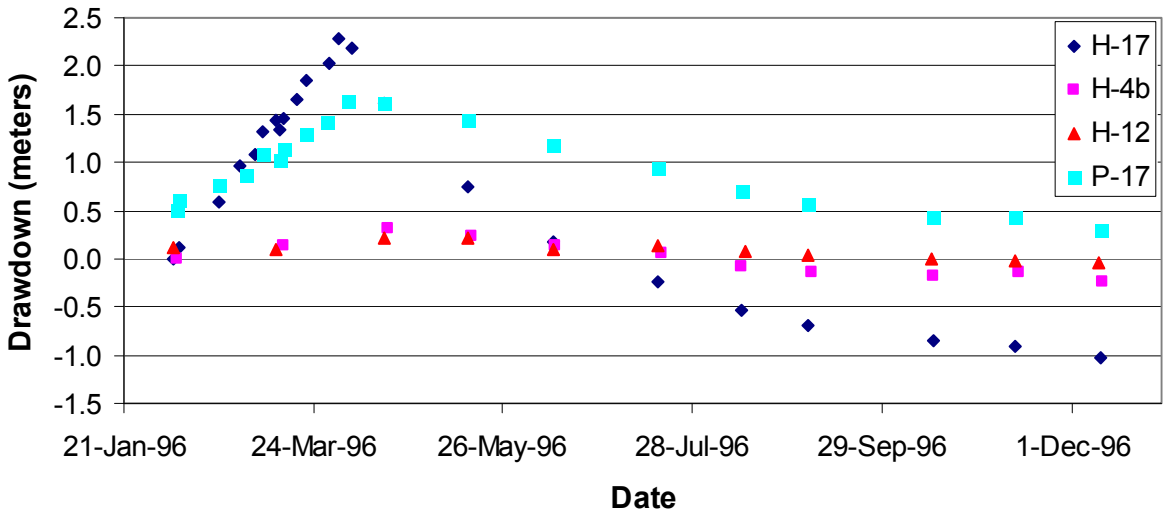


Figure TFIELD-34. Observed Drawdowns for the H-11 Hydraulic Test

The variogram model for the residuals between the transmissivity measurements and the base field has a range of 1,050 m (3,445 ft). Because the pilot-point approach to calibration uses this range as a radius of influence, locations of the adjustable pilot points were as much as possible set to be at least 1,050 m (3,445 ft) away from other pilot points (adjustable or fixed). For maximum impact, all pilot points should be at least 2,100 m (6,890 ft) away from any other pilot point but, given the existing well geometry, this distance was not always achievable.

TFIELD-6.9 Stochastic Inverse Calibration

The seed realizations are input to the inverse model using the pilot-point method. The seed realizations are calibrated to the steady-state and transient head measurements. The residuals and the T-field calculations are done in $\log_{10}$ space so that a unit change in the residual equates to a one order of magnitude change in the value of transmissivity. The initial values of the pilot points are equal to the value of the initial residual field at each pilot-point location. The pilot points are constrained to have a maximum perturbation of ±3.0 from the initial value except for those pilot points within the high-T zone in Nash Draw (Figure TFIELD-11) and the low-T zone on the eastern side of the model domain that are limited to perturbations of ±1.0. These limits are employed to maintain the influence of the geologic conceptual model on the calibrated T fields.

Figure TFIELD-11 is updated as Figure TFIELD-40 to show, conceptually, how the addition of two pilot points along the cross section can modify the residual field and then update the T field. The pilot points are shown as the open circles in Figure TFIELD-40 and are used to modify the residual field before it is added to the base T field. Compare the shape of the dashed red and blue lines in Figure TFIELD-40 to the same lines in Figure TFIELD-11. The values of the residuals at the observation points are held fixed so any adjacent pilot points cannot modify them.

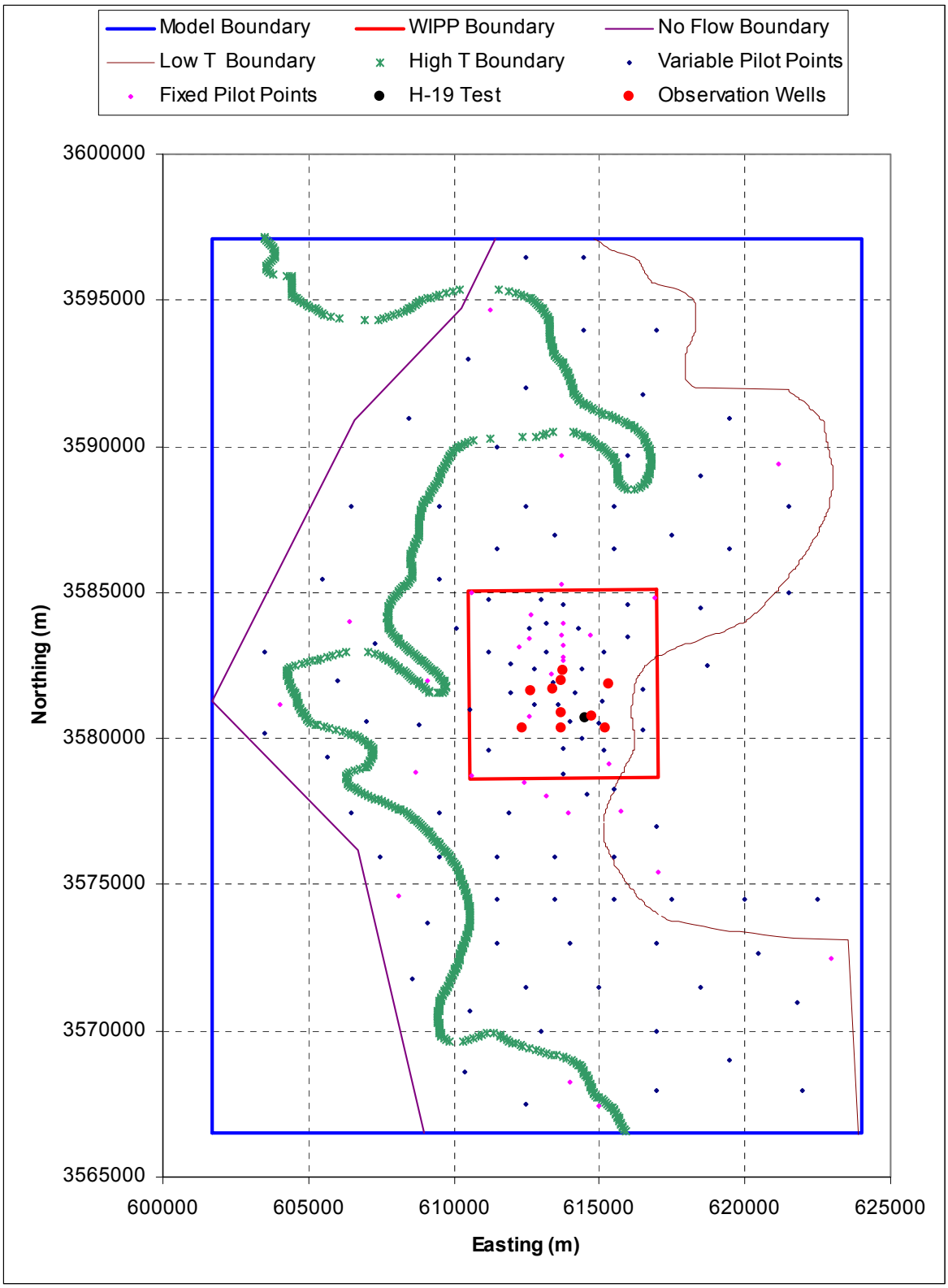


Figure TFIELD-35. Locations of the H-19 Hydraulic Test Well and Observation Wells

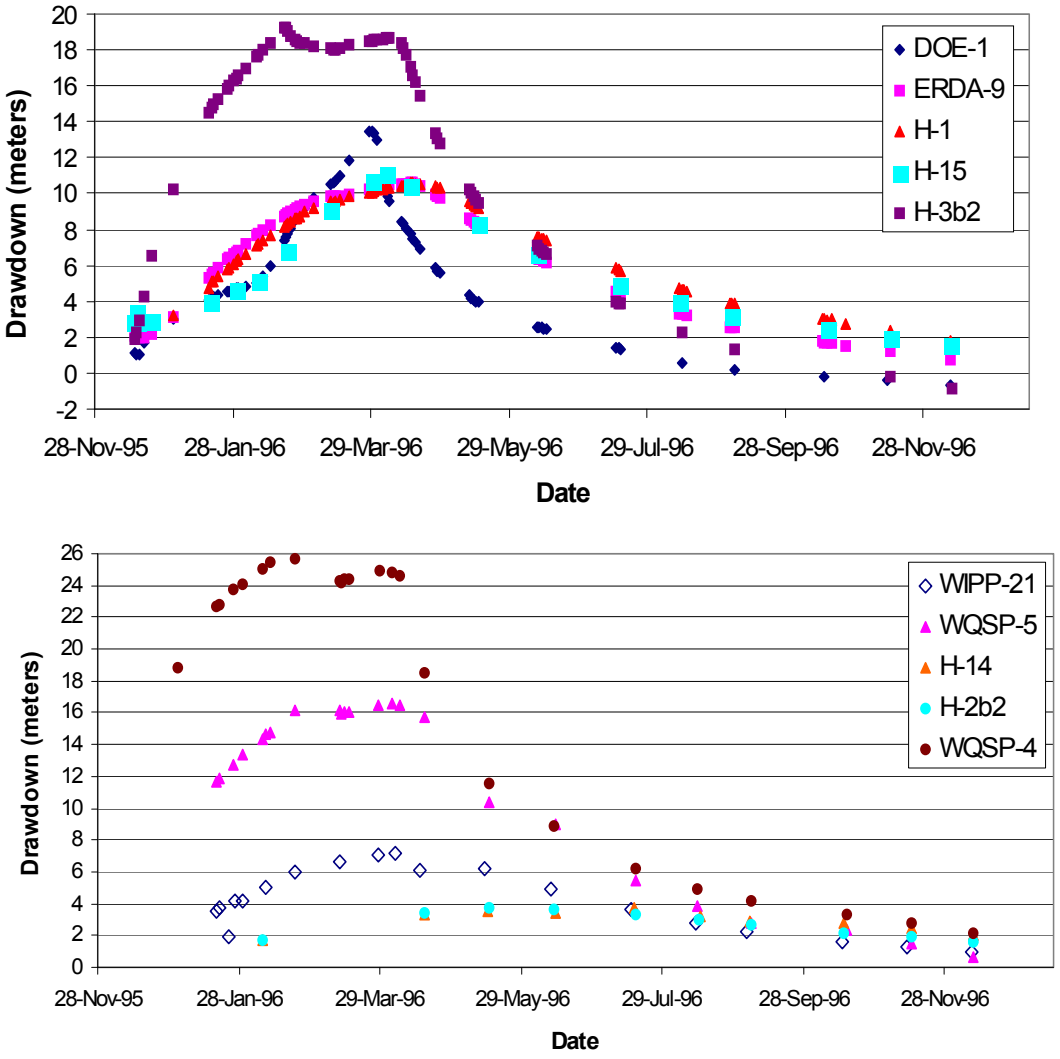


Figure TFIELD-36. Observed Drawdowns From the H-19 Hydraulic Test

At the heart of the calibration process is the iterative adjustment of the residual field at the pilot points by PEST and the subsequent updates of the residual field at the locations surrounding the pilot points based on the shape of the variogram modeled on the raw residuals. The updated residual field is then combined with the base T field (see Figure TFIELD-18) and then used in MODFLOW-2000 to calculate the current set of modeled heads. These modeled heads are then input to PEST for the next iteration.

The objective function minimized by PEST (phi) is a combination of the weighted sum of the squared residuals between the measured and observed steady-state head data, the weighted sum of the squared residuals between the measured and observed transient drawdown data, and the weighted sum of the squared differences in the estimated transmissivity value between pairs of pilot points.

Table TFIELD-9. Discretization of Time into 29 Stress Periods and 127 Time Steps with Pumping Well Names and Pumping Rates

Event Name	Global Stress Period No.	Internal Stress Period No.	Stress Period Length (s)	No. of Time Steps	Start Date	Stop Date	Pumping Well(s)	Pumping Rate(s) (m^3/s)
Steady	1	1	86400	1	10/14/859:00	10/15/859:00	0	0
H-3	2	1	5356800	8	10/15/859:00	12/16/859:00	H-3	3.03E-04
	3	2	10892700	8	12/16/859:00	4/21/8610:45	None	0.00E+00
	4	3	22976100	1	4/21/8610:45	1/12/879:00	None	0.00E+00
WIPP-13	5	1	3110400	8	1/12/879:00	2/17/879:00	WIPP-13	1.89E-03
	6	2	7539900	8	2/17/879:00	5/15/8715:25	None	0.00E+00
	7	3	55359360	1	5/15/8715:25	2/14/899:01	None	0.00E+00
P-14	8	1	44928	3	2/14/899:01	2/14/8921:29	P-14	3.92E-03
	9	2	174612	8	2/14/8921:29	2/16/8922:00	P-14	3.64E-03
	10	3	50400	3	2/16/8922:00	2/17/8912:00	P-14	3.37E-03
	11	4	1820396	8	2/17/8912:00	3/10/8913:39	None	0.00E+00
	12	5	193212124	1	3/10/8913:39	4/24/95 19:42	None	0.00E+00
H-19	13	1	148860	1	4/24/9519:42	4/26/95 13:03	H-19b0	2.26E-04
	14	2	4399020	1	4/26/9513:03	6/16/9511:00	None	0.00E+00
	15	3	3614400	1	6/16/9511:00	7/28/95 7:00	H-19b0	2.36E-04
	16	4	1168200	1	7/28/95 7:00	8/10/95 19:30	None	0.00E+00
	17	5	1292700	1	8/10/9519:30	8/25/9518:35	H11	2.44E-04
	18	6	9651300	1	8/25/9518:35	12/15/9511:30	None	0.00E+00
	19	7	2878200	8	12/15/9511:30	1/17/9619:00	H-19b0	2.71 E-04
	20	8	670680	3	1/17/9619:00	1/25/9613:18	H-19b0	2.52E-04
	21	9	238980	3	1/25/9613:18	1/28/96 7:41	H-19b0, WQSP-1	2.52E-04, 4.30E-04
	22	10	872340	3	1/28/96 7:41	2/7/9610:00	H-19b0	2.52E-04
	23	11	1047000	8	2/7/9610:00	2/19/9612:50	H-19b0, H-11	2.52E-04, 2.23E-04
	24	12	81600	3	2/19/9612:50	2/20/9611:30	H-19b0, H-11	1.55E-04, 2.23E-04
	25	13	345600	3	2/20/96 11:30	2/24/9611:30	H-19b0, H-11,WQSP-2	1.55E-04, 2.23E-04, 4.5E-04
	26	14	1395000	8	2/24/96 11:30	3/11/9615:00	H-19b0, H-11	1.55E-04, 2.23E-04
	27	15	1445100	8	3/11/9615:00	3/28/96 8:25	H-19b0, H-11	1.55E-04, 3.76E-04
	28	16	1220700	8	3/28/96 8:25	4/11/9611:30	H-19b0	1.55E-04
	29	17	21074400	8	4/11/9611:30	12/11/969:30	None	0.00E+00

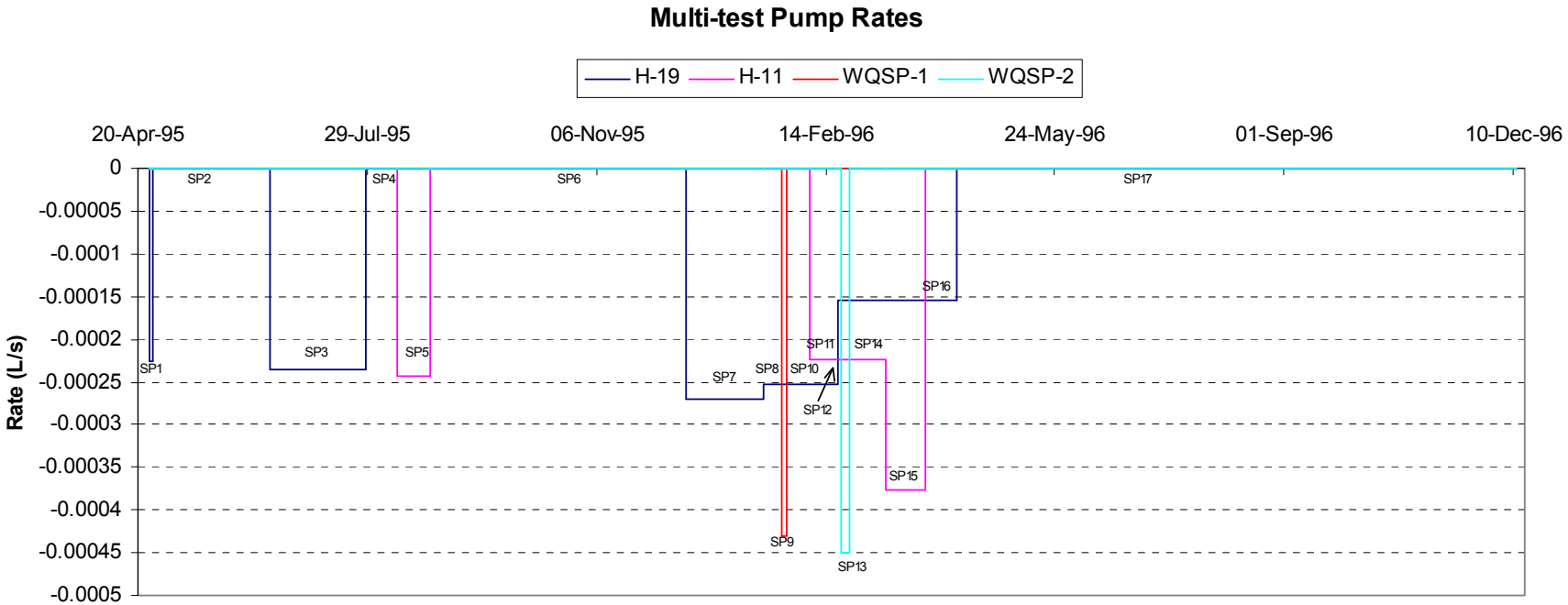


Figure TFIELD-37. Temporal Discretization and Pumping Rates for the Fifth Call to MODFLOW-2000. A Total of 17 Stress Periods (SPs) are Used to Discretize this Model Call.

Table TFIELD-10. Observation Weights for Each of the Observation Wells

Test Well Observation Well	Maximum Drawdown (m)	Weight	Number of Observations
Steady	NA	2.273	35
H3-DOE1	5.426	0.184	57
H3-H1	10.396	0.096	26
H3-H11b1	3.622	0.276	19
H3-H2b2	3.781	0.265	20
W13-DOE2	12.138	0.082	104
W13-H2b2	0.781	1.281	23
W13-H6	5.545	0.180	93
W13-P14	0.570	1.755	38
W13-W12	1.553	0.644	27
W13-W18	6.481	0.154	26
W13-W19	5.048	0.198	22
W13-W25	0.246	4.062	11
W13-W30	3.391	0.295	24
P14-D268	0.432	2.317	38
P14-H18	0.113	8.850	21
P14-H6b	0.701	1.427	21
P14-W25	0.432	2.315	22
P14-W26	0.137	7.310	20
WQSP1-H18	1.431	0.699	47
WQSP1-W13	1.260	0.794	47
WQSP1-WQSP3	0.000	20.000	25
WQSP2-DOE2	1.178	0.849	34
WQSP2-H18	0.529	1.892	35
WQSP2-W13	1.053	0.949	34
WQSP2-WQSP1	1.132	0.884	6
WQSP2-WQSP3	0.000	20.000	18
H11-H17	1.030	0.971	23
H11-H4b	0.232	4.317	11
H11-H12	0.021	20.190	11
H11-P17	1.628	3.304	19
H19-DOE1	13.463	0.074	70
H19-ERDA9	10.571	0.095	80
H19-H1	10.618	0.094	80
H19-H15	11.110	0.090	22
H19-H3b2	19.283	0.052	69
H19-W21	7.153	0.140	19
H19-WQSP5	16.623	0.060	24
H19-H14	3.759	0.602	11
H19-H2b2	3.794	0.608	11
H19-WQSP4	25.721	0.462	24

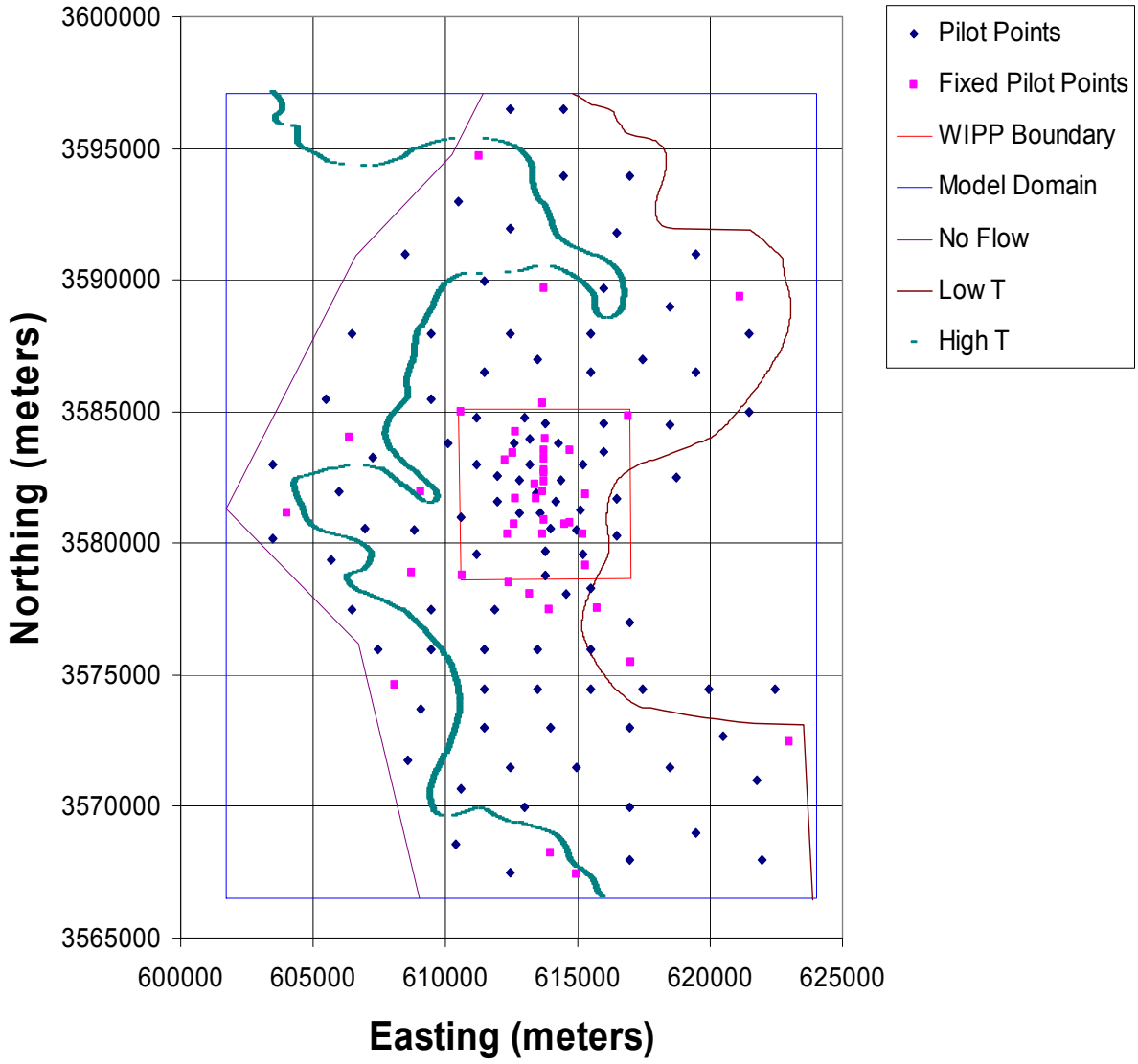


Figure TFIELD-38. Locations of the Adjustable and Fixed Pilot Points Within the Model Domain

Phi is defined as:

$$\phi = \sum_{i=1}^{n_{obs}^{SS}} (W^{SS}(H_i^{obs-SS} - H_i^{calc-SS}))^2 + \sum_{i=1}^{n_{wells}^{Tr}} \sum_{j=1}^{n_{obs}^{Tr}} (W_i^{Tr}(D_j^{obs-Tr} - D_j^{calc-Tr}))^2 + \sum_{i=1}^{n_{PP}} \sum_{j=j}^{n_{PP}} W_{ij}^{R}(PP_i - PP_j) \quad \text{(TFIELD.9)}$$

where n_{obs} is the number of head observations, n_{wells} is the number of wells, n_{PP} is the number of pilot points, W is the weight assigned to a group of measurements, H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively, D^{obs} and D^{calc} are the values of the observed and calculated drawdowns, respectively, PP refers to the $\log_{10}$ transmissivity value at a pilot point, and superscripts SS, Tr, and R refer to steady-state measurements, transient measurements, and pilot-point regularization, respectively. For this work, the weights on the head and

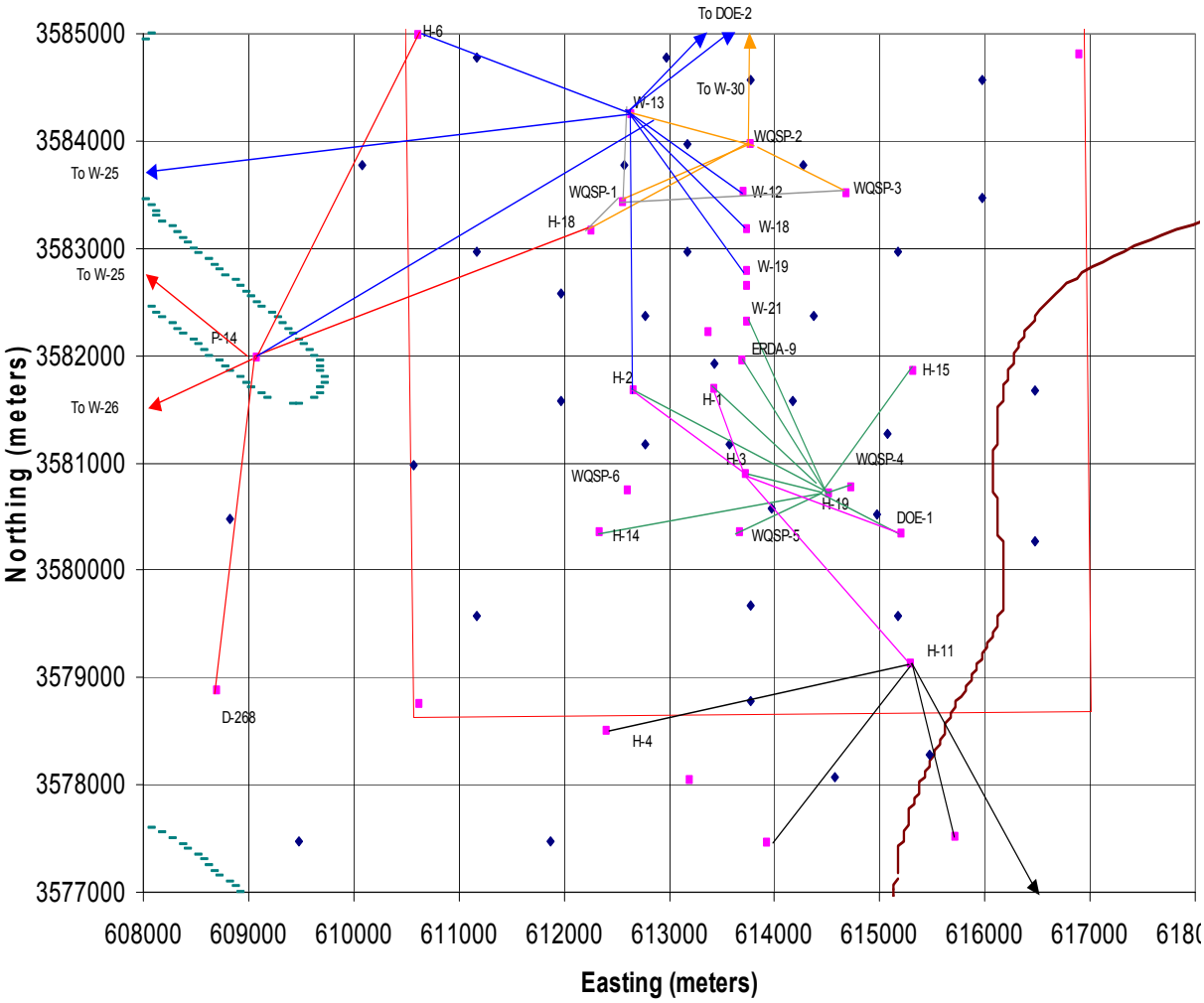


Figure TFIELD-39. Close-Up View of the Pilot-Point Locations in the Area of the WIPP Site. The Colored (Solid) Lines Connect the Pumping and Observation Wells. The Legend for this Figure is the Same as That for Figure TFIELD-38.

drawdown observations are as given in Table TFIELD-10. The third weighted sum of squares in the objective function is the regularization portion of the objective function. This weighted sum of squares involves the difference in transmissivity values between each pair of pilot points (PP_i–PP_j) and is designed to keep the T field as homogeneous as possible and to provide numerical stability when estimating more parameters than there are data. The pilot-point regularization weights, W_{ij}^R, are defined by the kriging factors and are a function of the distance between any two pilot points.

The stochastic inverse calibration process uses multiple pre- and post-processor codes in addition to PEST and MODFLOW-2000. The overall numerical approach to the T-field calibration is shown in Figure TFIELD-41 and Figure TFIELD-42 and the details on this approach are documented in McKenna and Hart (2003a, 2003b). The top of Figure TFIELD-41 shows the preprocessing steps. The large oval in the middle of the figure contains the link between MODFLOW-2000 and PEST. The "model process" portion of the figure is expanded and the

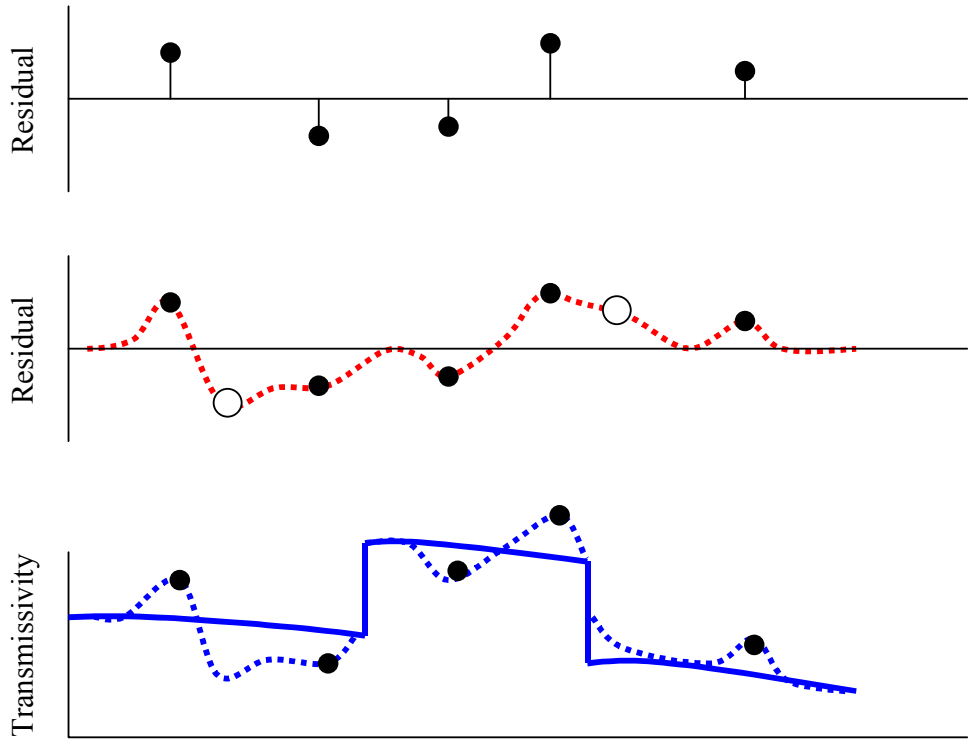


Figure TFIELD-40. Conceptual Cross-Section Showing the Addition of Pilot Points to the Optimization Process

details are shown in Figure TFIELD-42. The output files and the connection to the particle-tracking code are shown in the bottom of Figure TFIELD-41.

The calibration process is run iteratively until at least one of three conditions are met: (1) the number of iterations reaches the maximum allowable number of 15; (2) the objective function reaches a predefined minimum value of 1,000 square meters (m^2); or (3) the value of the objective function changes by less than 1% across three consecutive iterations.

At the end of the calibration process, a residual field is created that when added to the base T field reproduces the measured transmissivity values at the 43 measurement locations and provides a minimum sum of squared errors (SSE) between the observed and model-predicted heads/drawdowns. An example of the final step in the creation of a calibrated T field is shown in Figure TFIELD-43. The computational cost of calibrating to the multiple transient events is significant. For comparison, a single forward run of MODFLOW-2000 in steady-state takes on the order of 10–15 s on a 1.9-Gigahertz (GHz) AMD Athlon™ processor, whereas the run time for the combined steady-state and transient events is approximately 3 minutes (a factor of 12–18 times longer).

Due to these longer run times, two separate parallel PC clusters were employed. Each of these clusters consists of 16 computational nodes running 1.9-GHz Athlon processors with 1 gigabyte of random access memory. One cluster is located in Albuquerque, NM, and the other is in the

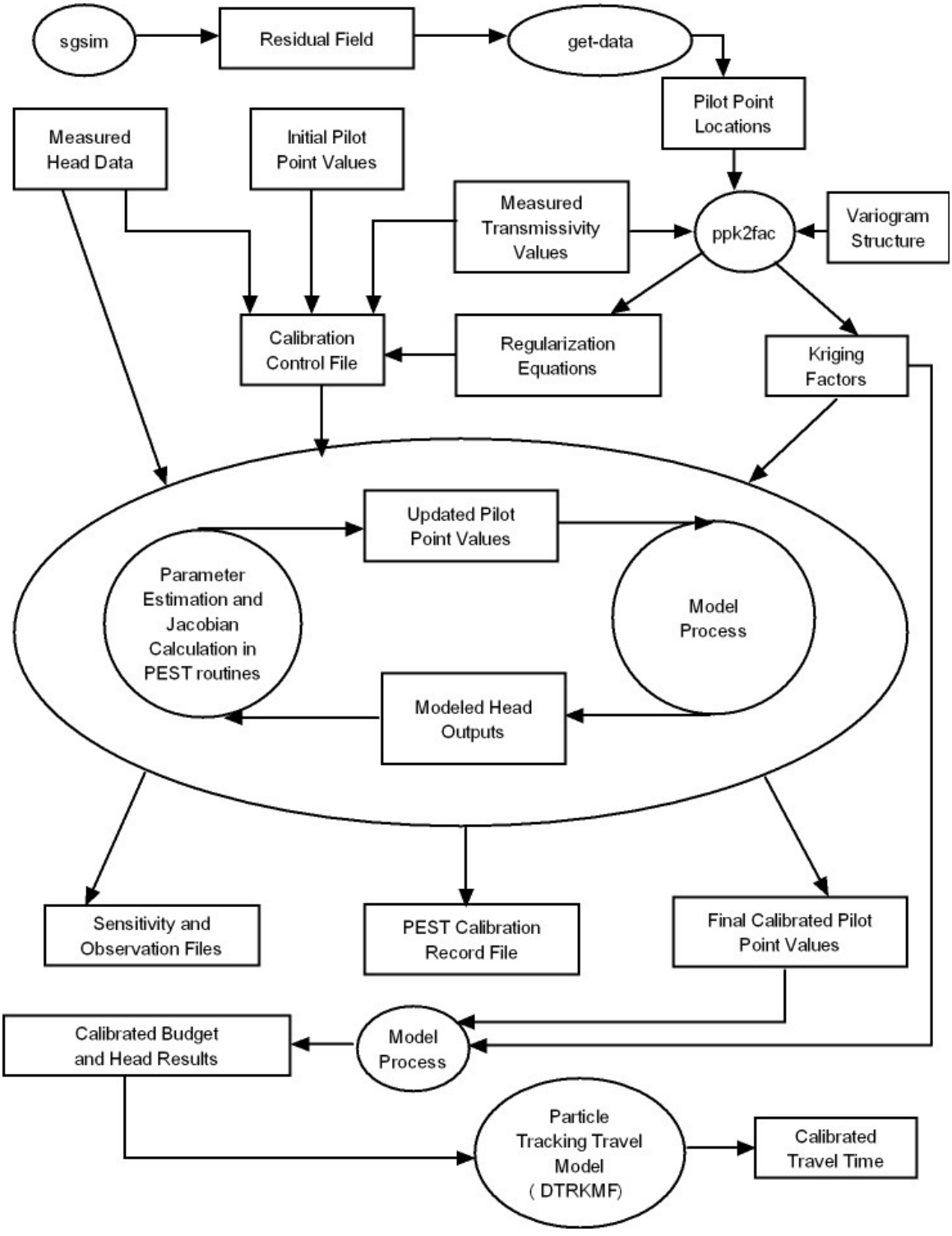


Figure TFIELD-41. Flow Chart of the Stochastic Inverse Calibration Process Used to Create the Final Calibrated T Fields

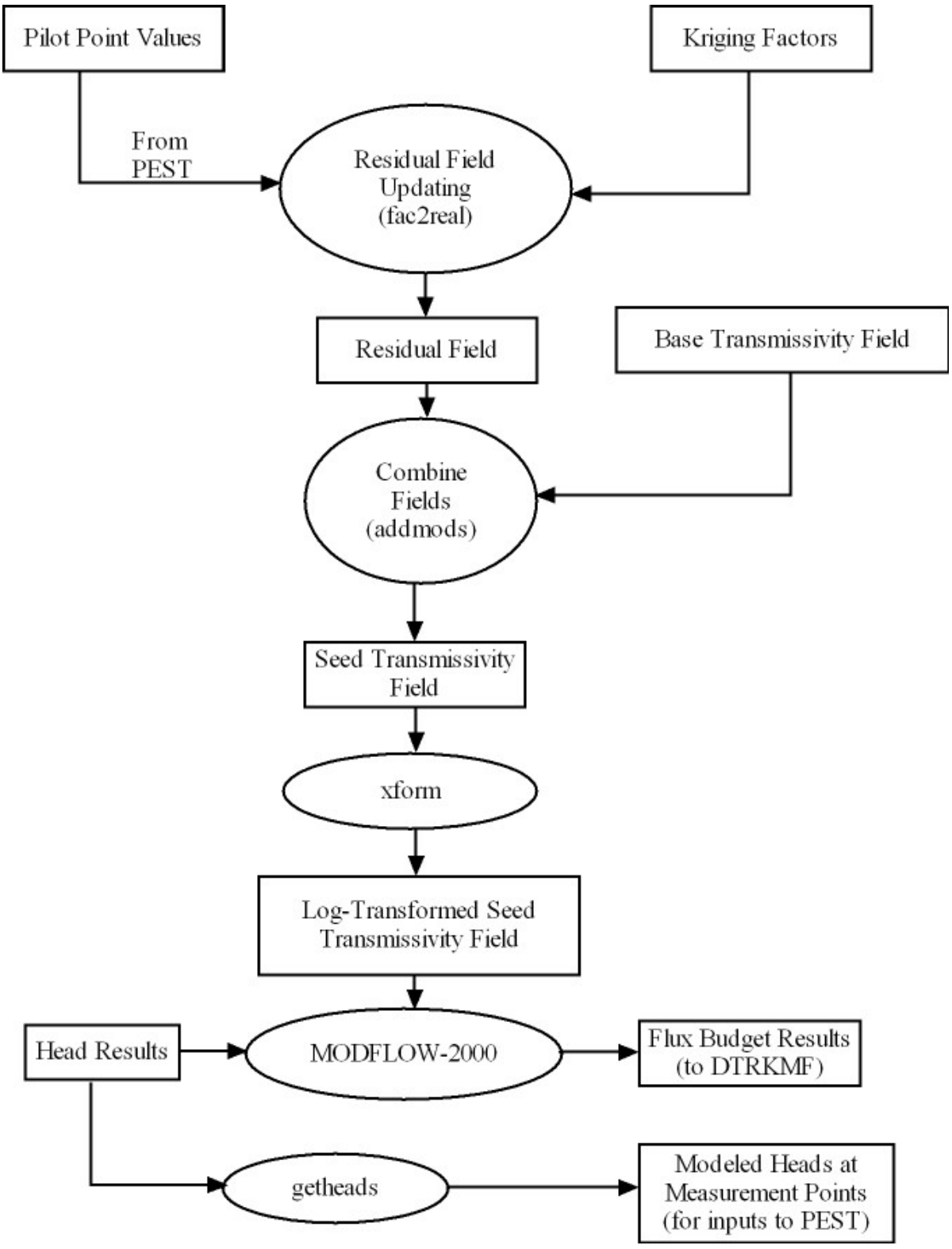


Figure TFIELD-42. Flow Chart of the Core of the Inversion Process Highlighting the Connection Between PEST and MODFLOW-2000

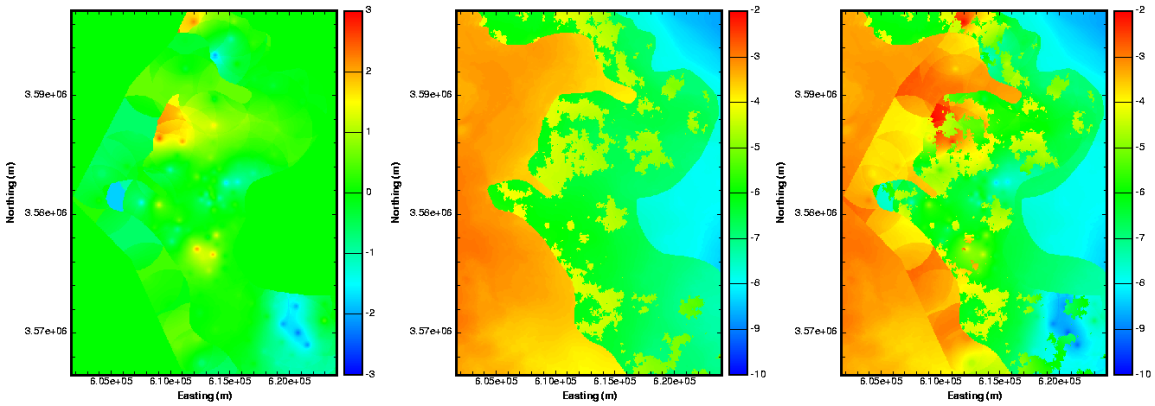


Figure TFIELD-43. Example Final Steps in the Creation of a Calibrated T Field. The Calibrated Residual Field (Left Image) is Added to the Base T Field (Middle Image) to Get the Final Calibrated T Field (Right Image). All Color Scales are in Units of $\log_{10}$ Transmissivity (m^2/s).

Sandia office in Carlsbad, NM. Both clusters use the Linux® operating system. The total number of forward runs necessary to complete the calibration process can be estimated as:

Total Runs ≅ (# of parameters) × (# of PEST iterations) × (average runs per iteration) × (# of base T fields).

The maximum number of iterations used in these runs was set to 15, although not all fields went to the maximum number of iterations. Additionally, on average for the first four iterations, PEST used forward derivatives to calculate the entries of the Jacobian matrix and each entry only required a single forward model evaluation. For the remaining 11 iterations, PEST used central derivatives to calculate the Jacobian entries and each calculation required 2 forward evaluations of the model (22 total). The average number of model evaluations is 1.733 = [(4 + 22)/15]. Therefore an estimate of the maximum possible total number of forward runs is equal to: 100 pilot points × 15 iterations/field × 1.73 runs/iteration × 150 T fields = 390,000 runs. The total time necessary to complete these calculations in serial mode on a single processor would be 813 days, or 2.22 years. PEST allows for parallel calculation of the Jacobian matrix, and this option was used to decrease the total run time significantly relative to the time needed for serial computation.

The model run times, as well as the time necessary to read and write input/output files across the cluster network, were examined to determine the optimal number of client, or slave, nodes for each server, or master, node. The optimal number of clients per server was determined to be eight. More clients per server degraded overall performance due to increased communication between machines and fewer clients per server resulted in underutilization of the system. By combining the client and server activities on a single machine using a virtual server setup, 4 different base T fields could be calibrated simultaneously on the 32 machines.

TFIELD-7.0 T-Field Acceptance Criteria

The calibration procedure described in Section TFIELD-6.0 was applied to 150 of the base T fields (the remaining 350 base fields were held in reserve, to be used only if necessary). Not all base T fields yielded a resulting calibrated T field. Four base T fields (d01r03, d01r09, d02r09, and d08r10) encountered numerical difficulties during the first iteration and did not calibrate at all. For each of the remaining 146 T fields, the calibration procedure stopped for 1 of 3 reasons:

1. PEST completed the maximum allowed number of iterations (15).
2. PEST was unable to improve the objective function (SSE of weighted residuals) for three successive iterations.
3. The optimization became numerically unstable.

Some of the T fields probably could have been calibrated better with more effort and adjustment of some of the PEST input parameters; however, these parameters were set to work across the largest number of fields possible and no calibration process will necessarily be able to make progress on every base field given the same set of parameters.

Because the T-field calibration procedure did not stop when some objective goodness-of-fit target was achieved, criteria had to be established to define what constitutes an acceptable calibration for use in the WIPP CRA calculations. Because the T fields were to be used for calculation of radionuclide transport, the travel times calculated in the T fields for a conservative particle released above the center of the WIPP waste panels (UTM X = 613,597.5 m and Y = 3,581,385.2 m [Ramsey, Wallace, and Jow 1996, p. 9]) to reach the WIPP LWB were used in developing acceptance criteria. That is, the sensitivity of the calculated travel-time distribution to potential acceptance criteria was used to identify those criteria that are important. Once the distribution of travel times showed no (remaining) sensitivity to continued refinement of the criteria applied (e.g., a reduction in some metric below a threshold value), all T fields meeting those criteria were considered to be acceptably calibrated.

The travel times discussed herein were obtained using the streamline particle-tracking algorithm implemented in DTRKMF v. 1.0 (Rudeen 2003) assuming a single-porosity medium with a porosity of 0.16. DTRKMF calculates particle tracks in two or three dimensions for steady-state and time-dependent, variably saturated flow fields. The particles are tracked cell-by-cell using a semi-analytical solution. DTRKMF assumes that the velocities vary linearly between the cell faces as a function of the space coordinate and, for time-dependent cases, that the velocities at the faces vary linearly between time planes. It directly reads the cell-by-cell flow budget file from MODFLOW-2000 and uses those values to calculate the velocity field. For each calibrated T field, a final forward run of MODFLOW-2000 was done and the cell-by-cell fluxes from this run were used as input to DTRKMF to calculate the travel time. For each calibrated T field, only a single particle was tracked, providing a single travel time. The MODFLOW-2000 modeling was performed using a 7.75-m (25.4-ft) thickness for the Culebra, whereas transport calculations assume that all flow is concentrated in the lower 4.0 m (13 ft) of Culebra (Meigs and McCord, 1996). Therefore, the travel times obtained from DTRKMF were scaled by multiplying by the factor 0.516 (4/7.75). These scaled travel times were then consistent with the travel times calculated and reported by Wallace (1996) for the T fields used in the WIPP CCA. These travel times do not, however, represent the actual predicted travel times of solutes, conservative or

nonconservative, through the Culebra. Culebra transport modeling treats the Culebra as a double-porosity medium with transport through advective porosity (e.g., fractures) retarded by diffusion into diffusive porosity (e.g., matrix porosity) and by sorption. The travel times presented herein are intended only to allow comparison among T fields.

TFIELD-7.1 Candidate Acceptance Criteria

Four factors were evaluated for their potential to provide T-field acceptance criteria: RMSE of the modeled fit to the measured steady-state heads, the agreement between the measured and modeled steady-state gradient/heads, the sum of squared weighted residuals (phi) for the transient data, and the agreement between the measured and modeled transient heads. These factors are not totally independent of one another, but are related in ways discussed below.

TFIELD-7.1.1 RMSE Values

The RMSE is a measure of how close MODFLOW-2000/PEST came to matching the measured steady-state heads for each T field. The RMSE is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n_{obs}} (H_i^{obs} - H_i^{calc})^2}{n_{obs}}} \qquad \text{(TFIELD.10)}$$

where n_{obs} is the number of head observations and H^{obs} and H^{calc} are the values of the observed and calculated heads, respectively. Previous Culebra T-field calibration exercises (e.g., LaVenue and RamaRao 1992) achieved RMSEs less than 3 m (9.5 ft) in most cases when calibration was being performed only to steady-state heads. This level of calibration was also achieved by McKenna and Hart (2003a) for four different sets of steady-state head measurements. RMSEs have not previously been reported for steady-state heads in Culebra T fields calibrated to transient heads.

TFIELD-7.1.2 Fit to Steady-State Heads

One measure of how well a T field has matched the steady-state heads can be obtained by simply plotting the measured heads versus the modeled heads. If the measured and modeled heads match exactly, the best-fit straight line through the data will have a slope of one. Exact agreement between measured and modeled heads is not to be expected, so an acceptance criterion on the slope of the best-fit line must be established.

The steady-state heads are important because the transport calculations performed in SECOTP2D rely on the steady-state velocity field provided by MODFLOW-2000. If MODFLOW-2000 has not accurately captured the steady-state heads, steady-state gradients and the associated steady-state velocities will be in error. With measured head plotted as the independent variable (x) and calculated head plotted as the dependent variable (y), a slope of the best-fit line less than unity implies that the calculated gradient is less than the measured gradient. Low gradients should lead to excessively long travel times. Therefore, it was important to

determine if a threshold value of the steady-state-fit slope exists above which the distribution of travel times is insensitive.

TFIELD-7.1.3 Phi Values

As shown in Equation (TFIELD.9), phi values have three components:

- A weighted sum of squared residuals for the steady-state heads
- A weighted sum of squared residuals for the transient drawdowns
- A weighted sum of squared differences between transmissivity values for each pair of pilot points

The steady-state component of phi is a weighted, squared, and summed expression of the RMSE given in Equation (TFIELD.10), above, and is not, therefore, meaningful to consider when RMSE is already being considered. The pilot-point-regularization component of phi relates to the smoothness of the T field, not to the goodness of fit of the measured and modeled responses. Hence, only the transient component of phi is considered in the discussion that follows.

For reasons discussed in Section TFIELD-6.7, transient phi values do not provide a completely unbiased measure of how well a calibrated T field represents the actual T field. "Measurements" of zero drawdown were given arbitrarily high weights in the calibration process, the number of measurements used from individual wells during individual tests and the number of measurements used from all wells during a single test varied, and some parts of the modeling domain are covered by multiple wells' responses, while other parts of the domain have no transient response data. Therefore, no simple numerical value can be established that represents an average residual of some meaningful value for each transient measurement, such as the RMSE used to evaluate T-field calibration to steady-state heads alone. Nevertheless, the transient phi values do provide an indication of how well a T field met the calibration targets as defined and could be used qualitatively to define acceptable T fields.

TFIELD-7.1.4 Fit to Transient Heads

Evaluating the model match to transient heads is not as straightforward as for the steady-state heads because the transient match involves both the magnitude and the timing of head changes. The magnitude and timing of a transient response are governed by both the transmissivity and storativity (S) of a system, but S was not included as a calibration parameter during the calibration process. A single S value of 1×10^{-5} ($\log_{10} = -5$) was used during T-field calibration. As reported by Beauheim and Fox (2003), the apparent storativities obtained from independent analyses of the test responses used for the calibration range from 5.1×10^{-6} ($\log_{10} = -5.29$) to 7.3×10^{-5} ($\log_{10} = -4.14$). Because the calibration method only allowed PEST to adjust transmissivity to try to match the measured heads, it might actually shift transmissivity away from the correct value in trying to compensate for an inappropriate value of S. Thus, some allowance needed to be made for how close PEST could actually come to matching the measured responses.

To establish the bounds of what might be considered acceptable matches to the transient heads, a series of well-test simulations using the code nSIGHTS (Roberts 2002) was performed. For base-case parameter values, a transmissivity of 1×10^{-5} m^2/s and an S of 1×10^{-5} were used. Pumping in a well was simulated for 5, 25, and/or 50 days, and the responses that would be observed in observations wells 1, 2, and/or 3 km away were calculated. Transmissivity and/or S were also varied by approximately a half order of magnitude upward and downward (3×10^{-5} and 3×10^{-6}). The results of these simulations are shown in Appendix A of Beauheim (2003).

Based on the simulations, a set of guidelines was developed to determine if a modeled response matched a measured response within a half order of magnitude uncertainty in transmissivity and/or S. The guidelines were structured around the position of the modeled maximum drawdown relative to the measured maximum drawdown on a linear-linear plot of elapsed time on the x-axis and drawdown (increasing upward) on the y-axis. The guidelines are as follows:

- If the modeled peak occurs early and high (relative to the measured peak), S is too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs early and low, transmissivity is too high and the maximum modeled drawdown can be up to two times lower than the maximum measured drawdown.

- If the modeled peak occurs late and high, transmissivity is too low and the maximum modeled drawdown can be up to two times higher than the maximum measured drawdown.

- If the modeled peak occurs late and low, S is too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is high, the diffusivity (transmissivity/S) is correct, but both values are too low and the maximum modeled drawdown can be up to three times greater than the maximum measured drawdown.

- If the modeled peak occurs at the same time as the measured peak but is low, the diffusivity (transmissivity/S) is correct, but both values are too high and the maximum modeled drawdown can be up to three times lower than the maximum measured drawdown.

No quantitative criteria were established for how much earlier or later modeled peaks could occur relative to measured peaks because of the wide range observed in the simple scoping calculations (calculated peaks occurring a factor of 5 sooner to a factor of 10 later than the observed peaks) and because of the variability in pumping durations and distances to observation wells associated with the measured responses.

Using these guidelines, plots of each of the 40 transient well responses of each calibrated T field were evaluated visually to determine if the T field represented that response within a half order of magnitude uncertainty in transmissivity and/or S. A threshold number of well responses that failed this test was then considered as a possible acceptance criterion for the T fields.

TFIELD-7.2 Application of Criteria to T Fields

The four criteria described above were applied to the calibrated Culebra T fields to determine if they allowed meaningful discrimination among the fields. Given that travel time is the performance measure of most concern, the four criteria were evaluated in terms of their effects on the calculated distribution of travel times from the T fields.

TFIELD-7.2.1 RMSE Values

Steady-state RMSE values for the 146 completed T fields are plotted in Figure TFIELD-44. The data for H-9b, the southernmost well, were excluded from the RMSE calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head, disproportionately affecting the calculation of the RMSE. The exclusion of the H-9b data should provide a better measure of the accuracy of the model in the rest of the model domain.

All nine RMSE values greater than 20 m (66 ft) correspond to T fields that were not considered to have been successfully calibrated by McKenna and Hart (2003b). Figure TFIELD-45 shows the RMSE values plotted against travel time, and shows that the high RMSE values tend to be associated with long travel times. For RMSE values less than approximately 6 m (20 ft), travel times tend to cluster below approximately 50,000 years. Applying an RMSE cutoff value of 6 m (20 ft) would leave 117 T fields, with all but one having travel times less than 102,000 years (Figure TFIELD-46; the outlier with a travel time of ~241,000 years, d01r06, is not shown).

TFIELD-7.2.2 Fit to Steady-State Heads

Figure TFIELD-47 provides an example plot of measured steady-state heads versus modeled steady-state heads for one T field, with a unit-slope line shown as a reference. For each plot of steady-state heads, the slope of the best-fit line through all of the data except for the data for H-9b was calculated using the Excel® SLOPE function. The data for H-9b, the southernmost well, were excluded from this calculation because the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head. Inasmuch as the gradient in the extreme southern portion of the modeling domain is unimportant with respect to transport across the southern half of the WIPP site, the exclusion of the H-9b data should improve the accuracy of the slope calculation in the area of interest.

The slopes of the best-fit lines through the measured vs. modeled steady-state heads are shown plotted against travel time in Figure TFIELD-48. Steady-state-fit slopes less than 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. Of the 116 T fields with steady-state-fit slopes greater than 0.5, all but 9 have travel times less than 50,000 years. Figure TFIELD-49 shows the slopes and travel times for these 116 fields (the outlier with a travel time of ~241,000 years, d01r06, is not shown), and indicates that travel time is not sensitive to steady-state-fit slopes above 0.5.

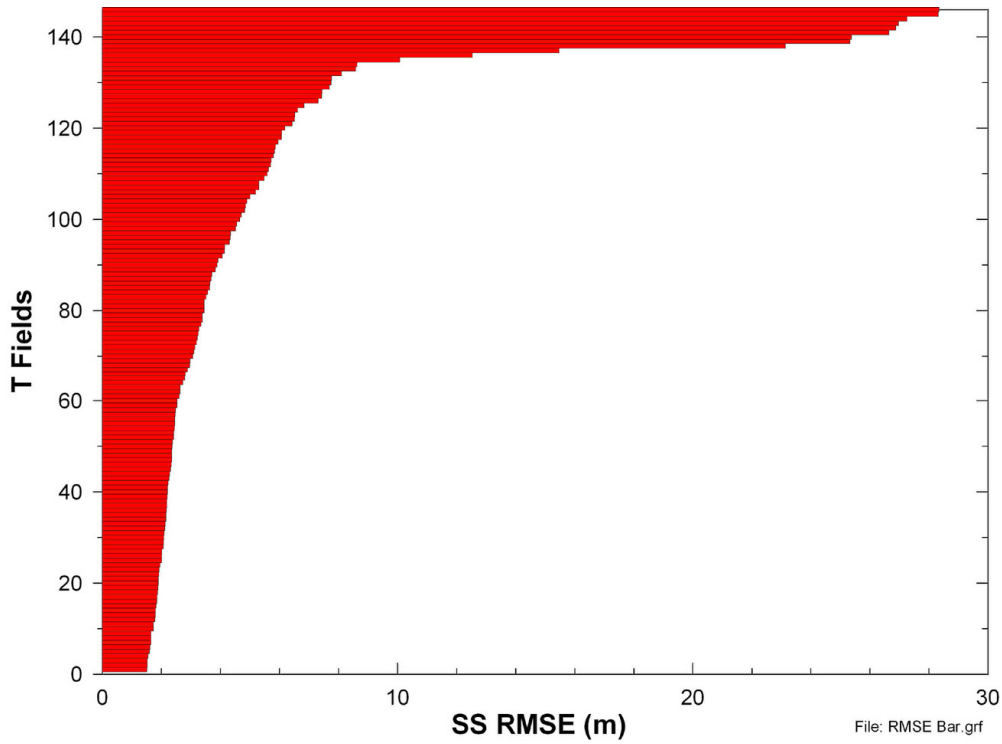


Figure TFIELD-44. Steady-State RMSE Values for 146 T Fields

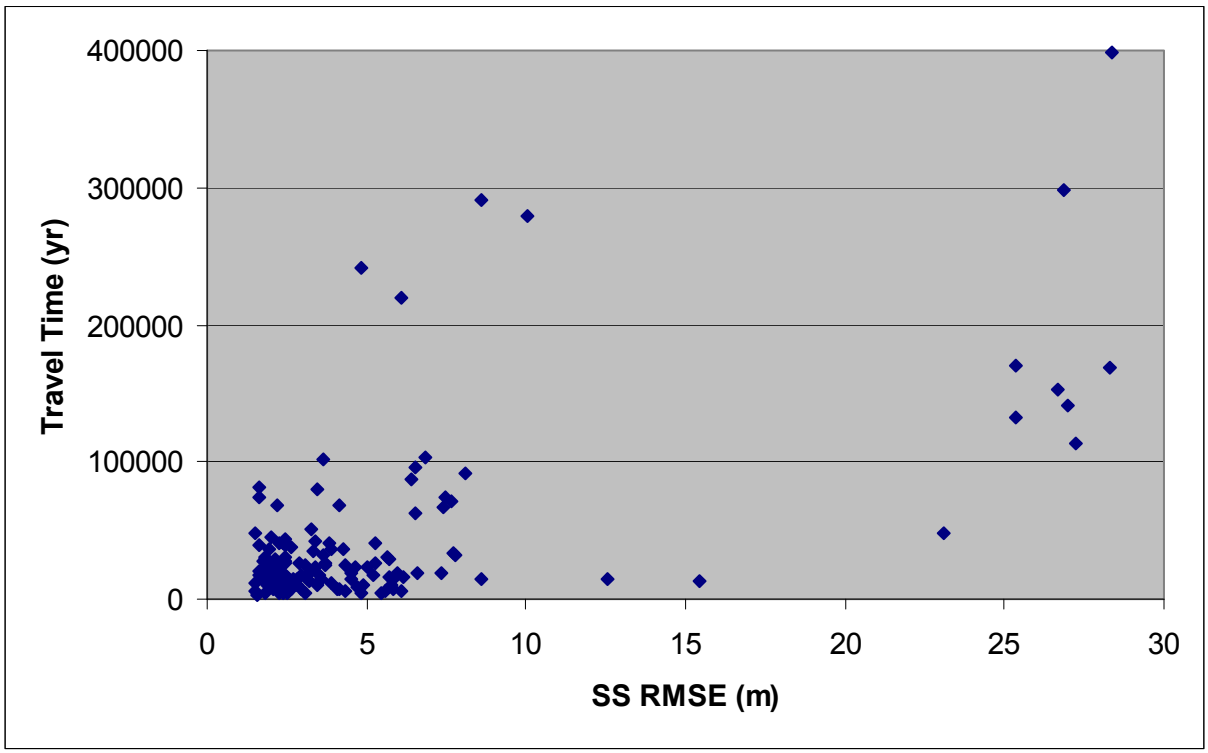


Figure TFIELD-45. Steady-State RMSE Values and Associated Travel Times

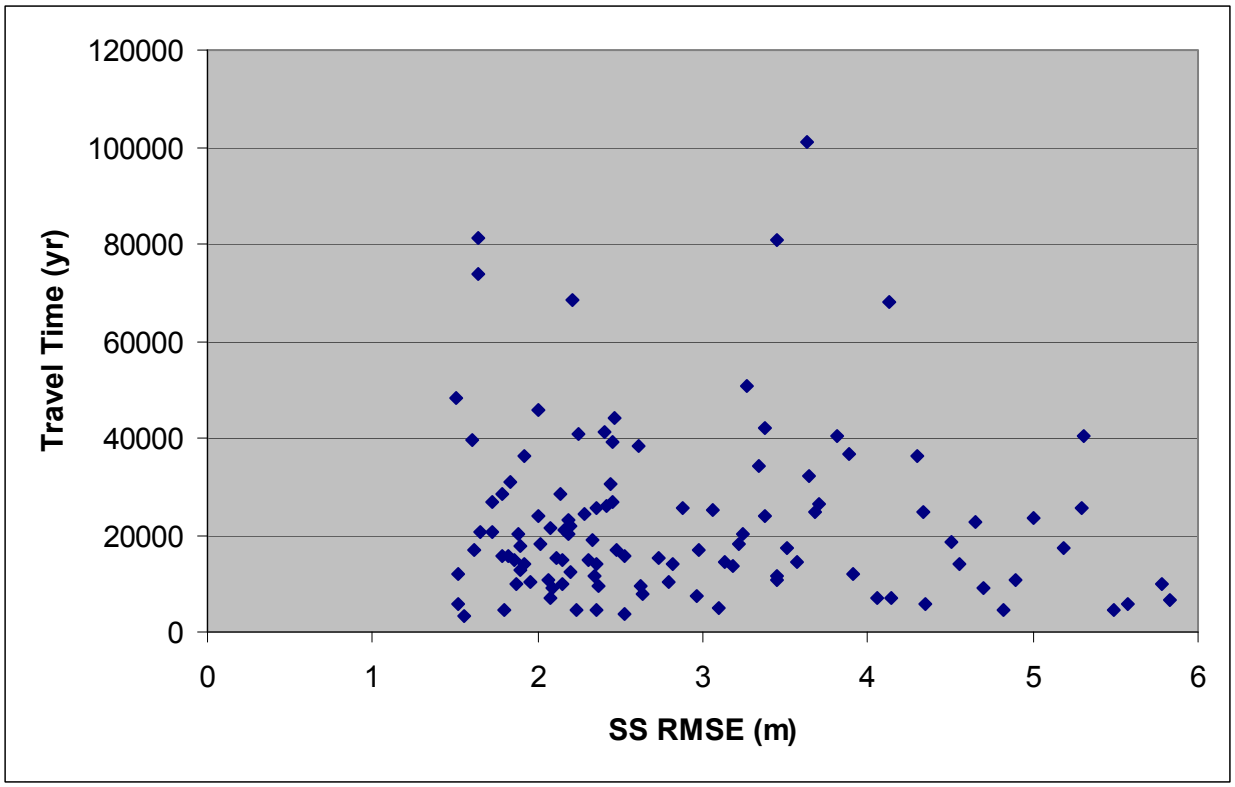


Figure TFIELD-46. Travel Times for Fields with Steady-State RMSE <6 m (20 ft)

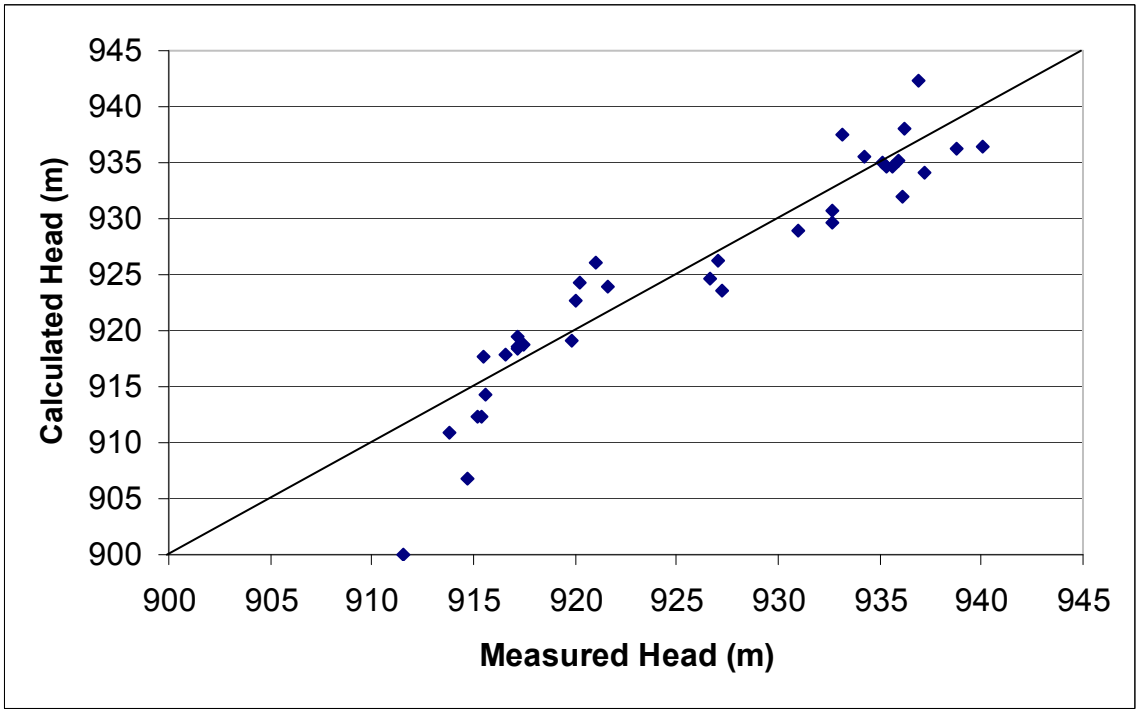


Figure TFIELD-47. Measured Versus Modeled Steady-State Heads for T Field d21r10

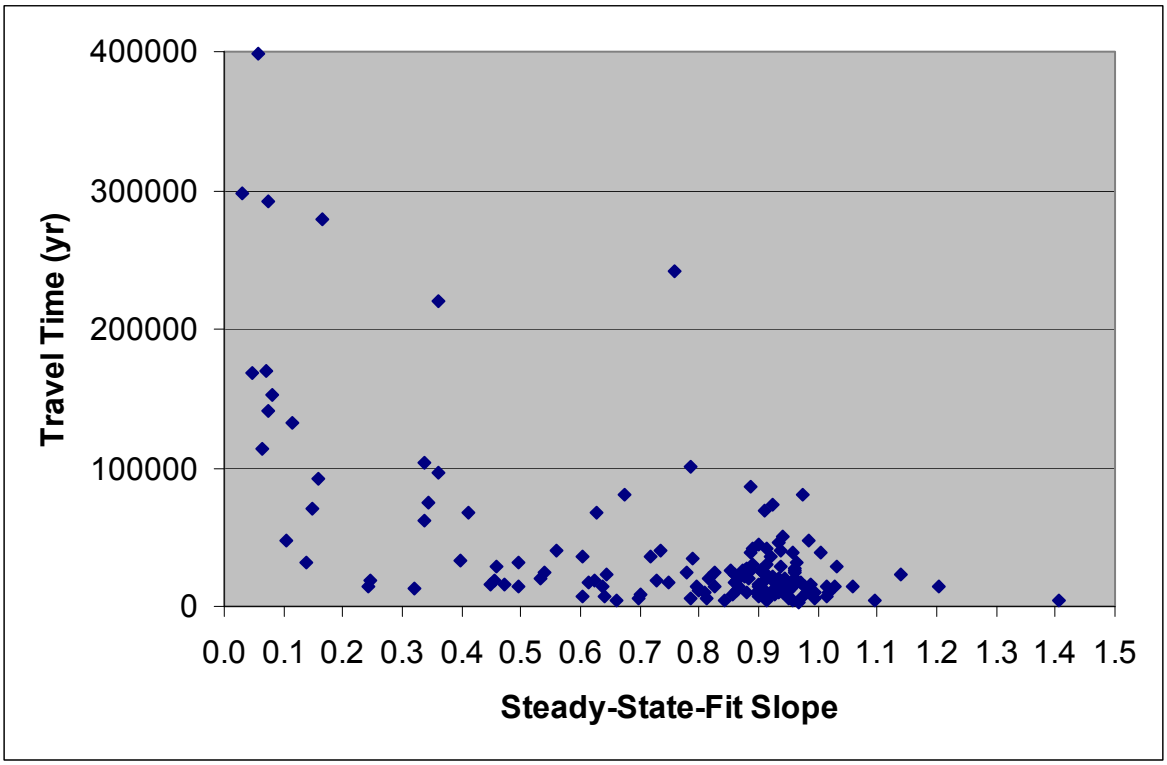


Figure TFIELD-48. Steady-State-Fit Slope Versus Travel Time for All Fields

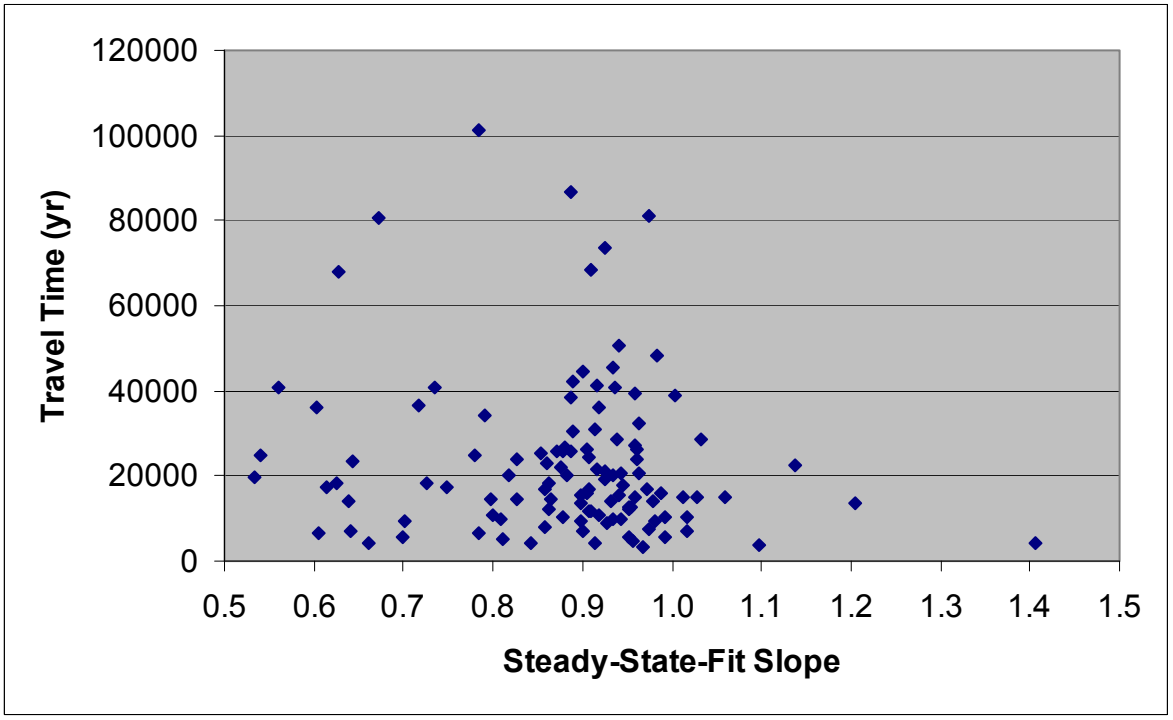


Figure TFIELD-49. Steady-State-Fit Slope Versus Travel Time for Slopes >0.5

TFIELD-7.2.3 Phi Values

Transient phi values for all the completed T fields are plotted against travel time in Figure TFIELD-50. As phi values decrease, particularly as they get below approximately 5,000 m^2 (53,800 square feet [ft^2]), travel times tend to cluster below approximately 50,000 years, but little correlation is seen between transient phi and travel time. Figure TFIELD-51 shows transient phi versus travel time for the 123 fields with transient phi values less than 8,000 m^2 (86,000 ft^2), excluding the 5 outliers that have travel times greater than 168,000 years. This plot suggests that despite the clustering of travel times below 50,000 years, the overall range of travel times does not decrease significantly as phi decreases. Thus, transient phi does not appear to provide an effective tool for distinguishing among T fields.

TFIELD-7.2.4 Fit to Transient Heads

In applying the tests described in Section TFIELD-7.1.4 to the well responses simulated for each T field, it was found that insufficient data (only six measurements) had been included for the WQSP-1 response to pumping at WQSP-2 to allow any determination of model adequacy. Thus, this response was eliminated from consideration for all T fields. Figure TFIELD-52 and Figure TFIELD-53 provide examples from T field d21r10 of well responses that were judged to pass and fail, respectively, the criteria outlined in Section TFIELD-7.1.4. The number of responses that failed for each T field is given in Table TFIELD-11. For the WQSP-3 responses to pumping at WQSP-1 and WQSP-2 (for which no clear drawdown was observed and "measured" values of zero were entered), the modeled response was accepted if it showed no more than 0.25 m (0.82 ft) of drawdown.

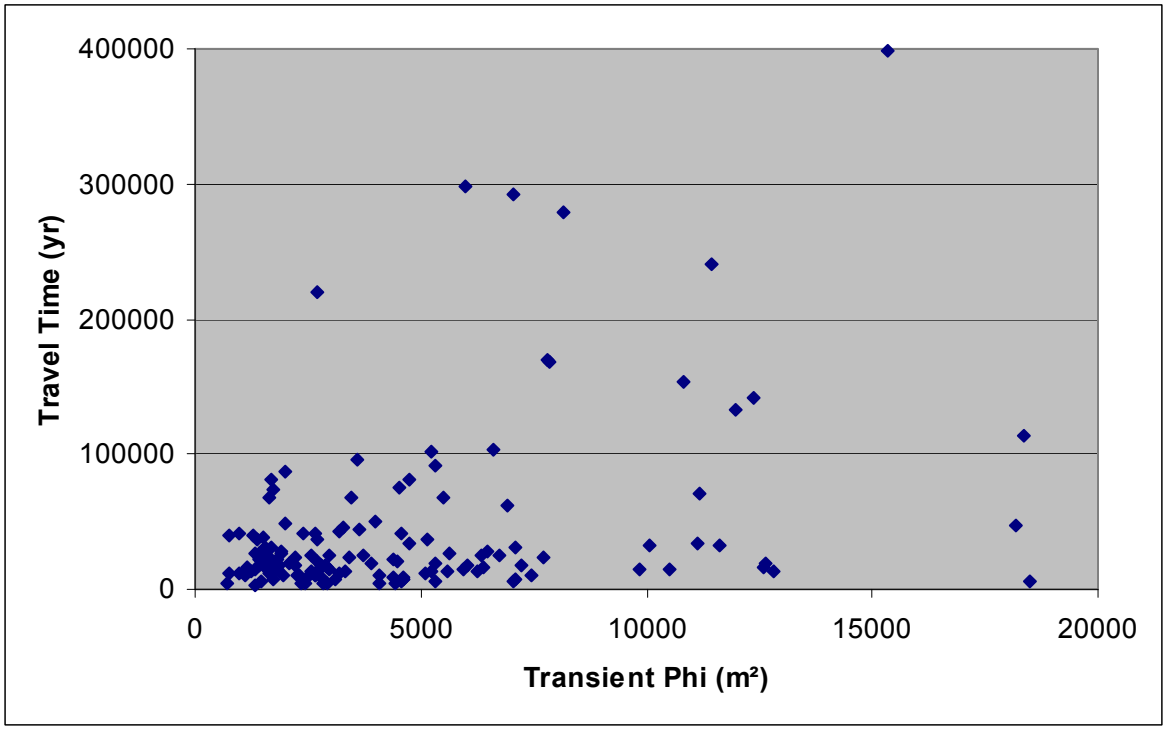


Figure TFIELD-50. Transient Phi Versus Travel Time for All Fields

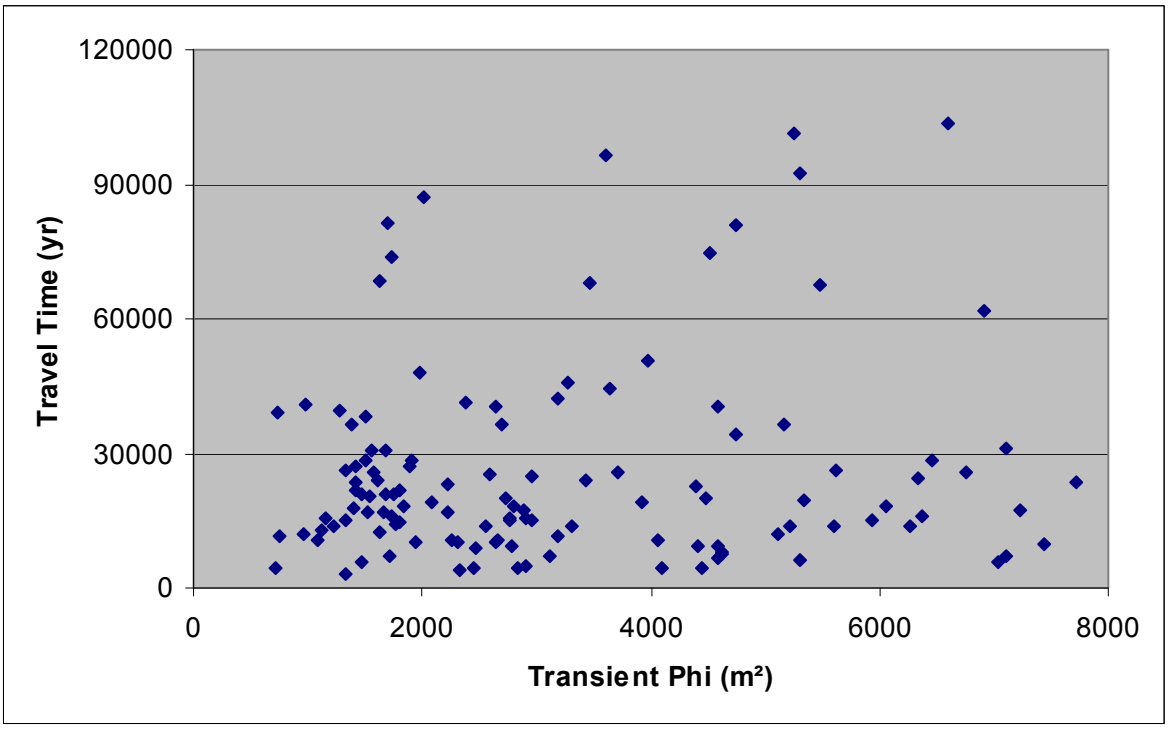


Figure TFIELD-51. Transient Phi Versus Travel Time for Phi <8,000 m^2

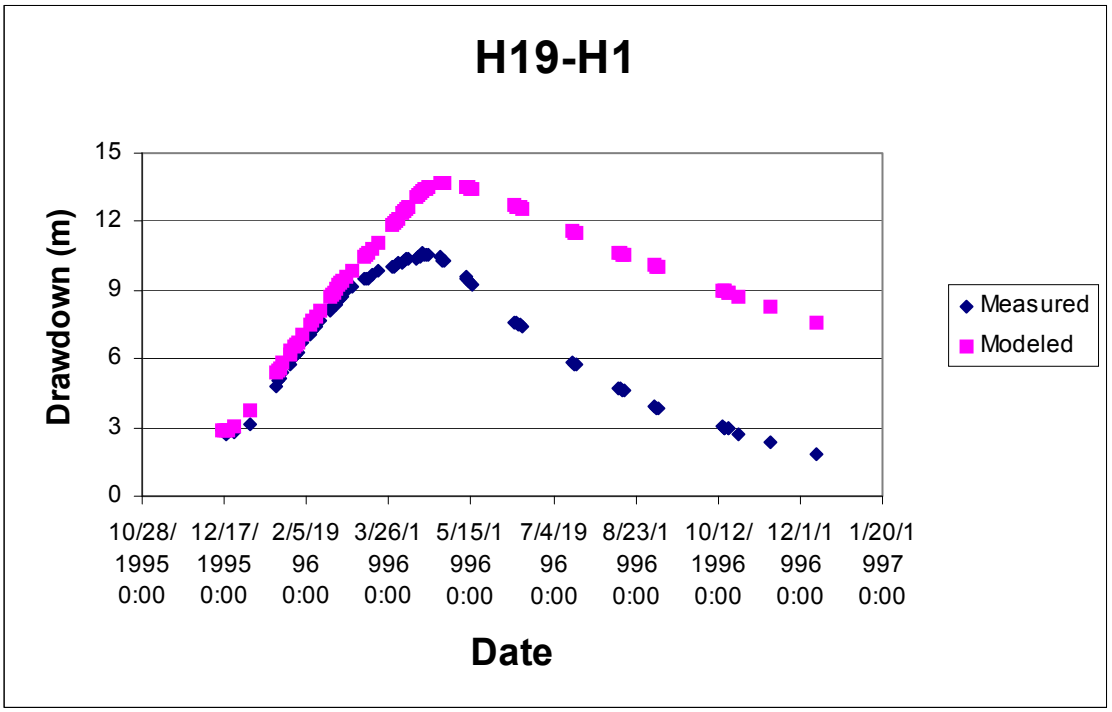


Figure TFIELD-52. Example of Passing Well Response from T Field d21r10

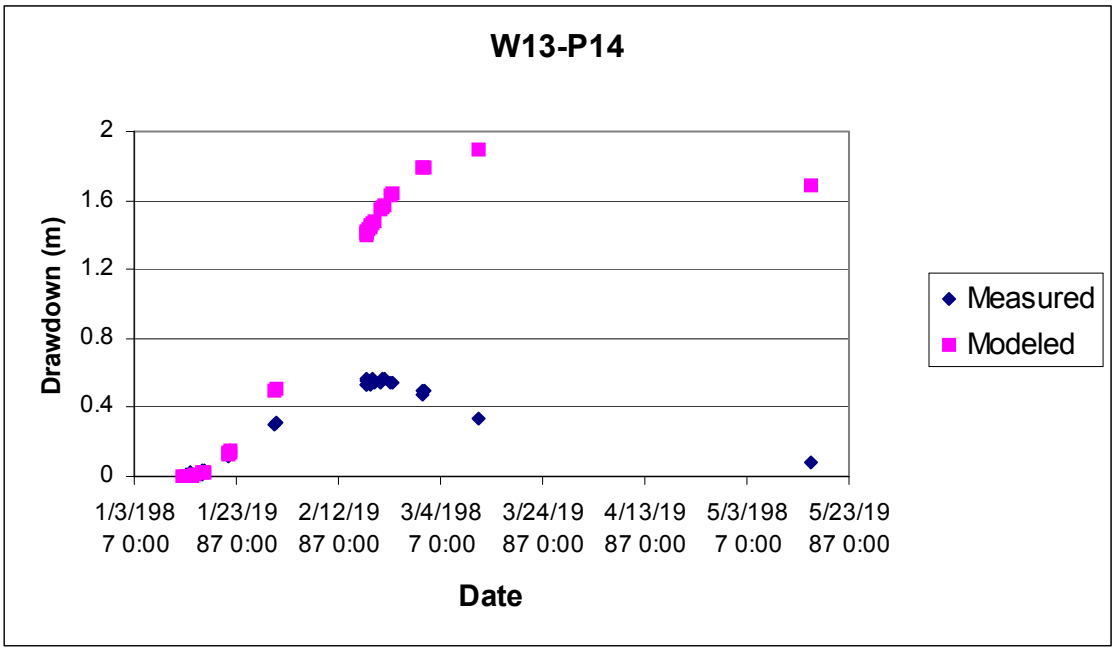


Figure TFIELD-53. Example of Failing Well Response from T Field d21r10

Table TFIELD-11. Summary Information on T Fields

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d01r01	7.427	10498	5486	0.411	13	67578
d01r02	3.915	3621	5110	0.862	20	12045
d01r04	2.812	2140	2563	1.204	11	13821
d01r05	7.313	10245	12643	0.245	16	18886
d01r06	4.856	5006	11426	0.759	15	241211
d01r07	3.377	2851	3187	0.889	9	42123
d01r08	5.484	6122	4091	1.407	14	4399
d01r10	1.646	1094	1476	0.943	9	20685
d02r01	26.966	128711	12359	0.075	19	141516
d02r02	3.507	2772	2889	0.748	11	17217
d02r03	10.070	18606	8173	0.165	15	279242
d02r04	8.104	12482	5305	0.158	12	92235
d02r05	5.184	5577	7224	0.614	17	17255
d02r06	25.325	113652	7810	0.071	16	169677
d02r07	3.648	3223	10047	0.963	15	32231
d02r08	5.001	5125	7713	0.643	17	23571
d02r10	6.066	6849	5312	0.785	13	6433
d03r01	4.506	4022	6053	0.625	17	18435

d01r01 signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section TFIELD-7.3.

Table TFIELD-11. Summary Information on T Fields (Continued)

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d03r02	28.346	142152	15357	0.056	16	398937
d03r03	4.146	3899	7102	1.016	17	7171
d03r04	25.367	114006	11991	0.114	14	132833
d03r05	5.836	6873	4585	0.605	13	6638
d03r06	1.729	1208	1899	0.959	13	27006
d03r07	4.655	4740	4399	1.138	13	22599
d03r08	4.550	4250	5593	0.638	17	13942
d03r09	2.352	1574	1580	0.877	7	25757
d03r10	8.584	13811	2766	1.060	13	15054
d04r01	3.447	2370	4736	0.673	17	80690
d04r02	3.818	3175	2647	0.736	12	40593
d04r03	2.352	1659	3317	0.979	12	13888
d04r04	4.298	3692	2697	0.602	13	36245
d04r05	1.507	1059	1980	0.984	9	48168
d04r06	3.705	3146	5618	0.961	16	26199
d04r07	2.183	1397	2226	0.860	10	23105
d04r08	2.444	1759	1560	0.890	11	30470
d04r09	27.256	131491	18356	0.064	16	114087
d04r10	3.060	2401	2593	0.853	9	25316
d05r01	6.427	8119	2015	0.886	13	86924
d05r02	5.298	5831	6755	0.872	16	25610
d05r03	3.444	2580	2655	0.799	11	10880
d05r04	5.862	6984	10518	0.497	17	14856
d05r05	4.346	4226	18478	0.952	16	5668
d05r06	6.518	8198	3609	0.360	13	96589
d05r07	3.188	2682	5216	0.899	9	13766
d05r08	7.686	11242	11194	0.147	16	70896
d05r09	26.644	125685	10840	0.081	17	152818
d05r10	5.623	6497	7110	0.497	16	30955
d06r01	6.828	9057	6592	0.338	17	103442
d06r02	1.957	1266	2639	0.993	9	10353
d06r03	1.637	1051	1703	0.974	10	81258
d06r04	3.214	2246	2805	0.727	13	18294
d06r05	3.886	3516	5164	0.718	18	36644
d06r06	2.149	1254	2954	1.013	10	14935

Reverse type signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section TFIELD-7.3.

Table TFIELD-11. Summary Information on T Fields (Continued)

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d06r07	1.518	784	965	0.951	7	12035
d06r08	7.440	10397	4518	0.343	18	74565
d06r09	28.309	141764	7864	0.046	18	168281
d06r10	2.196	1455	1801	0.876	11	21990
d07r01	3.101	2326	2905	0.811	14	5082
d07r02	2.010	1327	3271	0.934	15	45647
d07r03	15.470	42986	12795	0.320	19	12919
d07r04	5.579	6230	7033	0.699	18	5638
d07r05	2.727	1705	5942	0.958	10	15097
d07r06	4.334	3927	6345	0.540	12	24641
d07r07	2.477	1737	2225	0.908	9	17038
d07r08	2.232	1097	2836	0.843	9	4355
d07r09	2.207	1239	1628	0.909	8	68629
d07r10	1.782	839	1150	0.940	9	15680
d08r01	2.361	1736	2458	0.913	11	4388
d08r02	2.418	1168	1326	0.904	6	26115
d08r03	2.137	1489	1499	0.938	9	28570
d08r04	3.683	2674	2966	0.779	9	24773
d08r05	2.115	1384	2769	0.899	13	15358
d08r06	1.916	1388	1225	0.931	11	13917
d08r07	1.857	815	1333	1.029	10	15027
d08r08	12.534	28547	6267	0.244	12	13885
d08r09	5.785	6674	7437	0.809	17	9691
d09r01	8.621	13909	7050	0.074	11	291623
d09r02	3.243	2418	4482	0.817	12	20048
d09r03	2.252	1337	989	0.937	8	40948
d09r04	1.892	710	1123	0.952	8	12857
d09r05	2.061	954	1088	0.919	8	10726
d09r06	2.794	2313	2253	0.879	16	10509
d09r07	2.629	1676	4591	0.981	10	9472
d09r08	1.895	1030	1406	0.946	9	17741
d09r09	4.826	4945	4453	0.660	14	4359
d09r10	3.273	2790	3976	0.941	19	50791
d10r01	26.867	127794	6006	0.031	14	297840
d10r02	1.554	589	1330	0.967	8	3111
d10r03	2.201	1474	1626	0.955	9	12533

Reverse type signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section TFIELD-7.3.

Table TFIELD-11. Summary Information on T Fields (Continued)

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d10r04	2.527	1788	2334	1.097	9	3799
d10r05	5.722	6646	6463	0.460	18	28390
d10r06	4.702	4644	4412	0.702	13	9210
d10r07	1.870	810	1937	0.935	10	10068
d10r08	2.334	1613	2083	0.925	8	19093
d10r09	4.128	3643	3466	0.628	11	68052
d10r10	1.789	982	1915	1.033	13	28367
d11r01	2.970	2297	1655	0.859	9	17015
d11r02	2.308	1799	1801	0.865	12	14677
d11r03	5.700	6093	6376	0.473	9	16014
d11r04	6.514	8401	6922	0.336	23	61862
d11r05	5.952	7166	3921	0.455	17	18998
d11r06	2.607	1949	1503	0.886	9	38399
d11r07	1.639	602	1727	0.925	9	73634
d11r08	1.801	1206	723	0.957	6	4520
d11r09	2.073	858	1712	0.901	7	7199
d11r10	3.135	2363	1767	0.827	5	14358
d12r01	3.378	2921	3432	0.827	14	23936
d12r02	2.459	1795	1426	0.880	10	26919
d12r03	1.618	558	1530	0.971	11	16780
d12r04	6.182	7395	12605	0.449	20	15619
d12r05	1.522	918	1463	0.993	6	5655
d12r06	1.602	539	1271	0.958	13	39399
d12r07	2.016	945	1844	0.862	9	18283
d12r08	2.630	1879	4627	0.857	16	7981
d12r09	2.369	1671	2784	0.898	11	9414
d12r10	7.762	11431	11606	0.138	18	32059
d13r01	2.163	1061	1753	0.924	11	21032
d13r02	2.881	2054	3715	0.888	14	25639
d13r03	3.444	2580	3192	0.909	11	11493
d13r04	5.302	5856	4588	0.561	13	40601
d13r05	3.343	2671	4750	0.790	12	34247
d13r06	2.410	1441	2377	0.915	10	41400
d13r07	2.280	1395	1606	0.908	10	24211
d13r08	1.879	779	1544	0.882	9	20313
d13r09	1.919	776	1379	0.919	14	36260

Reverse type signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section TFIELD-7.3.

Table TFIELD-11. Summary Information on T Fields (Continued)

T Field	SS RMSE (m)	SS Phi (m^2)	Transient Phi (m^2)	Steady-State-Fit Slope	# of Failed Well Responses	Time to WIPP boundary (yr)
d13r10	6.063	6685	2693	0.360	14	220354
d21r01	2.151	1555	2307	0.942	13	10042
d21r02	2.087	1431	2473	0.928	9	9023
d21r03	2.346	1299	744	0.907	6	11671
d21r04	2.523	1978	2908	0.905	13	15717
d21r05	2.001	932	1417	0.960	10	23750
d21r06	1.721	655	1688	0.962	8	20715
d21r07	2.182	1179	2725	0.934	9	20141
d21r08	6.620	8618	5337	0.534	14	19534
d21r09	7.750	11501	11124	0.397	19	33308
d21r10	2.959	2226	4615	0.974	13	7384
d22r01	23.126	94895	18190	0.103	15	47563
d22r02	3.629	3197	5250	0.785	10	101205
d22r03	4.061	3464	3119	0.642	11	7067
d22r04	4.894	5073	4068	1.017	12	10537
d22r05	3.566	3160	9863	0.797	18	14385
d22r06	2.469	1145	3635	0.900	9	44309
d22r07	2.080	999	1413	0.916	9	21589
d22r08	1.837	809	1681	0.914	10	30771
d22r09	1.822	724	1734	0.988	19	15870
d22r10	2.452	1684	735	1.004	5	39116

Reverse type signifies T fields not meeting final acceptance criteria.
Bold italics type signifies 100 final T fields as discussed in Section TFIELD-7.3.

The number of well responses that fail the tests described in Section TFIELD-7.1.3 should be related to the transient phi for each T field because both are measures of the match between the measured and modeled transient heads. Figure TFIELD-54 shows a plot of transient phi versus the number of failed well responses for all 146 T fields. A definite correlation is evident up to a phi of approximately 8,000 m^2 (86,000 ft^2). Beyond that value, the number of failed well responses simply remains high (≥14).

The number of failed well responses is plotted against travel time in Figure TFIELD-55 for each of the T fields. The scatter in travel time appears to increase with 14 or more failures, but the majority of T fields still have travel times in the same range as the fields with less than 14 failures. Thus, the number of failed well responses alone does not appear to discriminate well among T fields.

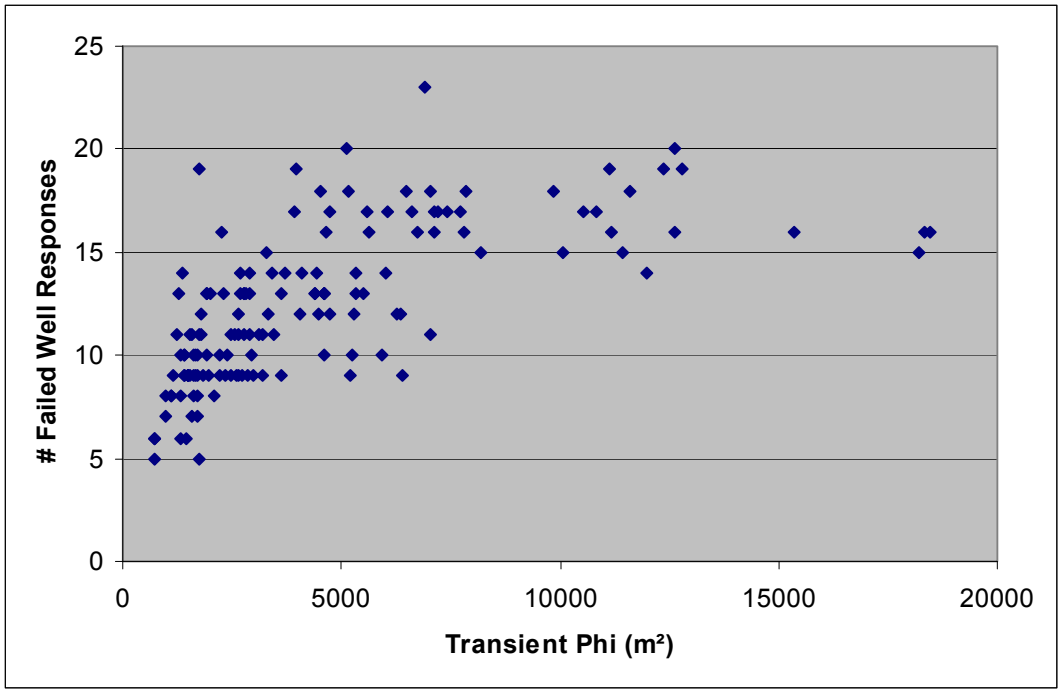


Figure TFIELD-54. Transient Phi Versus Number of Failed Well Responses

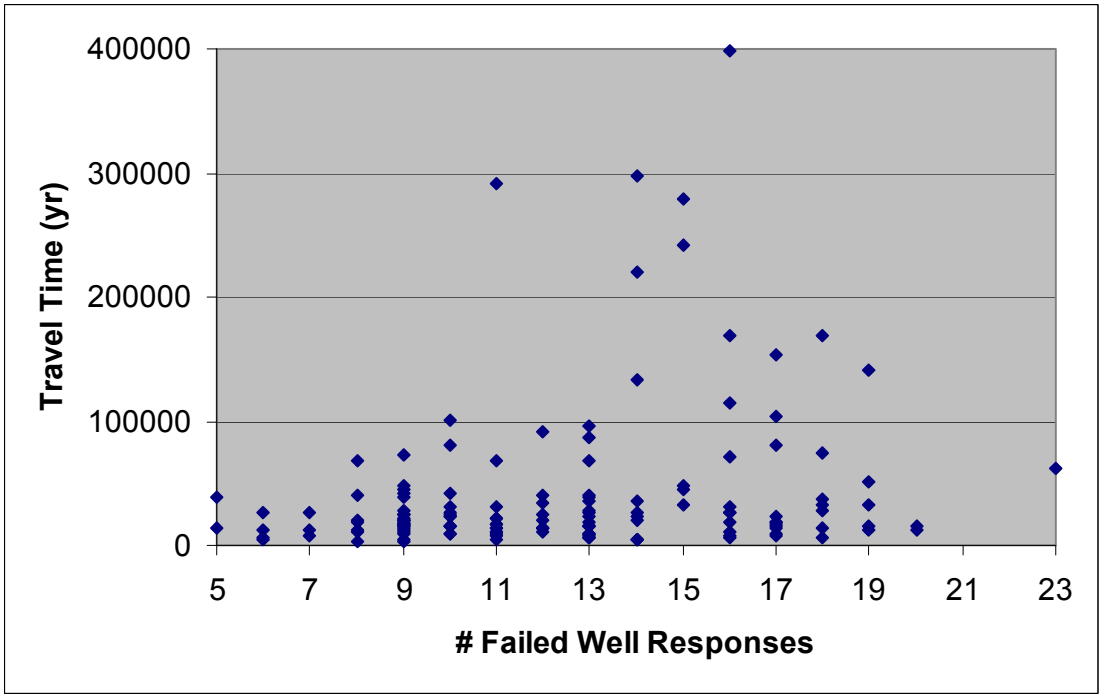


Figure TFIELD-55. Number of Failed Well Responses Versus Travel Time

TFIELD-7.3 Final Acceptance Criteria

Of the criteria discussed above, the two related to the steady-state heads (RMSE and steady-state-fit slope) appear to be more effective at identifying poorly calibrated T fields than the two related to transient heads (transient phi and number of failed well responses). The range and scatter of travel times appears to increase at RMSE values beyond 6 m (20 ft). Applying an RMSE cutoff of 6 m (20 ft) leaves 117 T fields, all with travel times less than 102,000 years except one (d01r06). This cutoff also excludes all T fields with steady-state-fit slopes less than 0.45. Steady-state-fit slopes less than approximately 0.5 appear to lead to significantly longer travel times, consistent with the low hydraulic gradients the low slopes imply. If a simple cutoff of a minimum steady-state-fit slope of 0.5 is applied, 116 T fields are left, again with travel times less than 102,000 years (except d01r06), and also with RMSE values less than 8.6 m (28.2 ft).

Five T fields that meet the RMSE less than 6 m (20 ft) criterion fail the steady-state-fit slope greater than 0.5 criterion, while 4 T fields meeting the slope criterion fail the RMSE criterion. Thus, 112 T fields meet both criteria while 121 T fields meet at least one of the criteria.

Figure TFIELD-56 shows a CDF for the 121 T fields meeting the RMSE and/or steady-state-fit slope criteria discussed above. Also shown are curves representing the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 (86,111 ft^2), and the 100 T fields with the largest steady-state-fit slopes (>0.72). All three CDFs are very similar, the most significant difference being that imposing a cutoff value on transient phi eliminates the T field with the longest travel time (d01r06). To illustrate the effects of imposing more stringent constraints on T-field acceptance, a fourth CDF is shown in Figure TFIELD-56 that represents the 23 T fields that have RMSE values less than 2 m (7 ft) and transient phi values less than 2,000 m^2

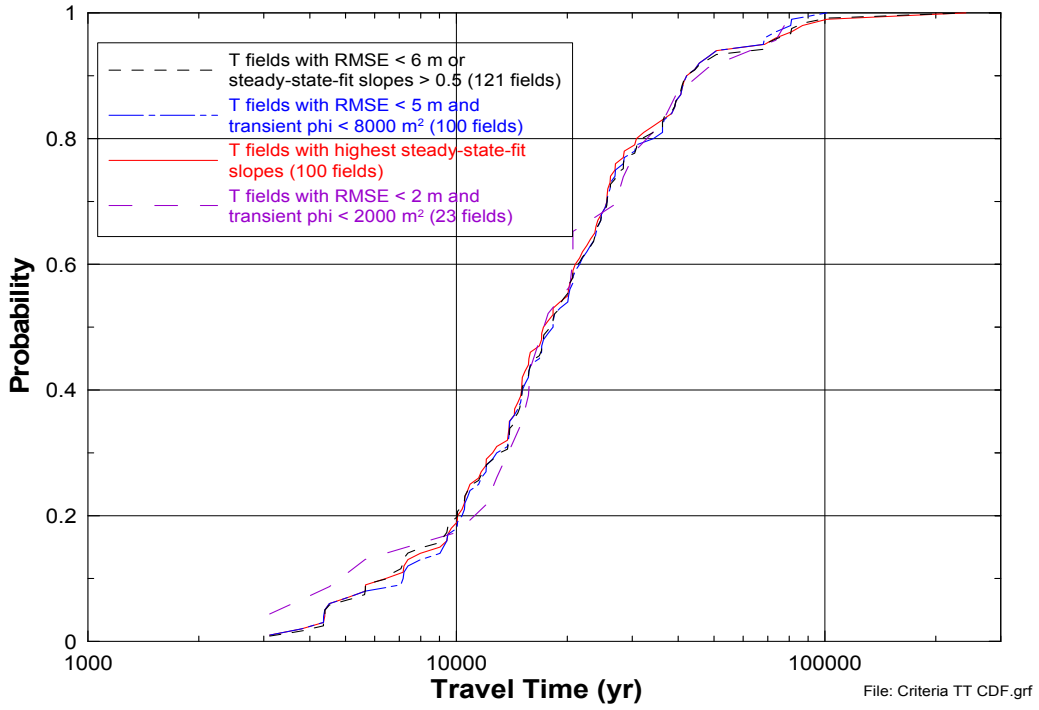


Figure TFIELD-56. Travel-Time CDFs for Different Sets of T Fields

(21,527 ft^2). These 23 T fields all have steady-state-fit slopes greater than 0.88. This CDF generally shows travel times similar to those of the other CDFs, except at the tails of the distribution which are poorly defined because of the relatively small sample size. Thus, because all the CDFs shown are similar, all 121 T fields meeting the steady-state-fit slope or RMSE criteria were considered to be acceptably calibrated. The T fields that have been rejected are shown in reverse type in Table TFIELD-11.

Because only 100 T fields were needed, the criteria were refined to eliminate more T fields. Given that lower travel times provide a conservative (in terms of leading to increased solute transport) way to discriminate among sets of T fields, the 100 T fields with RMSE values <5 m (16 ft) and transient phi values <8,000 m^2 were selected for use in CRA-2004 calculations of radionuclide transport through the Culebra because that set excluded the calibrated T field with the longest travel time. These T fields are highlighted in bold italicized type in Table TFIELD-11.

For comparison purposes, the CDF of travel times for these 100 T fields is plotted in Figure TFIELD-57 with the CDF of travel times for the 100 transient-calibrated T fields used in the CCA (Wallace 1996). Generally speaking, travel times are two to three times as long in the CRA-2004 fields as in the CCA fields. Considering the degree of uncertainty involved in characterizing a geologic medium on the scale of the T fields, a factor of two or three difference in travel-time CDFs represents excellent agreement.

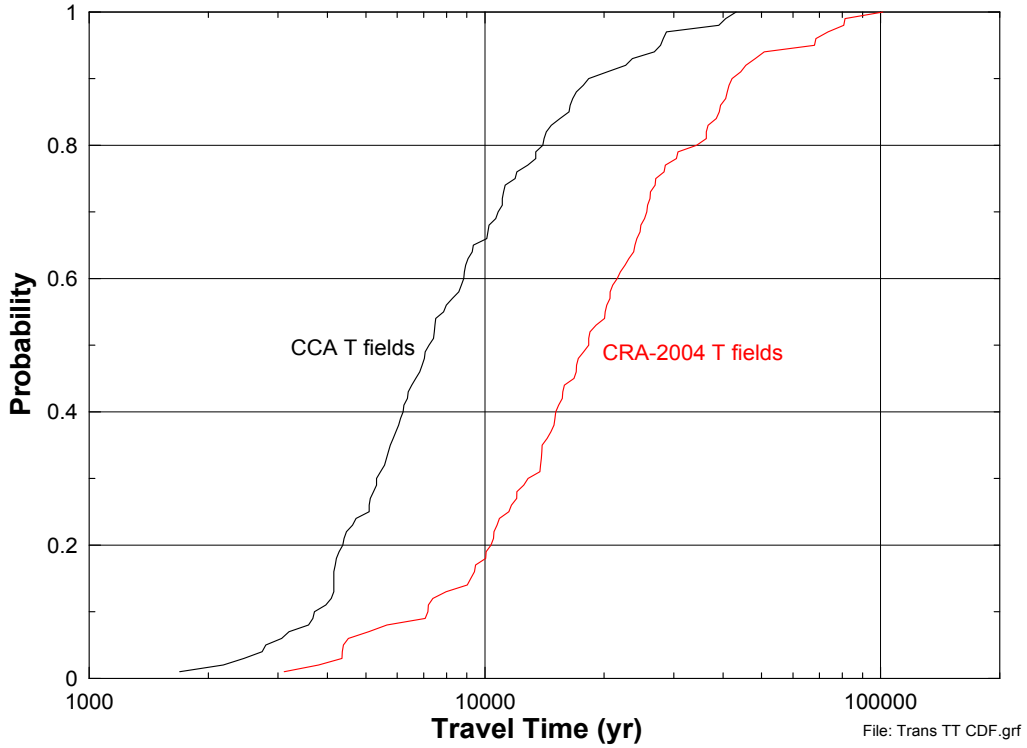


Figure TFIELD-57. Travel-Time CDFs for CCA and CRA-2004 T Fields

TFIELD-8.0 Inverse Modeling Results

Some fit statistics (phi, RMSE, etc.) for the 121 T fields that were judged to be acceptably calibrated were presented in Section TFIELD-7.0. Visualizations of the T fields are included in Attachment A. Additional properties or characteristics of the T fields are given below.

TFIELD-8.1 Particle Tracking

Particle tracking was performed in the 121 calibrated T fields from a point above the center of the WIPP disposal panels to both the LWB and the boundary of the model domain, as discussed in Section TFIELD-7.0. The locations of all the particle tracks are show in Figure TFIELD-58 and Figure TFIELD-59. In both figures, the particle tracks are shown using only every 20th point along the track because of a limitation in the graphing software. This filtering leads to the particle tracks appearing less smooth than they actually are. Figure TFIELD-58 shows a close-up view of the particle tracks within the WIPP LWB. All of the particles exit the southern edge of the LWB and the majority of the particles exit the LWB to the southeast of the release point, although not as far to the east as the particle tracks for the CCA T fields showed (Ramsey et al. 1996, p. 49). Figure TFIELD-59 shows the particle tracks within the entire model domain. The majority of the particles exit the domain nearly due south of the release point. The particles that migrate to the west tend to travel along the boundary of the high-T zone. This result is due to the large amount of groundwater flux within the high-T zone creating a streamline at the high-T zone boundary.

TFIELD-8.2 Fit to Steady-State Heads

Some information about how well the calibrated T fields matched the observed steady-state heads is given in Section TFIELD-7.2.1 and Section TFIELD-7.2.2. Additional information is shown in Figure TFIELD-60 and Figure TFIELD-61. Figure TFIELD-60 shows a scatterplot of the modeled steady-state heads in the 121 calibrated T fields versus the measured heads. Also shown is a unit-slope line representing perfect agreement between the measured and modeled heads, and parallel lines showing a 5-m (16-ft) range on either side. Most modeled head values fall within the ±5 m (16 ft) lines except for the modeled heads for H-9b, the well with the lowest measured head. As discussed in Section TFIELD-7.2.1, H-9b is the southernmost well in the model domain, and the southern model boundary condition consistently caused the modeled H-9b head to be significantly lower than the measured head.

Figure TFIELD-61 shows a histogram of the differences between the modeled and measured heads. The majority of modeled head values more than 8 m (26 ft) lower than the measured values are associated with H-9b. Excluding the H-9b values, the histogram shows a normal distribution of errors with 48% of the modeled heads within 2 m (7 ft) of the measured heads, and 79% of the modeled heads within 4 m (13 ft) of the measured heads. The fit between measured and modeled steady-state heads could probably have been improved by allowing PEST to perform more calibration iterations but, as shown in Section TFIELD-7.3, the travel-time distribution for the T fields would be unlikely to be affected.

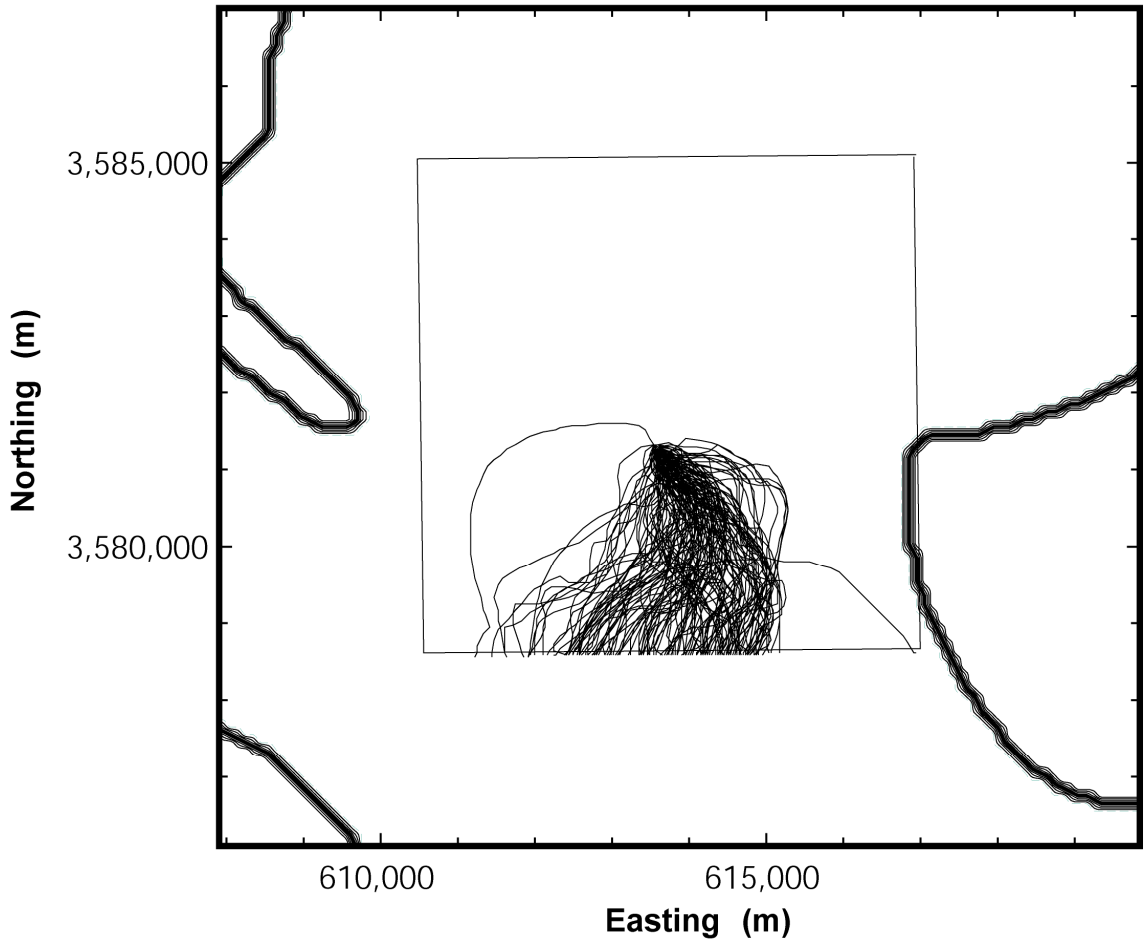


Figure TFIELD-58. All Particle Tracks Within the WIPP LWB. The Bold Lines Show the Boundaries of the High-T (Left Side) and Low-T (Right Side) Zones.

TFIELD-8.3 Pilot-Point Sensitivity

Transmissivities at each of the pilot points within the model domain were altered during the calibration process. The maximum allowable change was ± three orders of magnitude in the middle region of the model domain and ± one order of magnitude in the low-T (eastern) and high-T (western) regions of the model domain. Figure TFIELD-62 and Figure TFIELD-63 show the percentage of calibrated T fields in which each pilot point hit the maximum and minimum possible value, respectively. The size of the bubble is proportional to the number of times the value hits one constraint or the other. Figure TFIELD-62 shows that the pilot points south of the western portion of the southern LWB were most likely to reach their maximum allowable values, indicating that the base T fields may have underestimated transmissivities in this area. Figure TFIELD-63 shows that the pilot point placed in the inferred dissolution reentrant between P-14 and WIPP-25 west of the LWB (see Figure TFIELD-38) was most likely to reach its minimum allowable value, indicating that this reentrant may not be as hydraulically significant as originally assumed.

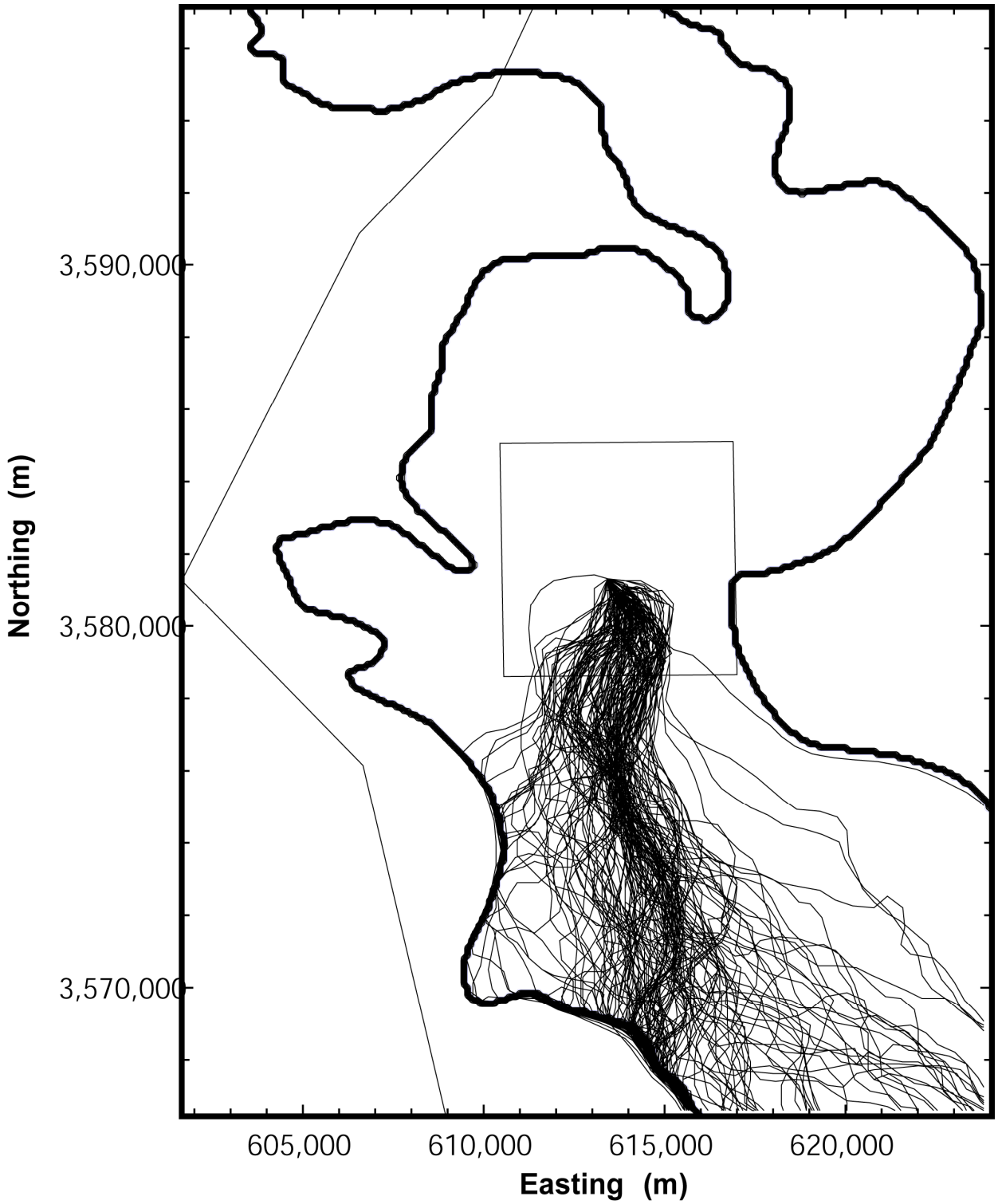


Figure TFIELD-59. All Particle Tracks Within the Model Domain. The Bold Lines Show the Boundaries of the High-T (Left) and Low-T (Right) Zone Boundaries. The No-Flow and WIPP Site Boundaries are Also Shown.

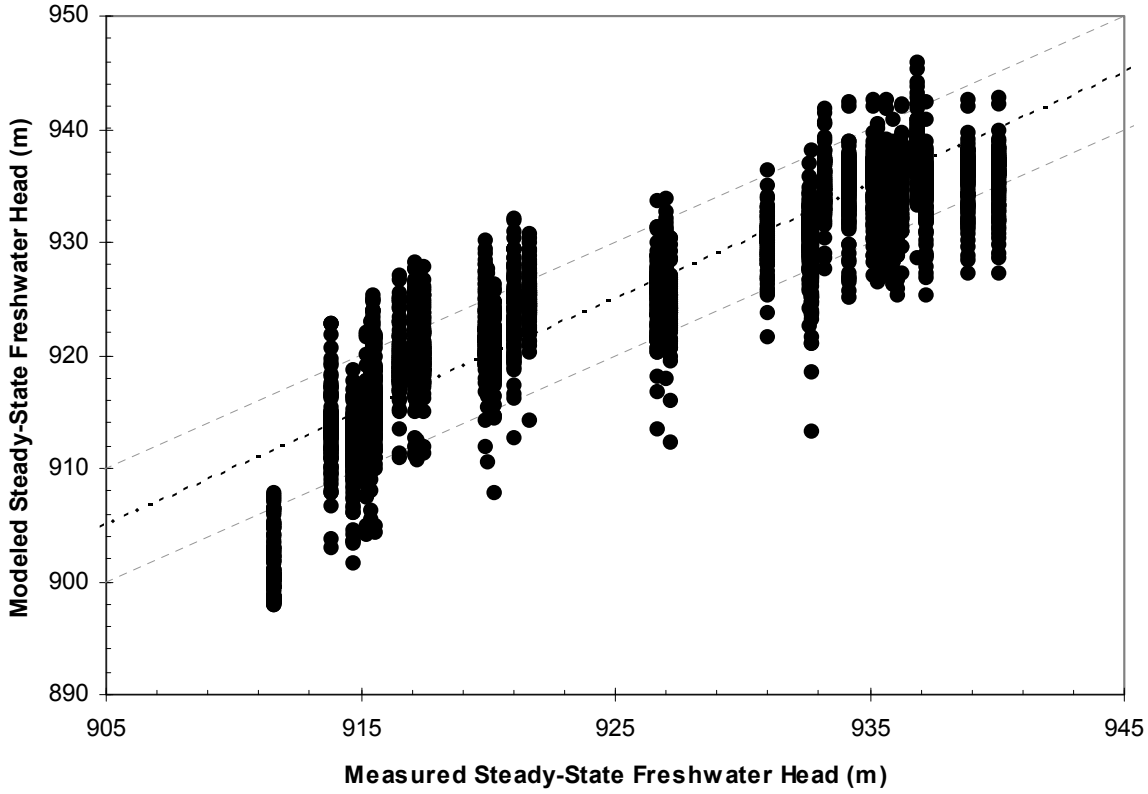


Figure TFIELD-60. Scatterplot of Measured Versus Modeled Steady-State Heads

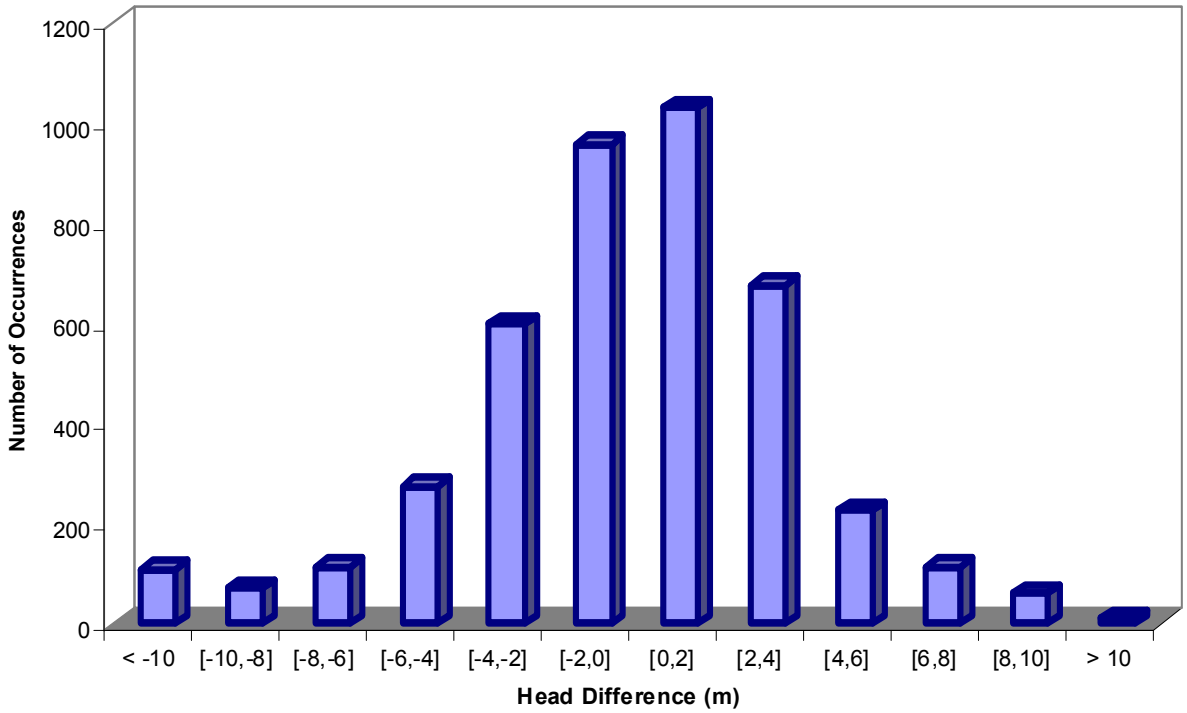


Figure TFIELD-61. Histogram of Differences Between Measured and Modeled Steady-State Heads

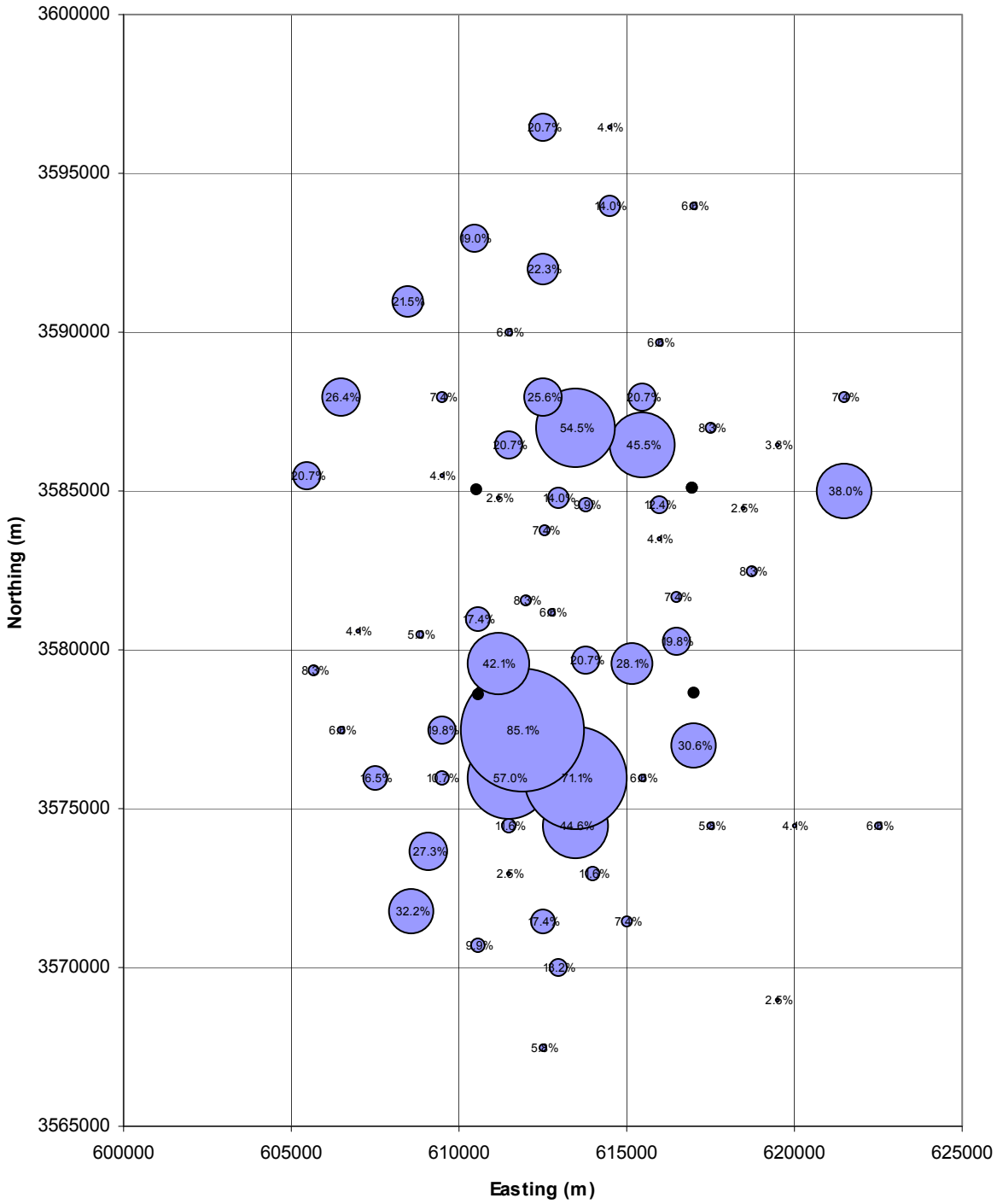


Figure TFIELD-62. Percentage of T Fields in which Pilot Points Hit Maximum Allowable Values. Corners of WIPP LWB are Shown by Unlabeled Black Dots.

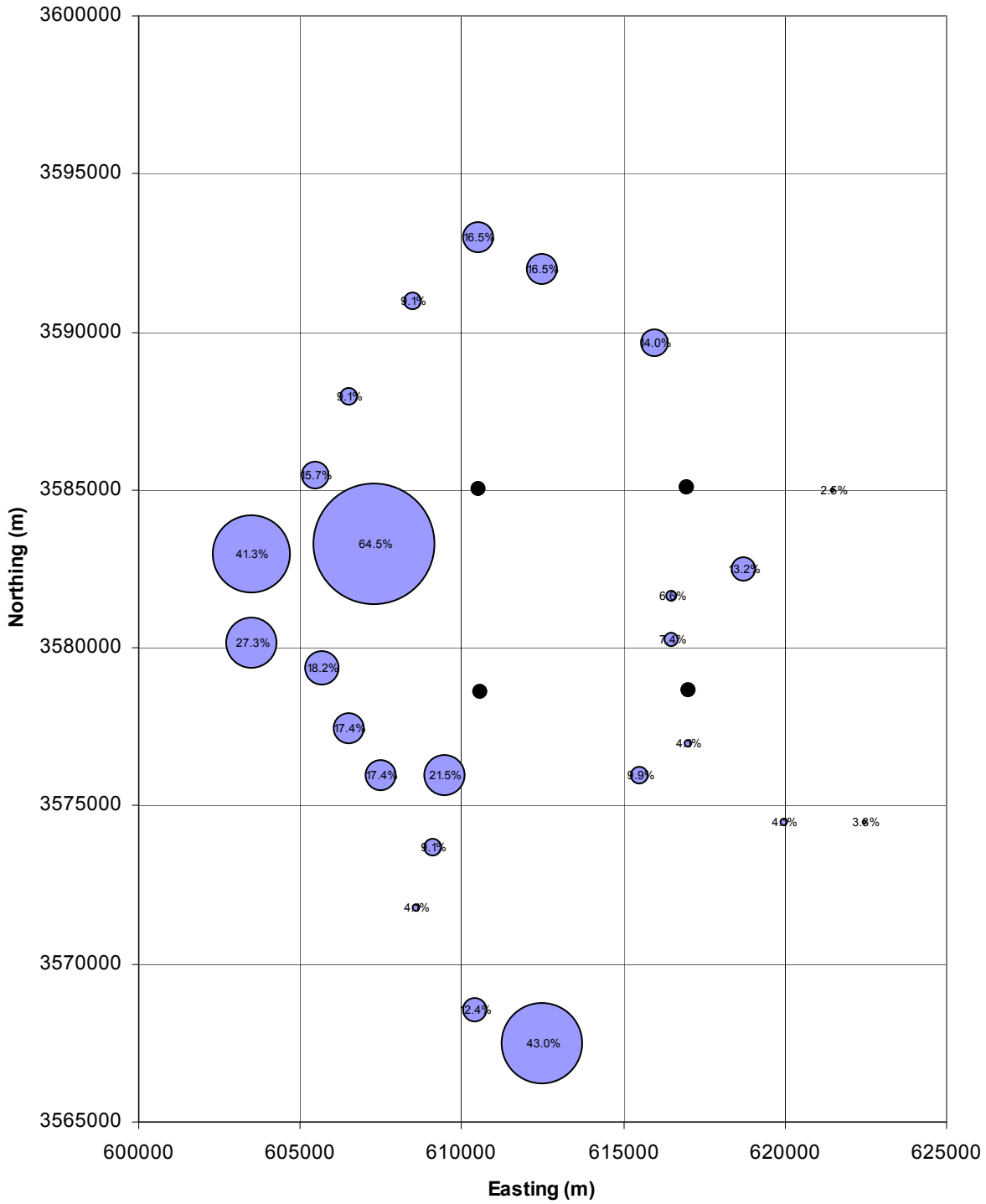


Figure TFIELD-63. Percentage of T Fields in which Pilot Points Hit Minimum Allowable Values. Corners of WIPP LWB are Shown by Unlabeled Black Dots.

TFIELD-8.4 Ensemble Average T Field

The 121 T fields that were acceptably calibrated can be combined into an ensemble average T field showing the average properties of the T fields (Figure TFIELD-64). The averaging is performed on a cell-by-cell basis, taking the arithmetic mean of the 121 transmissivity values assigned to each cell. Figure TFIELD-65 shows a close-up view of the ensemble average of the 100 T fields used for subsequent calculations in the area surrounding the WIPP site, using a different color scale with transmissivity values "binned" by order of magnitude for clarity. This figure does not show a continuous north-south high-T zone exiting the southeastern portion of the WIPP site, as was present in the ensemble average T field provided in the CCA, Appendix TFIELD, Figure 30. It also shows higher transmissivities in the southwestern portion of the WIPP site than were present in the CCA ensemble average field. These differences explain why the travel paths in the CRA-2004 T fields (Figure TFIELD-58) take a more westerly course, on average, than those in the CCA T fields, and why the CRA-2004 travel times are longer than the CCA travel times (Figure TFIELD-57).

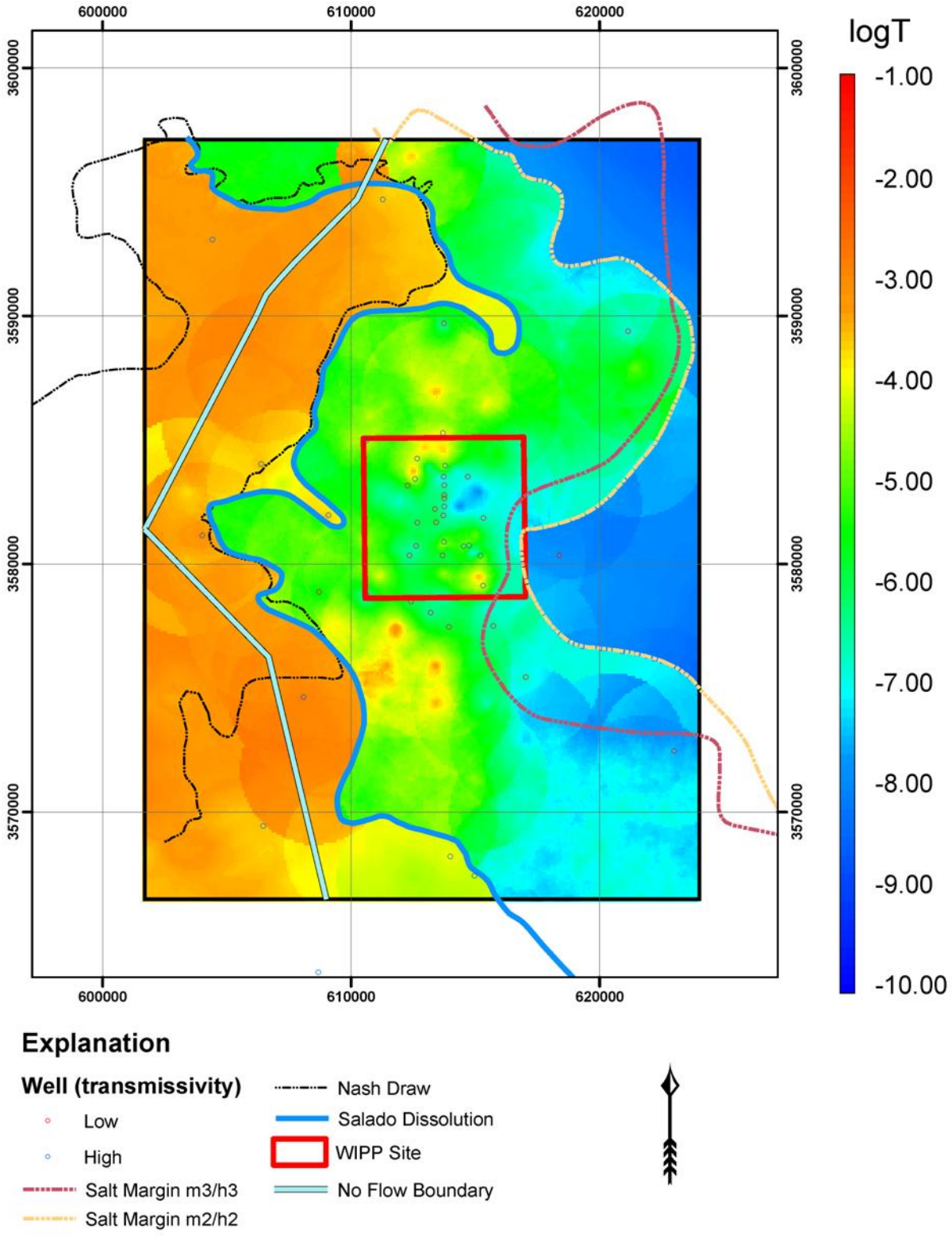


Figure TFIELD-64. Ensemble Average of 121 Calibrated T Fields

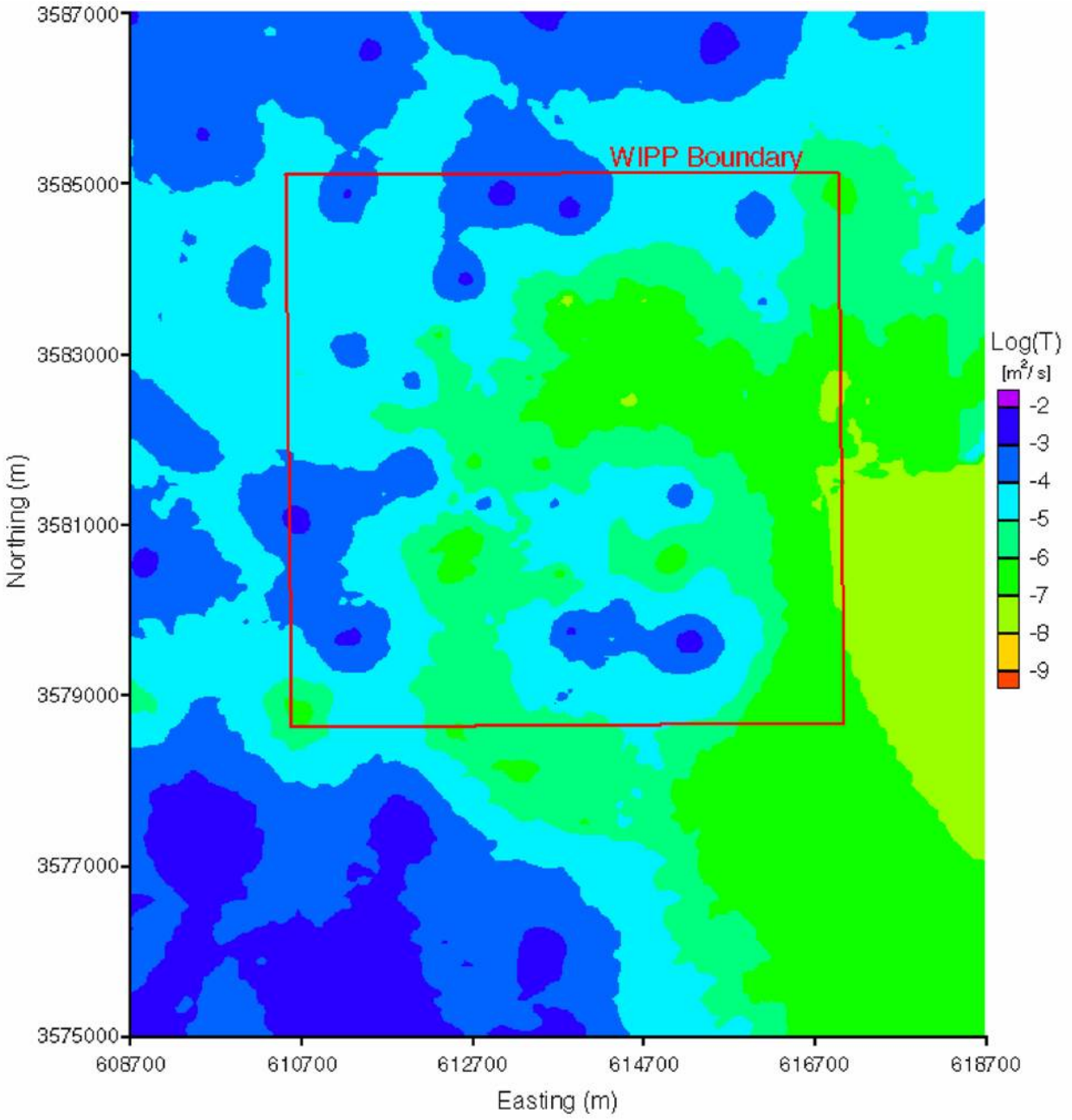


Figure TFIELD-65. Close-Up View of the Ensemble Average T Field Near the WIPP Site. Note the Different $\log_{10}$ Color Scale from Figure TFIELD-64.

TFIELD-9.0 Modification of T Fields For Mining Scenarios

The WIPP site lies within the Carlsbad mining district of southeastern New Mexico. Potash mining in the WIPP area involves resource extraction below the Culebra in the underlying McNutt potash zone of the Salado. In the future, potash mining is expected to occur in all areas where economically extractable ore is present, both outside and inside the WIPP LWB. It is hypothesized that mining of potash leads to subsidence and fracturing of the Culebra, resulting in increased Culebra transmissivity. This increase in transmissivity may change the regional groundwater flow pattern in the Culebra and affect the transport of any radionuclides entering the Culebra from the WIPP repository.

The U.S. Environmental Protection Agency (EPA) (1996, p. 5242) guidance for how the potential effects of future mining should be considered in WIPP PA follows:

> 40 CFR §194.32, Scope of performance assessments.
>
> (a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.
>
> (b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.
>
> (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can reasonably be expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

U.S. Environmental Protection Agency (1996) further states (p. 5229),

> In order to consider the effects of mining in performance assessments, DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters with each having a range of values varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.

Accordingly, for PA purposes, the DOE assumes that all economically extractable potash is mined outside of the WIPP LWB during the 100 years after closure of the WIPP repository during which active institutional control of the site is maintained. Following that 100-year period, the DOE assumes there is a one in 100 probability that the potash within the LWB will be mined during any given century. Therefore, all PA calculations of transport of radionuclides released to the Culebra through inadvertent human intrusion of the repository assume that all potash outside the LWB has already been mined (the "partial-mining" scenario) by the time the intrusion occurs. The "full-mining" scenario is invoked when the sampled time of human

intrusion is coincident with or later than the sampled time of mining within the LWB. Under both scenarios, the hydraulic conductivity (or transmissivity) of the Culebra is assumed to be increased by a random factor between one and 1,000 in the areas affected by mining. The process by which the calibrated Culebra T fields were modified to account for the effects of mining, and the characteristics of the resulting modified T fields, are discussed below.

TFIELD-9.1 Determination of Potential Mining Areas

Figure TFIELD-66 shows current potash mines and economically recoverable resources (reserves) in the known potash lease area around the WIPP site, which are the areas where subsidence might occur in the future. The map is based on the BLM map *Preliminary Map Showing Distribution of Potash Resources, Carlsbad Mining District, Eddy and Lea Counties, New Mexico* (1993). The current version of the map differs from the one used for the CCA calculations in that areas with unleased potash resources, as well as areas that were previously excluded because they were within a one-half mile radius of oil or gas wells, are now included in the area assumed to be mined. Figure TFIELD-67 shows the estimated extent of economically extractable potash within the WIPP LWB.

Because the potash mining horizon is located in the Salado, below the Culebra, the areas in the Culebra that might be disturbed by the mining activities are larger than shown on Figure TFIELD-66 and Figure TFIELD-67 due to angle-of-draw effects associated with subsidence. The rationale for determining the extent of these effects is described in Wallace (1996) with the final conclusion stating that an additional 253-m (830-ft)-wide "collar" was to be added to the mining-impacted areas to approximate a 45-degree angle of draw. For the current T fields, a buffer of three cell widths (300 m [984 ft]) was manually digitized and added to the mining zones. This new delineation was then compared to the CCA model mining zones to make sure there were no significant differences outside of those that can be explained by different gridding of the two model domains and the addition of new data (Figure TFIELD-68). The most notable differences between the two versions is that the area of potential future mining along the northeastern boundary of the LWB is now directly connected to Nash Draw to the west, allowing water to bypass the lower transmissivities on the WIPP site, and the area of potential mining extending down the eastern portion of the WIPP site is now directly connected to Nash Draw to the southwest.

TFIELD-9.2 Scaling of Transmissivity

For each of the final 100 T fields selected as described in Section TFIELD-7.3, a random transmissivity multiplier between 1 and 1,000 was assigned using Latin hypercube sampling (LHS) (Long 2004). That multiplier was then applied to the modeled transmissivity values in the mining-affected areas shown in Figure TFIELD-68 outside of the WIPP LWB to create a partial-mining T field, and to the modeled transmissivity values in mining-affected areas both inside and outside the LWB to create a full-mining T field. LHS was performed three times to provide three replicates of 100 full-mining and 100 partial-mining T fields. The purpose of using three replicates is to demonstrate that the LHS has adequately captured the uncertainty in the T fields. The transmissivity multipliers applied to each field for the three replicates are shown in Table TFIELD-12.

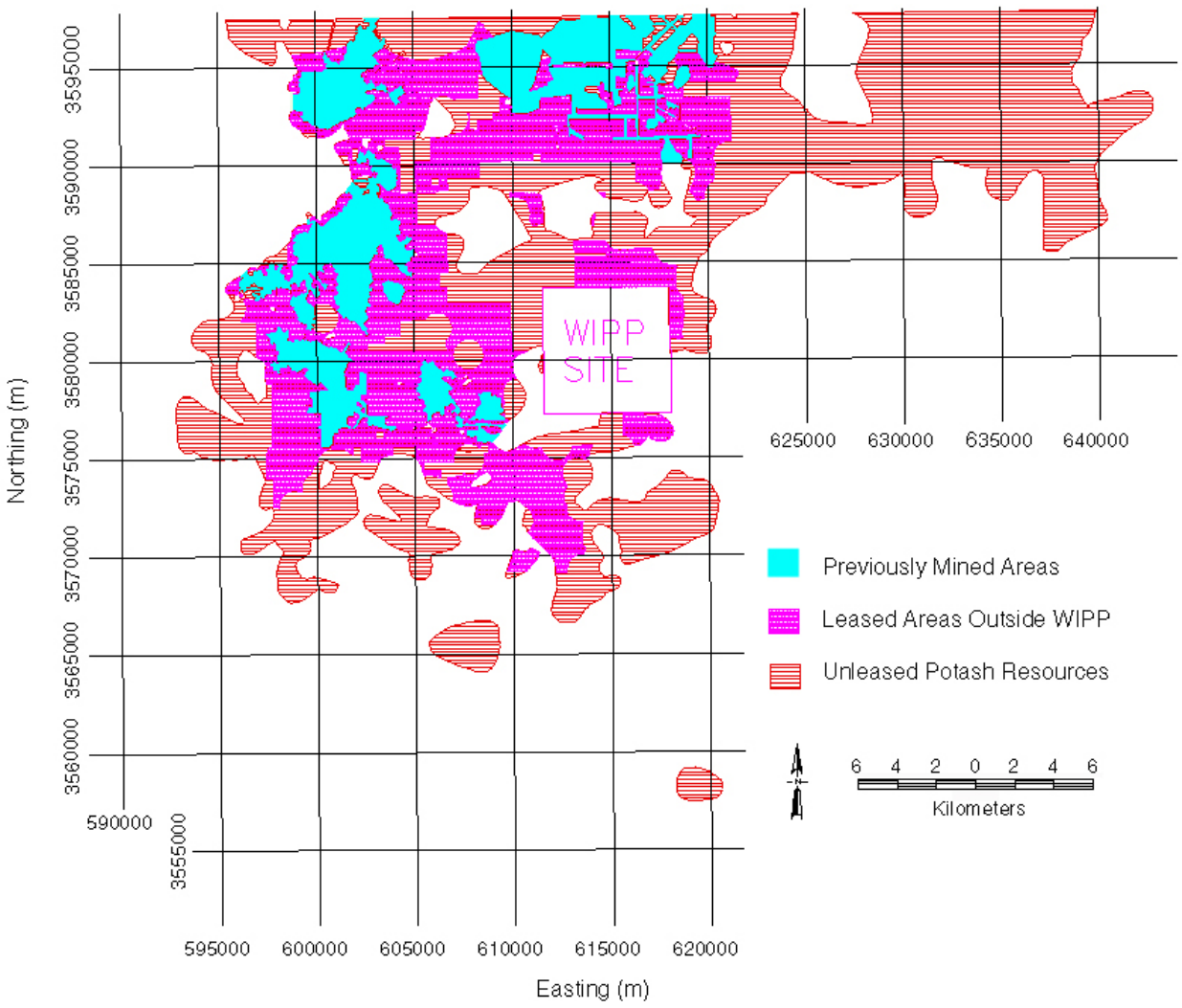


Figure TFIELD-66. Potash Resources Near the WIPP Site

TFIELD-9.3 Forward Runs

A forward steady-state flow model was run for each of the 100 new T fields under each mining scenario (full and partial) for the three replicates of transmissivity multipliers, resulting in 600 simulations. Particle tracking was performed using DTRKMF on the modified flow fields to determine the flow path and groundwater travel time from a point above the center of the WIPP disposal panels to the LWB. A CDF was produced for each mining scenario (as well as an undisturbed scenario) that describes the probability of a conservative tracer reaching the LWB at a given time.

As was done for the CCA, it was assumed that mining impacts would not significantly change the boundary conditions used in T-field calibration. Potash mining has already occurred along the northern boundary of the model domain, and the western model boundary is in Nash Draw where subsidence and fracturing of the Culebra are already incorporated in the model.

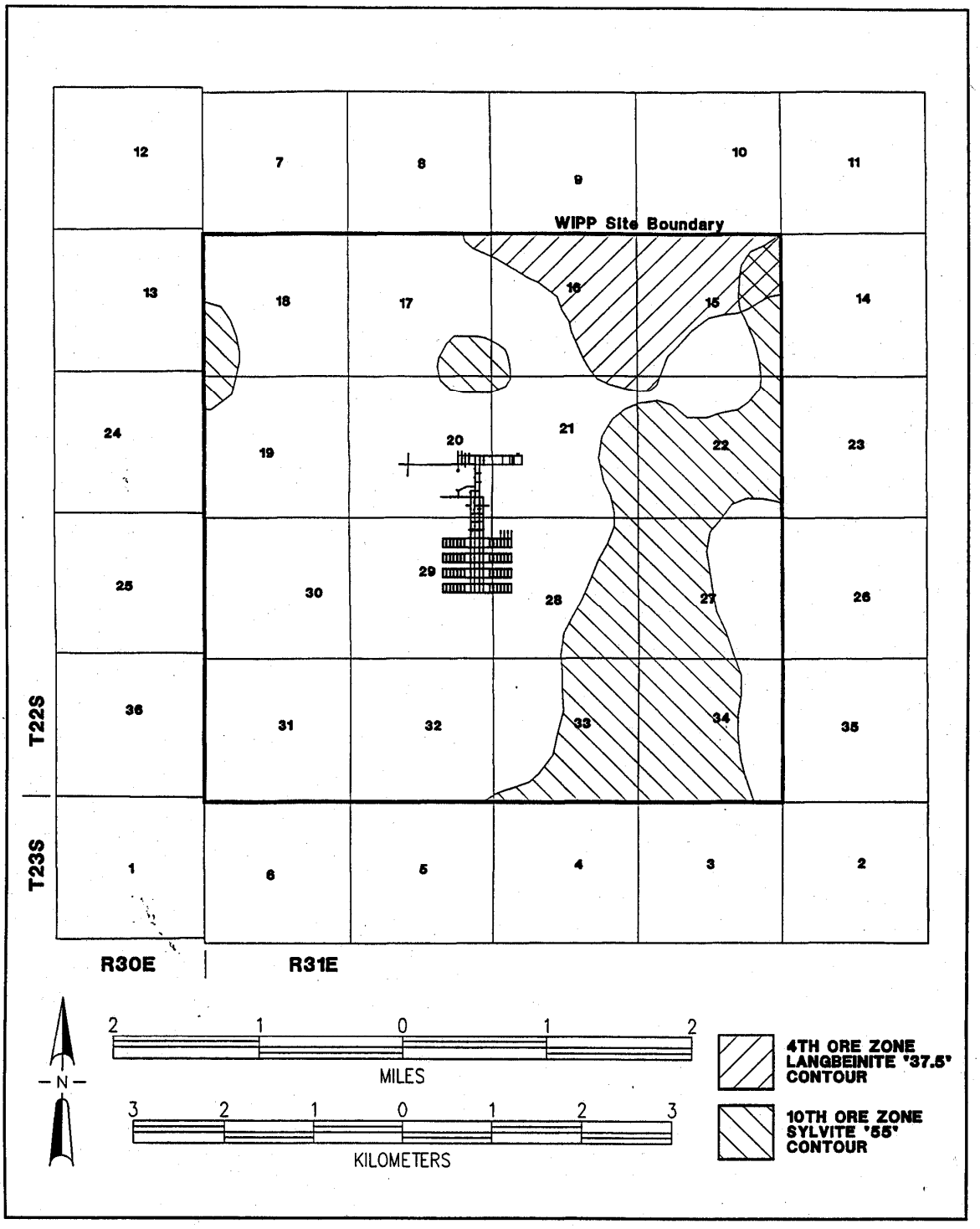


Figure TFIELD-67. Potential Potash Distribution Within the WIPP LWB. The Repository Excavations are Shown in the Center.

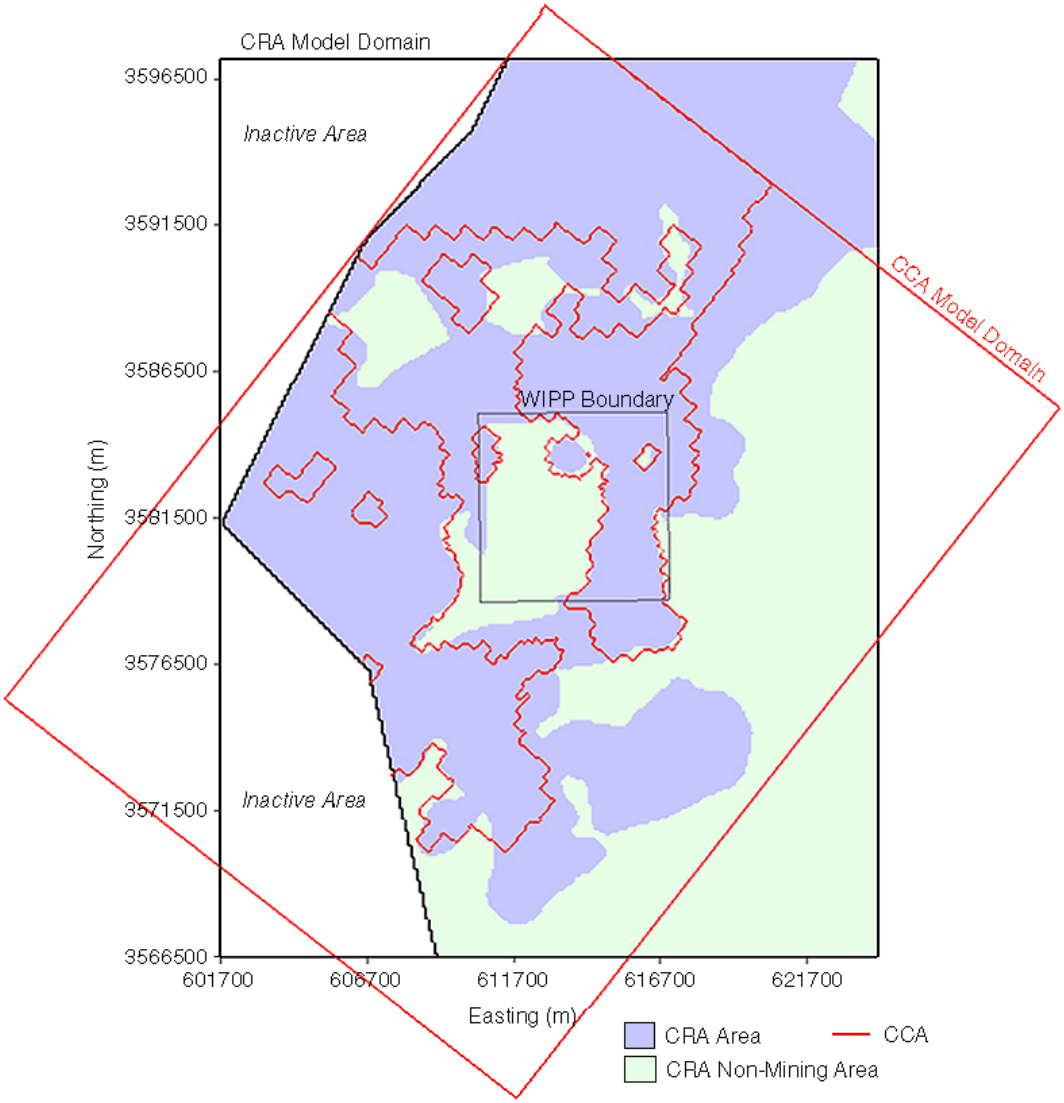


Figure TFIELD-68. Comparison of CRA-2004 and CCA Areas Affected by Mining

TFIELD-9.4 Results

TFIELD-9.4.1 Travel Times

Figure TFIELD-69 shows CDFs of travel time for the unmodified T fields and for the Replicate 1 full- and partial-mining T fields. The partial-mining travel times are consistently longer than the no-mining travel times. Some of the full-mining travel times are shorter than the no-mining times, but most are considerably longer. The median travel times across all three replicates for the full- and partial-mining scenarios are approximately 4.1 and 7.1 times greater, respectively, than for the no-mining scenario. Figure TFIELD-70 and Figure TFIELD-71 compare the CDFs of travel time for all three replicates of the partial- and full-mining cases, respectively, to the Replicate 1 results from the CCA T fields (Wallace 1996). These plots show, first, that all three CRA-2004 replicates provided very similar results and, second, that the new travel times are consistently longer than the CCA travel times.

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d01r02	905.50	32.85	13.54	d09r08	66.07	339.80	327.30
d01r04	508.40	345.10	202.20	d09r09	375.70	806.30	374.20
d01r07	340.30	996.50	936.30	d09r10	521.10	906.90	24.83
d01r10	615.20	828.20	391.80	d10r02	181.60	274.60	651.90
d02r02	575.30	579.30	306.80	d10r03	298.50	796.60	816.70
d03r01	104.00	760.50	955.80	d10r04	705.30	364.70	518.20
d03r03	94.06	514.90	77.79	d10r06	84.20	819.40	690.80
d03r06	913.30	187.60	238.40	d10r07	627.30	728.60	551.20
d03r07	630.50	567.10	725.20	d10r08	403.20	414.80	670.30
d03r08	208.90	475.90	85.67	d10r09	464.20	649.90	885.40
d03r09	769.30	750.00	647.80	d10r10	821.40	607.80	925.70
d04r01	130.20	630.30	478.70	d11r01	307.60	895.10	492.90
d04r02	351.90	453.30	996.70	d11r02	236.50	918.30	364.50
d04r03	46.87	310.90	123.90	d11r06	249.90	159.70	5.43
d04r04	194.60	487.90	217.30	d11r07	543.50	86.78	966.70
d04r05	806.90	923.80	138.30	d11r08	18.75	16.92	973.80
d04r06	264.40	584.00	835.30	d11r09	215.40	618.30	576.30
d04r07	931.50	733.90	802.00	d11r10	73.60	168.90	403.20
d04r08	897.90	51.08	96.80	d12r01	317.40	683.30	756.20
d04r10	32.56	256.50	34.02	d12r02	958.60	204.90	598.10
d05r03	394.10	108.30	159.00	d12r03	686.00	322.00	333.80
d05r07	998.20	535.90	145.50	d12r05	860.70	637.50	589.70
d06r02	790.00	679.40	826.70	d12r06	363.80	359.00	56.05
d06r03	384.10	171.20	261.20	d12r07	660.40	434.90	463.10
d06r04	258.50	860.00	293.90	d12r08	940.20	708.20	312.10
d06r05	432.50	754.10	257.60	d12r09	132.50	464.10	794.60
d06r06	10.02	653.20	172.50	d13r01	983.00	971.30	901.70
d06r07	514.10	221.50	915.60	d13r02	672.80	144.50	224.80
d06r10	282.90	70.11	861.40	d13r03	643.20	849.00	415.20
d07r01	927.30	694.20	625.20	d13r05	425.80	118.60	688.00
d07r02	691.30	864.90	737.80	d13r06	961.10	785.90	385.40
d07r05	738.40	775.30	241.60	d13r07	346.10	282.90	711.40
d07r06	450.20	591.70	548.70	d13r08	838.60	78.26	64.98
d07r07	609.60	447.20	841.00	d13r09	491.00	8.68	458.00
d07r08	557.70	942.30	349.00	d21r01	755.40	307.30	632.40
d07r09	538.60	98.94	285.00	d21r02	172.60	396.20	614.80

1

Table TFIELD-12. T-Field Transmissivity Multipliers for Mining Scenarios (Continued)

T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier	T Field	Replicate 1 Multiplier	Replicate 2 Multiplier	Replicate 3 Multiplier
d07r10	713.60	379.60	187.30	d21r03	591.50	422.30	45.61
d08r01	849.30	408.40	194.00	d21r04	322.70	715.50	276.80
d08r02	569.70	989.10	893.90	d21r05	855.70	870.90	105.80
d08r03	419.50	43.16	356.30	d21r06	272.00	501.20	984.40
d08r04	160.00	834.00	857.00	d21r07	652.50	296.70	940.20
d08r05	971.90	881.10	671.60	d21r10	790.50	212.70	562.50
d08r06	118.80	558.90	743.20	d22r02	163.20	527.50	870.60
d08r07	741.30	130.20	706.70	d22r03	812.70	264.30	534.50
d09r02	729.70	497.00	429.30	d22r04	144.70	140.70	526.30
d09r03	483.00	197.30	168.20	d22r06	26.04	962.70	111.70
d09r04	580.60	661.30	766.40	d22r07	870.30	548.10	609.10
d09r05	228.50	240.90	481.90	d22r08	773.60	235.30	771.70
d09r06	474.10	383.50	449.10	d22r09	53.04	937.70	784.10
d09r07	887.20	952.10	503.30	d22r10	460.40	24.35	434.60

Given the increase in transmissivity due to mining, the increase in travel time may seem counter-intuitive. However, upon examination of the head contours and flow patterns of the mining cases, the high-T areas corresponding to the mining zones create preferential pathways through the system. Figure TFIELD-72 shows the normalized velocity in each cell for the T field/replicate averaged case for the full-mining scenario. The normalized velocity is the velocity magnitude in each cell divided by the maximum velocity magnitude across the domain. Since the velocity magnitudes are highly skewed, the color bands for Figure TFIELD-72 are nonuniformly scaled at the high end (i.e., a wider range of velocity magnitudes is used to designate the orange and red bands). This allows for a better qualitative comparison of the spatial distribution of high and low velocities. "T field/replicate averaged" means the transmissivity value for each cell is the average of the transmissivities across all T field/replicate combinations for the full-mining scenario (300 T fields in total). Not surprisingly, it is clear that the areas of high velocities correspond with the mining zones. Figure TFIELD-72 also shows how flow is able to move eastward to Nash Draw immediately north of the WIPP site, instead of being channeled down through the site. This effect is even more pronounced for the partial-mining T fields, which have no mined areas of high-T on the eastern portion of the WIPP site. The higher velocities and corresponding higher flow rates through the mining zone areas translate to slower velocities in the unmined areas. Because the starting point for the particle tracking is in an unmined area, travel times are increased compared to the no-mining scenario. A comparison of the average, maximum, and minimum values for the full-, partial-, and no-mining scenario travel times is presented in Table TFIELD-13.

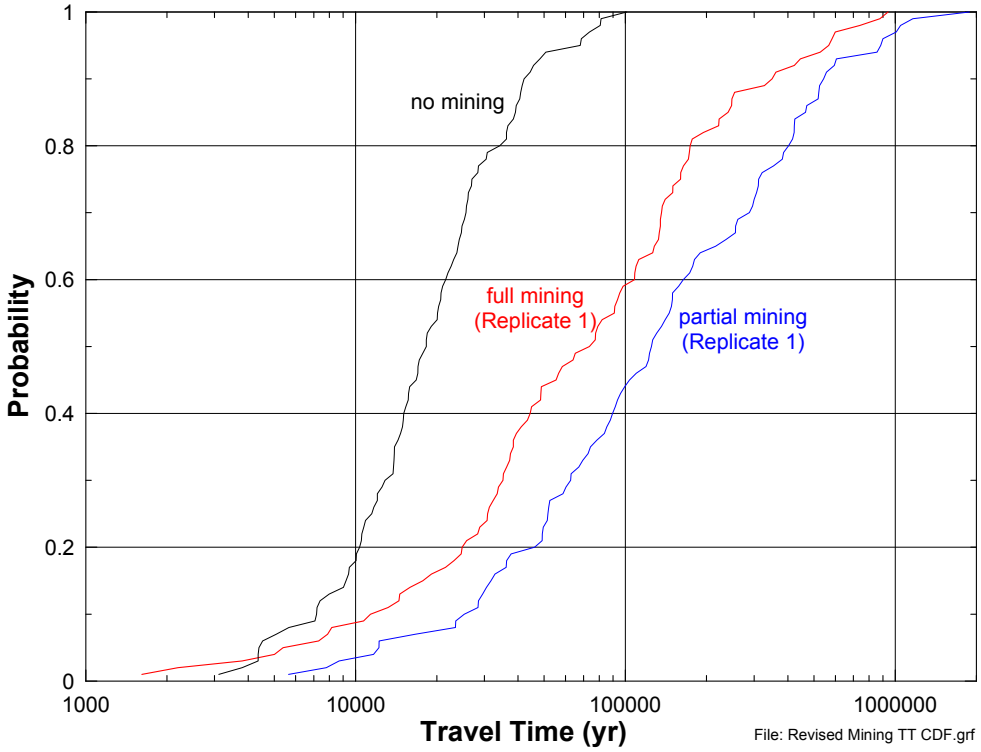


Figure TFIELD-69. CDFs of Travel Times for the Full-, Partial-, and No-Mining Scenarios

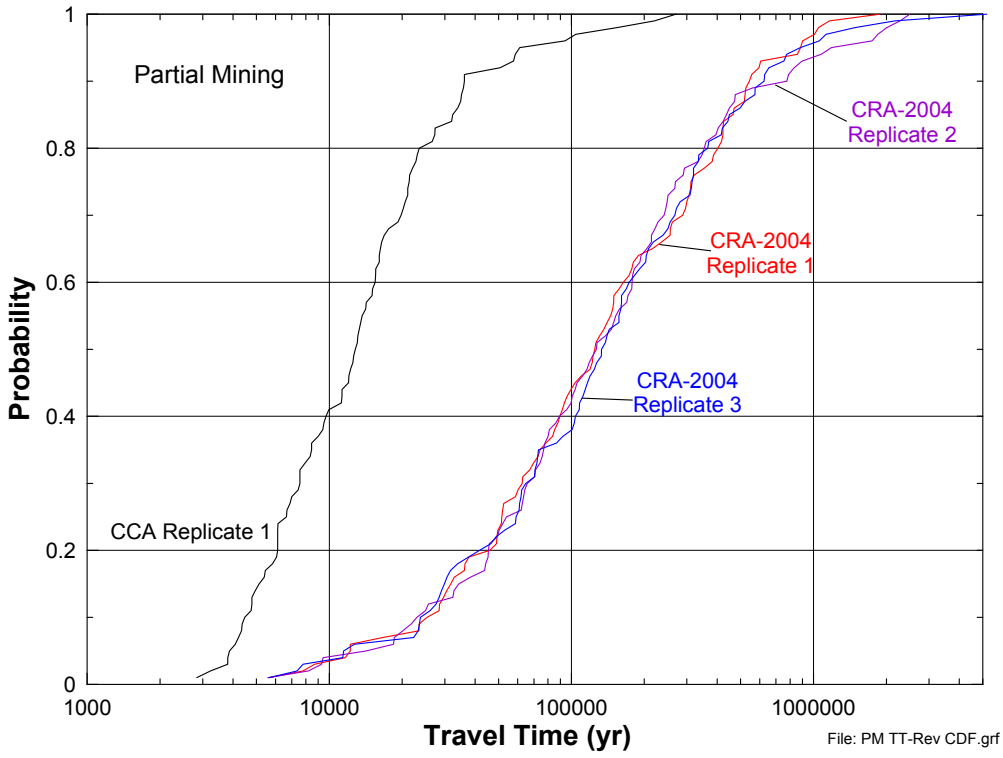


Figure TFIELD-70. CDFs of Partial-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

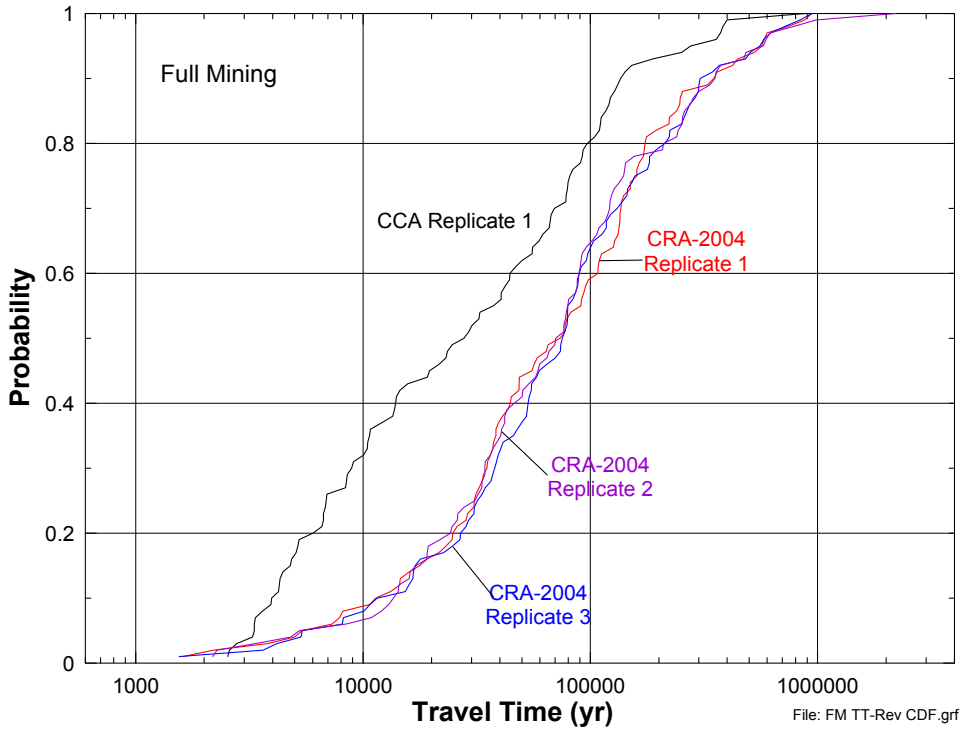


Figure TFIELD-71. CDFs of Full-Mining Travel Times for Three CRA-2004 Replicates and One CCA Replicate

TFIELD-9.4.2 Travel Directions

In almost all cases, the effects of mining do not alter the generally southward direction of flow from the release point to the WIPP site boundary shown in Figure TFIELD-58 for the unaltered fields. The particle-track directions for the partial- and full-mining scenarios are illustrated in Figure TFIELD-73, Figure TFIELD-74, Figure TFIELD-75, Figure TFIELD-76, Figure TFIELD-77, and Figure TFIELD-78. For the partial-mining scenario, particle tracks are drawn slightly to the east (relative to the fields without mining) toward the mined area along the eastern portion of the southern WIPP boundary. For the full-mining scenario, particle tracks tend to move from the release point to the east to the mined area on the WIPP site, and then to the south along the margin of the mined area.

There is a strong similarity within each replicate for each scenario. Individual tracks can be recognized from one replicate to the next, with some slight variations. This indicates that track directions are determined more by the spatial variation of the calibrated T field than by the random mining factors. As long as there is some (see below) increase in the mining zone transmissivities over that of the unmined areas, the tracks for each T field will be similar from one replicate to the next.

The partial-mining particle tracks in Figure TFIELD-73, Figure TFIELD-74, and TFIELD-75 follow paths very similar to the partial-mining particle tracks through the CCA T fields (Ramsey, Wallace, and Jow 1996, Figure 7.12). The full-mining particle tracks in Figure TFIELD-76, Figure TFIELD-77, and Figure TFIELD-78 are very similar to the majority of the full-mining

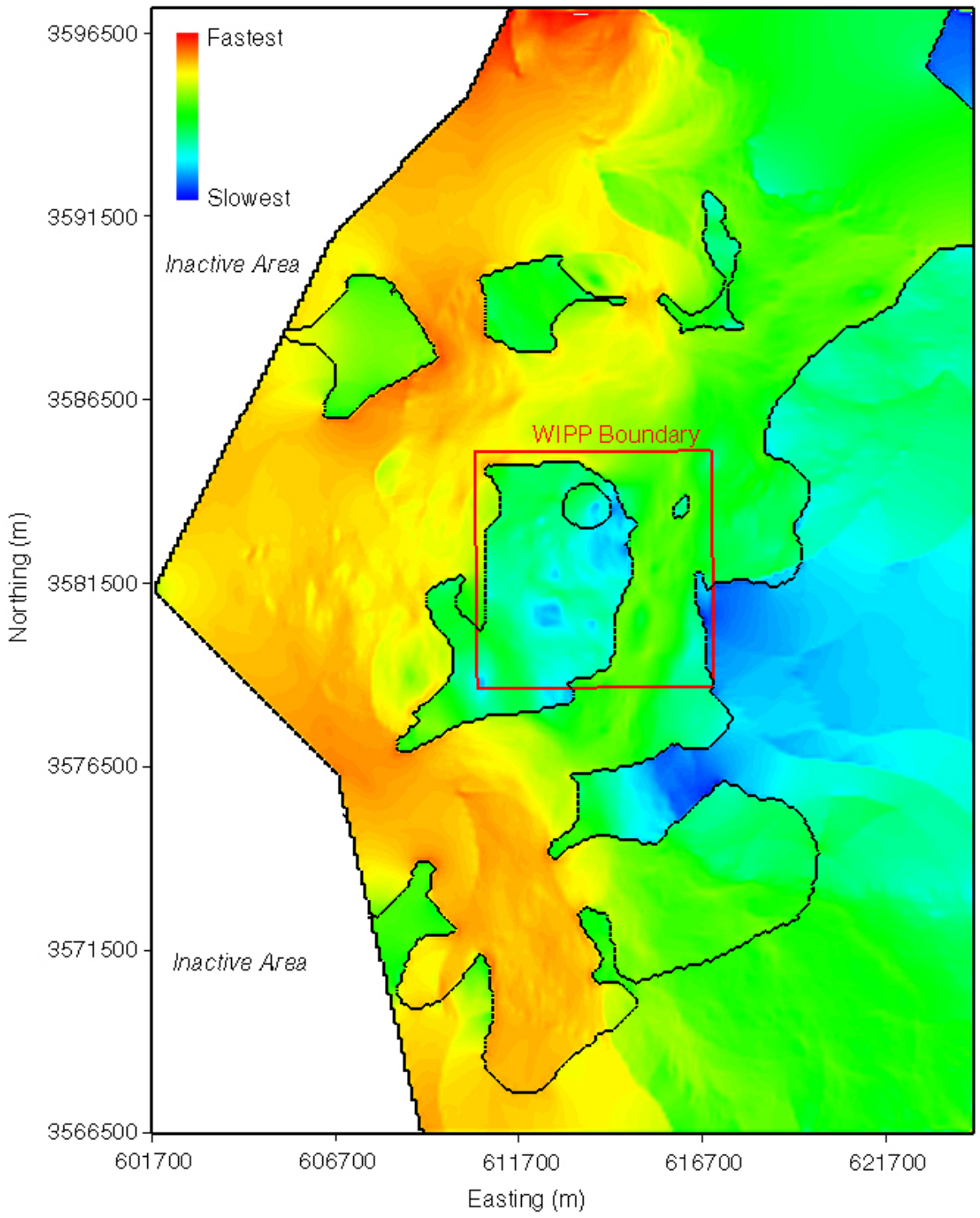


Figure TFIELD-72. Normalized Pore Velocities for the Full-Mining Case. Red Indicates Zones of High Velocity. The Black Outline Shows the Full-Mining Zones and the Red Box is the WIPP LWB. The T Field Used to Produce the Velocity Profile is Averaged Across All T Field/Replicate Combinations for the Full-Mining Scenario (300 T Fields in Total).

Table TFIELD-13. Travel Time Statistics for the Full- and Partial-Mining Scenarios as Compared to the No-Mining Scenario

Replicate	Statistic	Full-Mining Travel Time (yr)	Partial-Mining Travel Time (yr)	No-Mining Travel Time (yr)
R1	Median	75,410	125,712	—
	Maximum	941,529	1,882,522	—
	Minimum	1,615	5,645	—
R2	Median	73,327	127,265	—
	Maximum	2,196,690	2,499,469	—
	Minimum	2,178	5,573	—
R3	Median	76,097	135,686	—
	Maximum	944,251	5,195,535	—
	Minimum	1,550	5,635	—
Global	Median	75,774	129,202	18,289
	Maximum	2,196,690	5,195,535	101,205
	Minimum	1,550	5,573	3,111

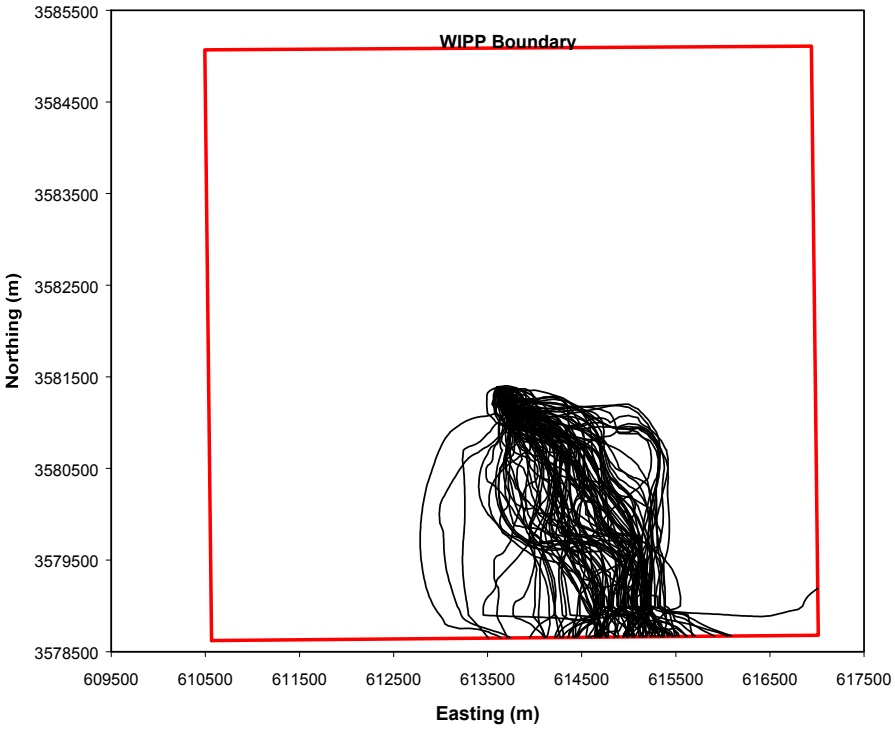


Figure TFIELD-73. Particle Tracks for Replicate 1 for the Partial-Mining Scenario

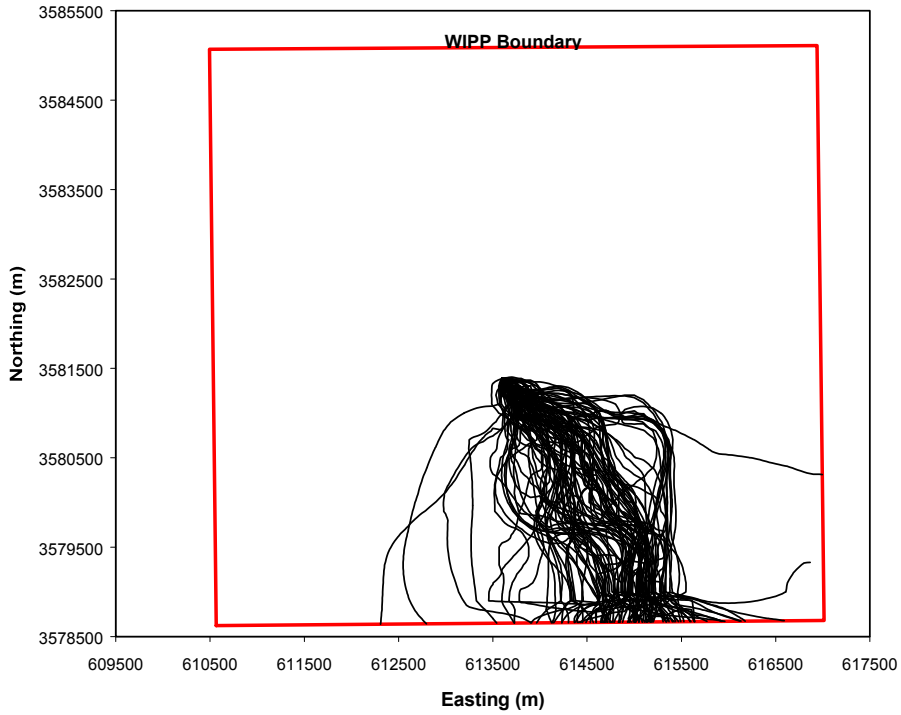


Figure TFIELD-74. Particle Tracks for Replicate 2 for the Partial-Mining Scenario

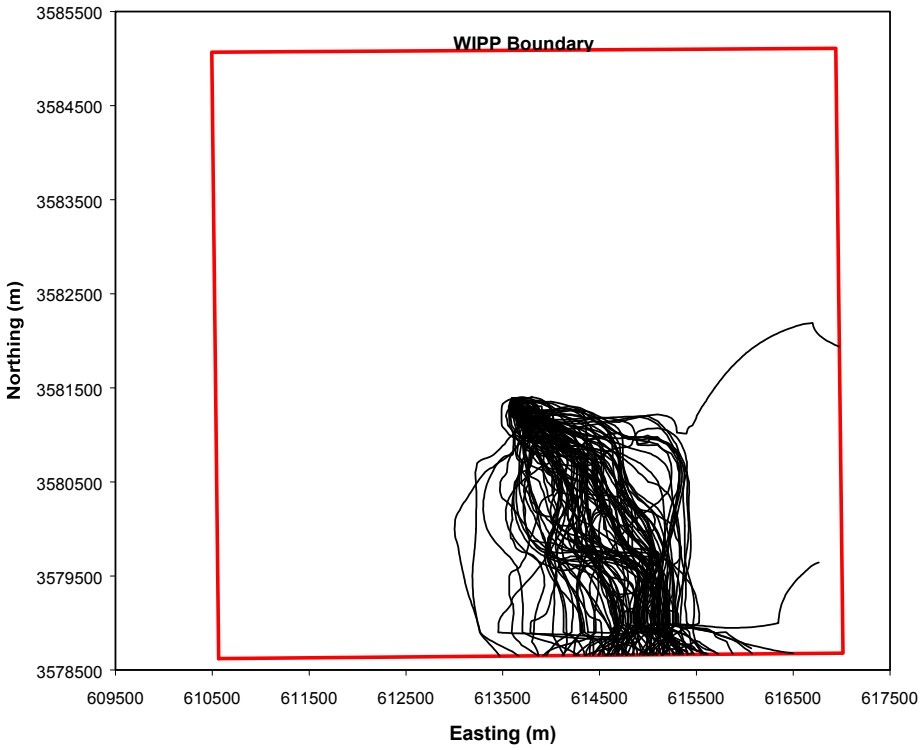


Figure TFIELD-75. Particle Tracks for Replicate 3 for the Partial-Mining Scenario

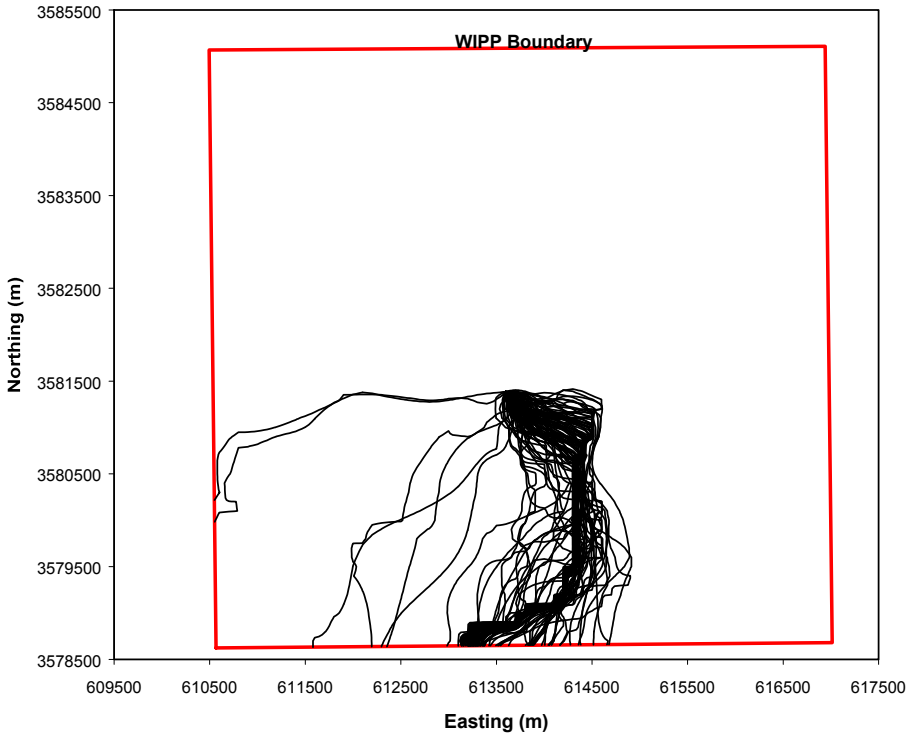


Figure TFIELD-76. Particle Tracks for Replicate 1 for the Full-Mining Scenario

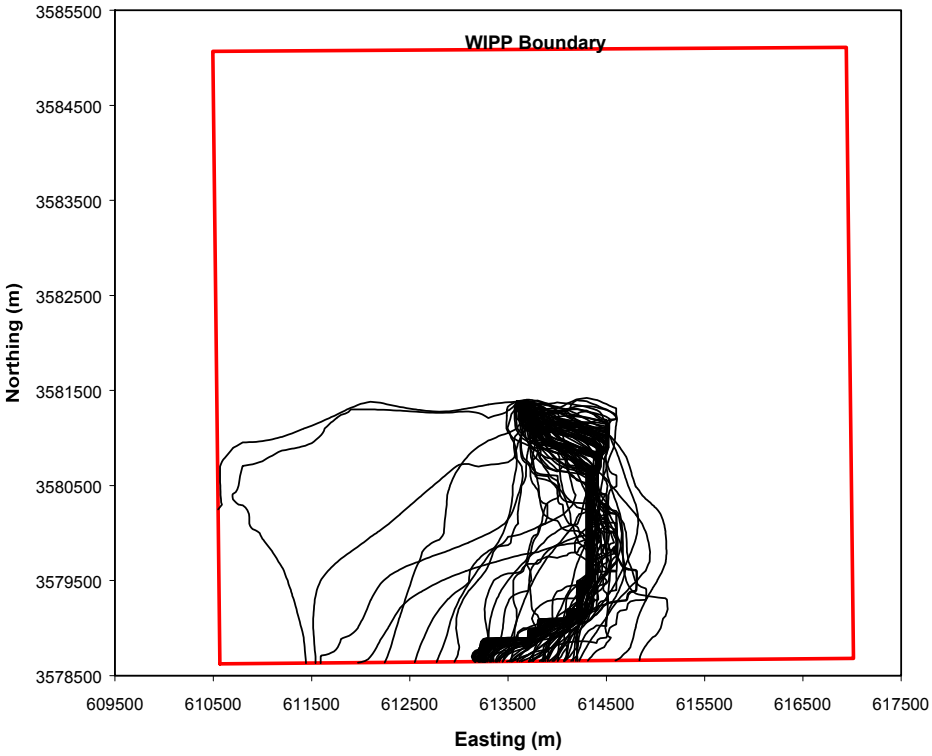


Figure TFIELD-77. Particle Tracks for Replicate 2 for the Full-Mining Scenario

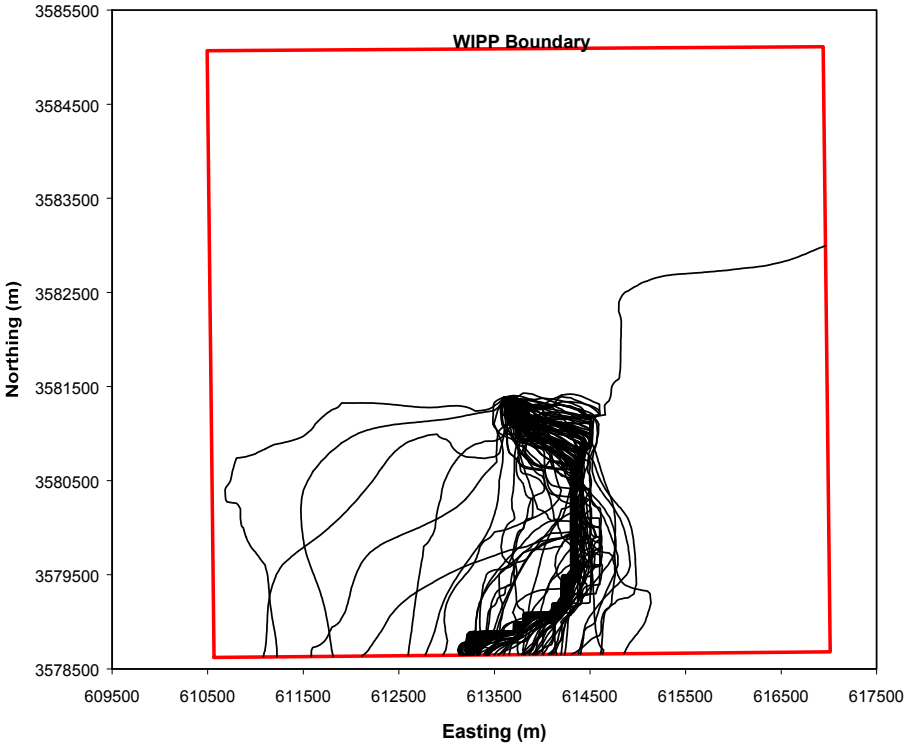


Figure TFIELD-78. Particle Tracks for Replicate 3 for the Full-Mining Scenario

particle tracks through the CCA T fields (Ramsey, Wallace, and Jow 1996, Figure 7.13), with fewer tracks trending to the west through the unmined area.

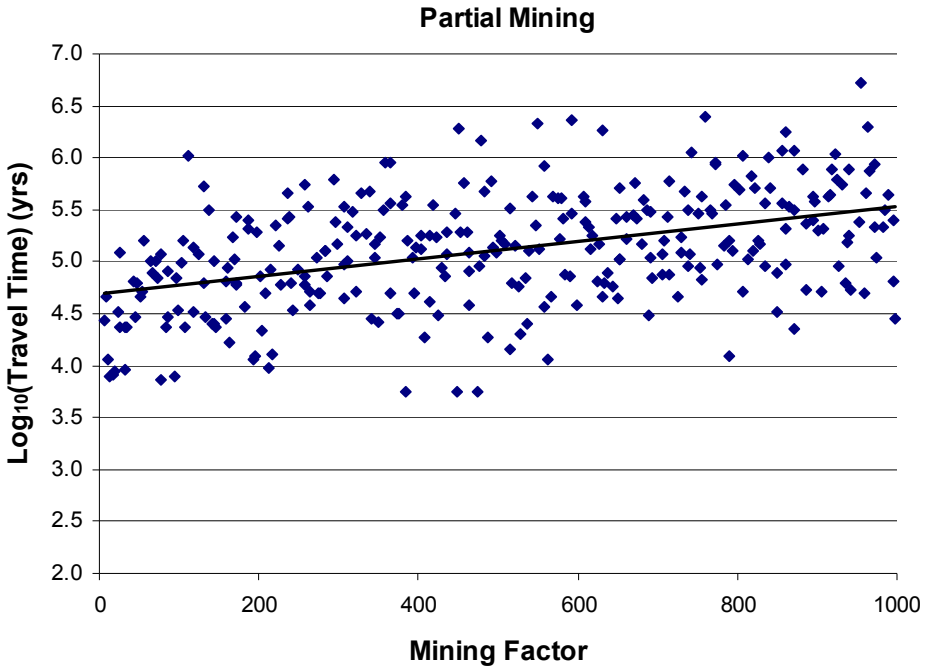
Correlation analysis shows weak positive correlations between travel time and the random mining factor for the full and partial-mining scenarios of 0.32 and 0.30, respectively. Figure TFIELD-79 shows the $\log_{10}$ travel times versus the random mining factor for the full- and partial-mining scenarios across all replicates. The weak correlation between the random mining factor and the travel time can be explained as follows. The flow fields are highly influenced by the large mining zone to the west of the WIPP site. This can be seen in the velocity plot in Figure TFIELD-79. An increase in transmissivity in the mining zone means higher flow rates through those areas, and correspondingly lower flow rates through the non-mining areas. Thus, as the mining factor increases, so do travel times.

The high scatter shown in Figure TFIELD-79 indicates that the initial (pre-mining) distribution of transmissivity plays a significant role in determining the travel time. The standard deviation of the $\log_{10}$ travel time due only to differences in the T field is 0.5 for both the full- and partial-mining scenarios. The variability around the trendline of Figure TFIELD-79 is normally distributed, with most values falling within three standard deviations of the trendline. This means that the initial distribution of transmissivity accounts for the majority of the three orders of magnitude range of travel times.

TFIELD-9.4.3 Extreme Values

Examination of the extreme travel time values and the causes behind those values is useful in quantifying the range of outcomes given the amount of uncertainty incorporated into the models. Figure TFIELD-80 shows the head contours and particle track for the partial-mining T field (d03r01 from Replicate 3) with the longest travel time, 5,195,535 years. This was the only T field for which the direction of flow was to the east, and the T field also had extremely low gradients across the WIPP site. T field d09r06 from Replicate 2 (Figure TFIELD-81) had the shortest travel time of 5,573 years because of high north-to-south gradients across the WIPP site relative to other T fields. The median travel time is best represented by T field d13r07 from Replicate 2 (Figure TFIELD-82) with a travel time of 129,202 years, which had low gradients across the WIPP site.

Most of the full-mining T fields had particle tracks moving from the release point to the mined area to the east, and then south to the WIPP boundary. For the full-mining scenario, T field d22r06 from Replicate 2 (Figure TFIELD-83) had the longest travel time, 2,196,690 years, because of low gradients and the particle track staying in the unmined area for much of its distance. T field d03r03 from Replicate 3 (Figure TFIELD-84) had the shortest travel time of 1,550 years because of high gradients in the unmined zone sending the particle directly east to the mined zone. The median travel time is best represented by T field d12r08 in Replicate 3 (Figure TFIELD-85) with a travel time of 75,774 years, in which the particle also moved fairly directly to the mined zone.



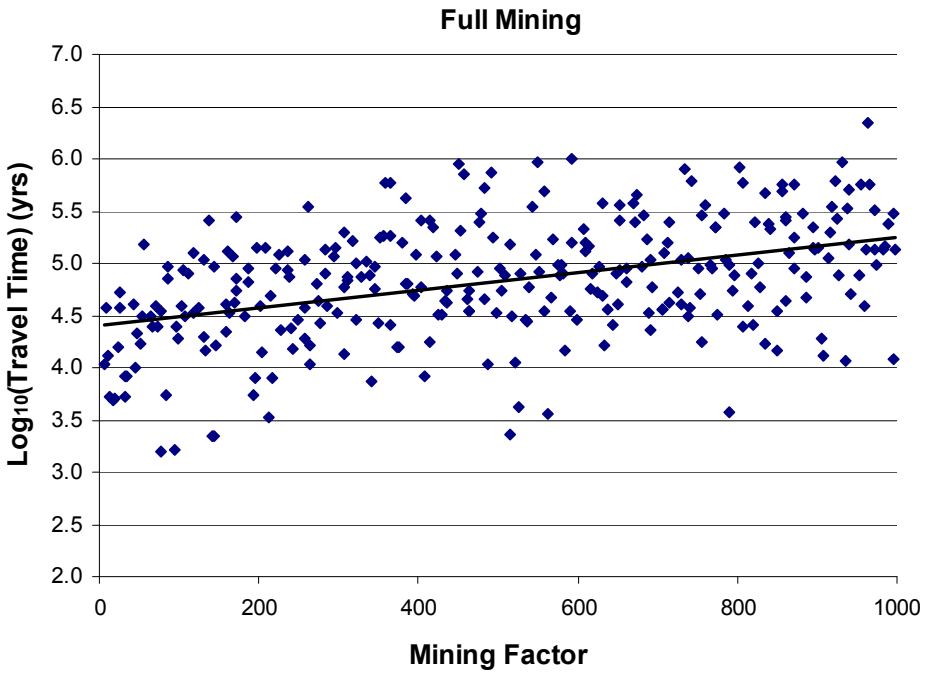


Figure TFIELD-79. Correlation Between the Random Mining Factor and $\log_{10}$ of Travel Time

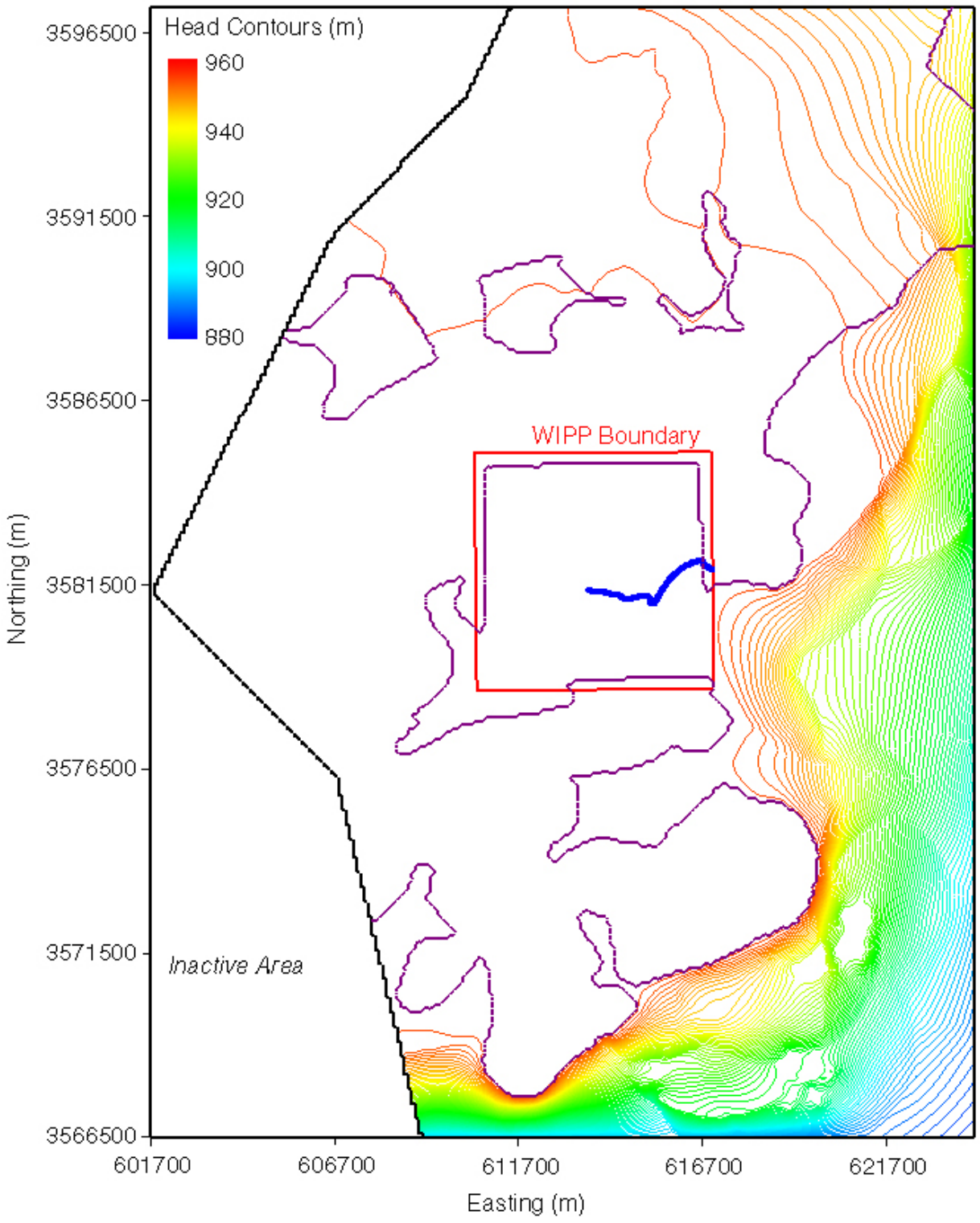


Figure TFIELD-80. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d03r01-R3) for the Partial-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

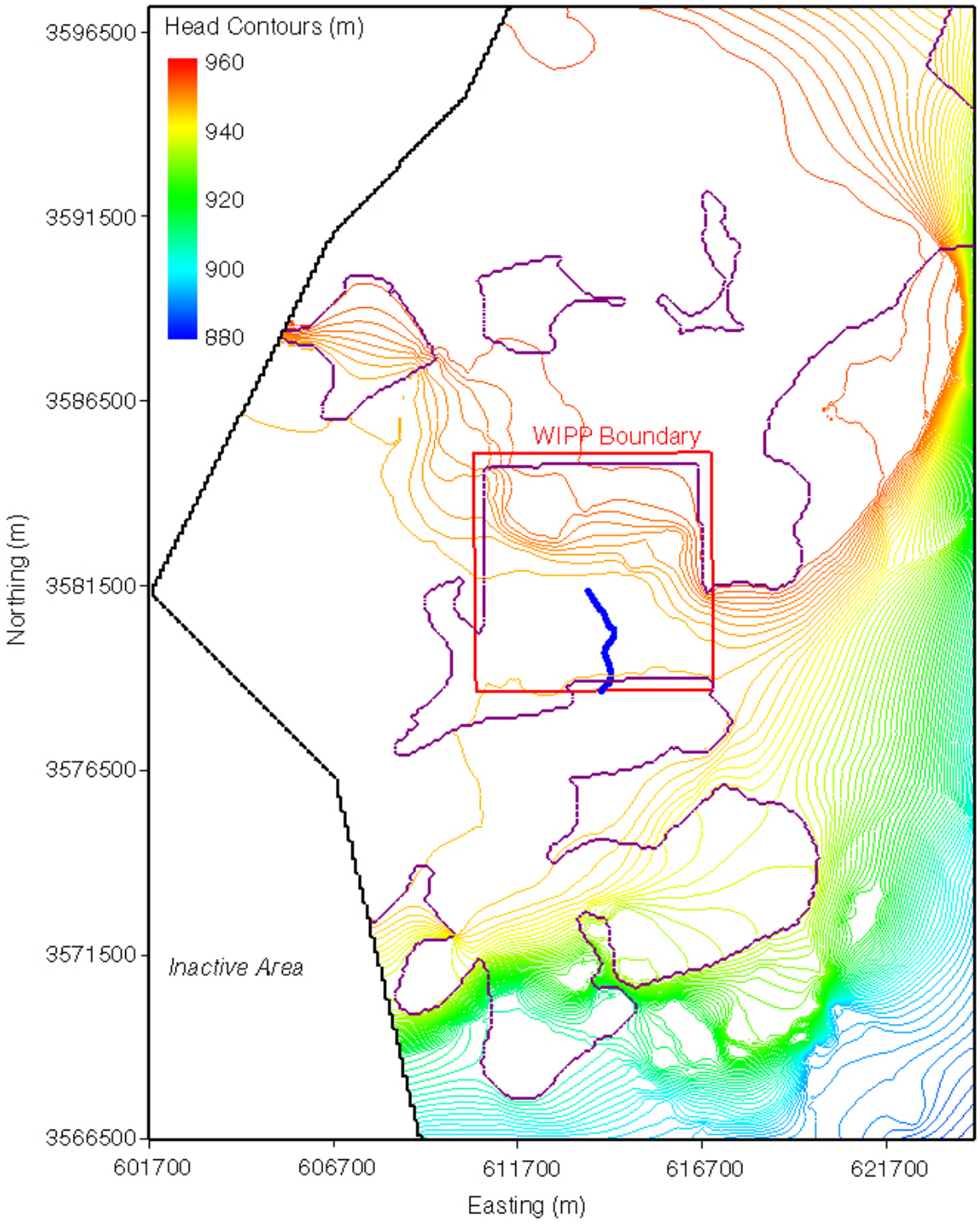


Figure TFIELD-81. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d09r06-R2) for the Partial-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

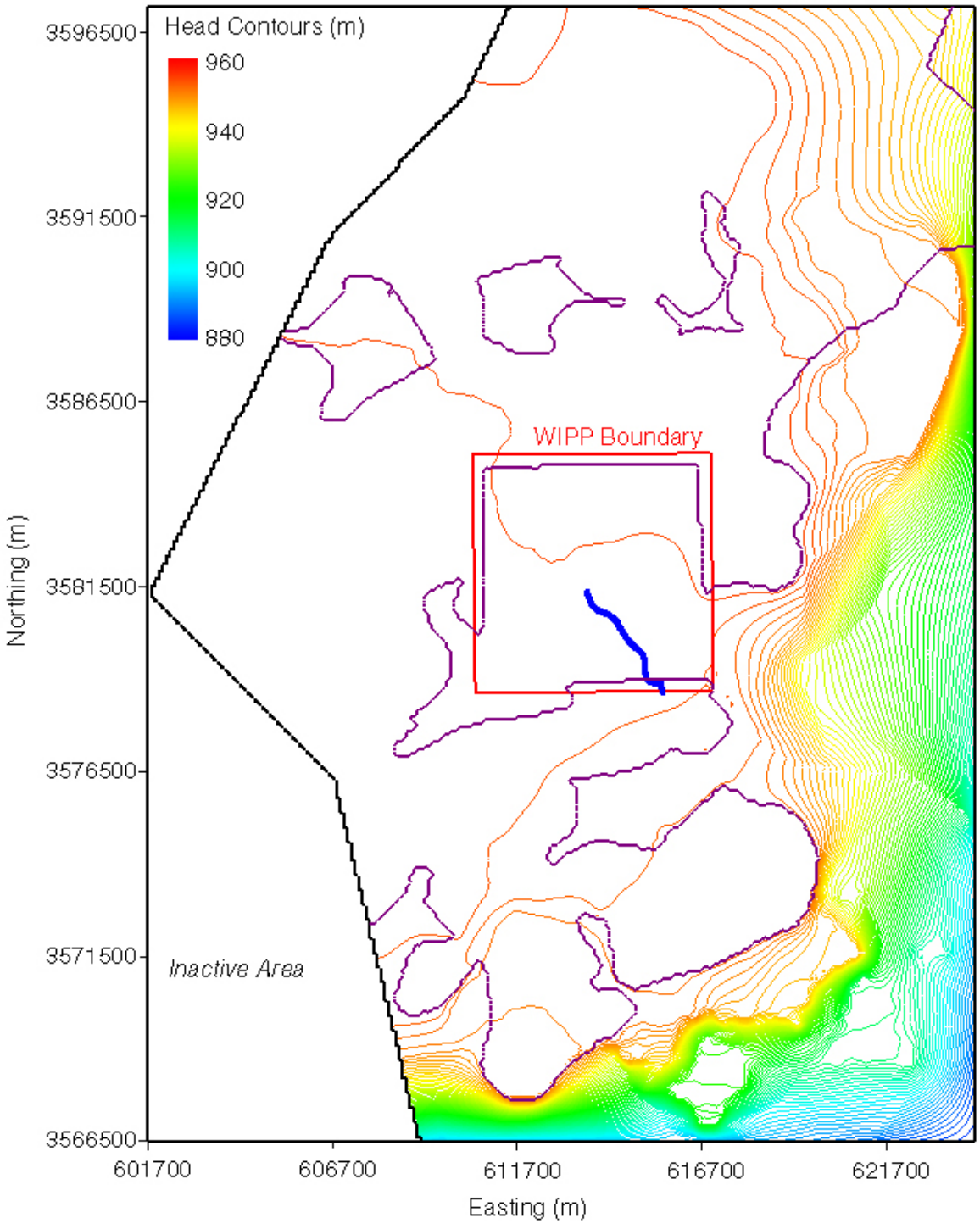


Figure TFIELD-82. Head Contours and Particle Track for the Median-Travel-Time T Field (d13r07-R2) for the Partial-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

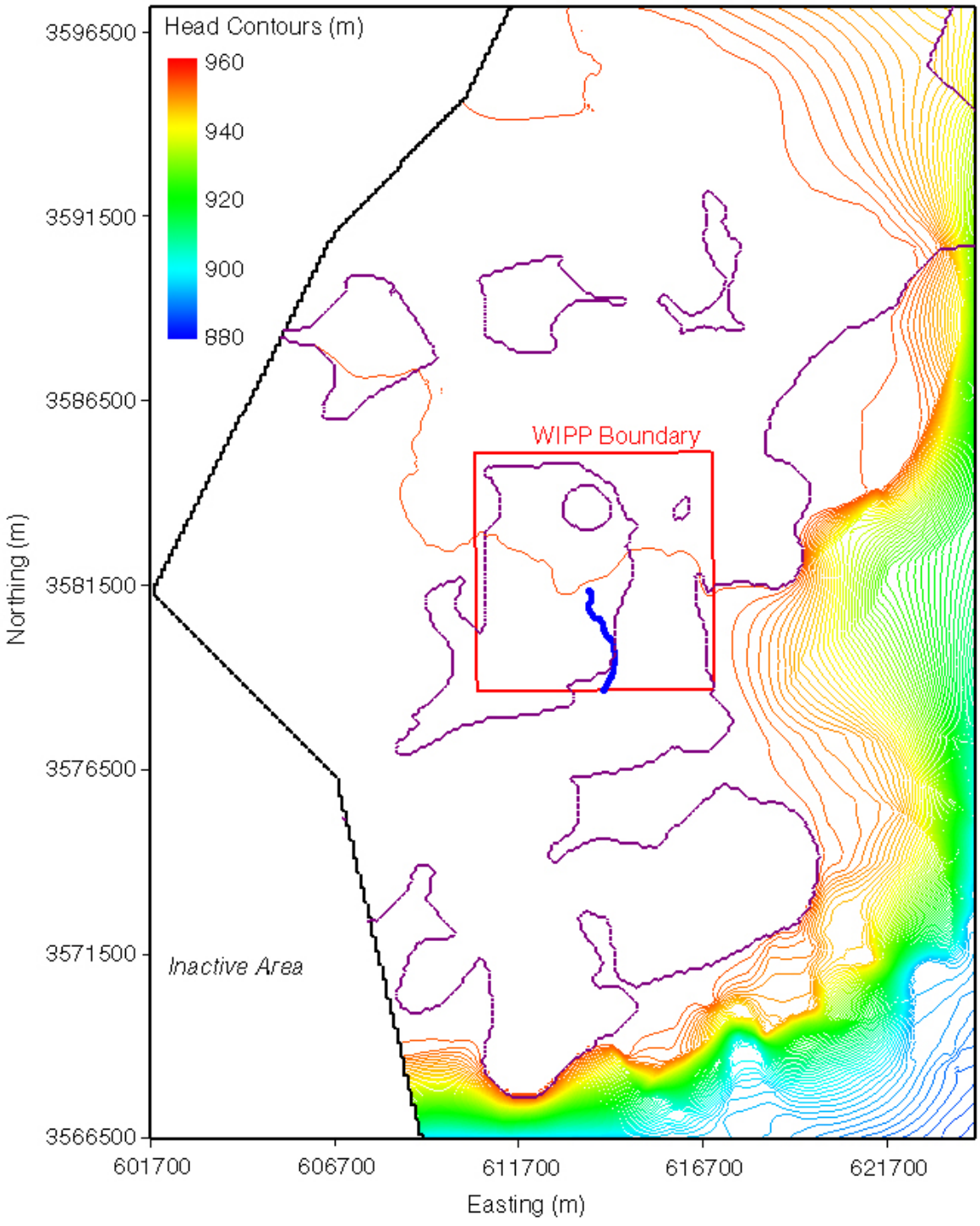


Figure TFIELD-83. Head Contours and Particle Track for the Maximum-Travel-Time T Field (d22r06-R2) for the Full-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

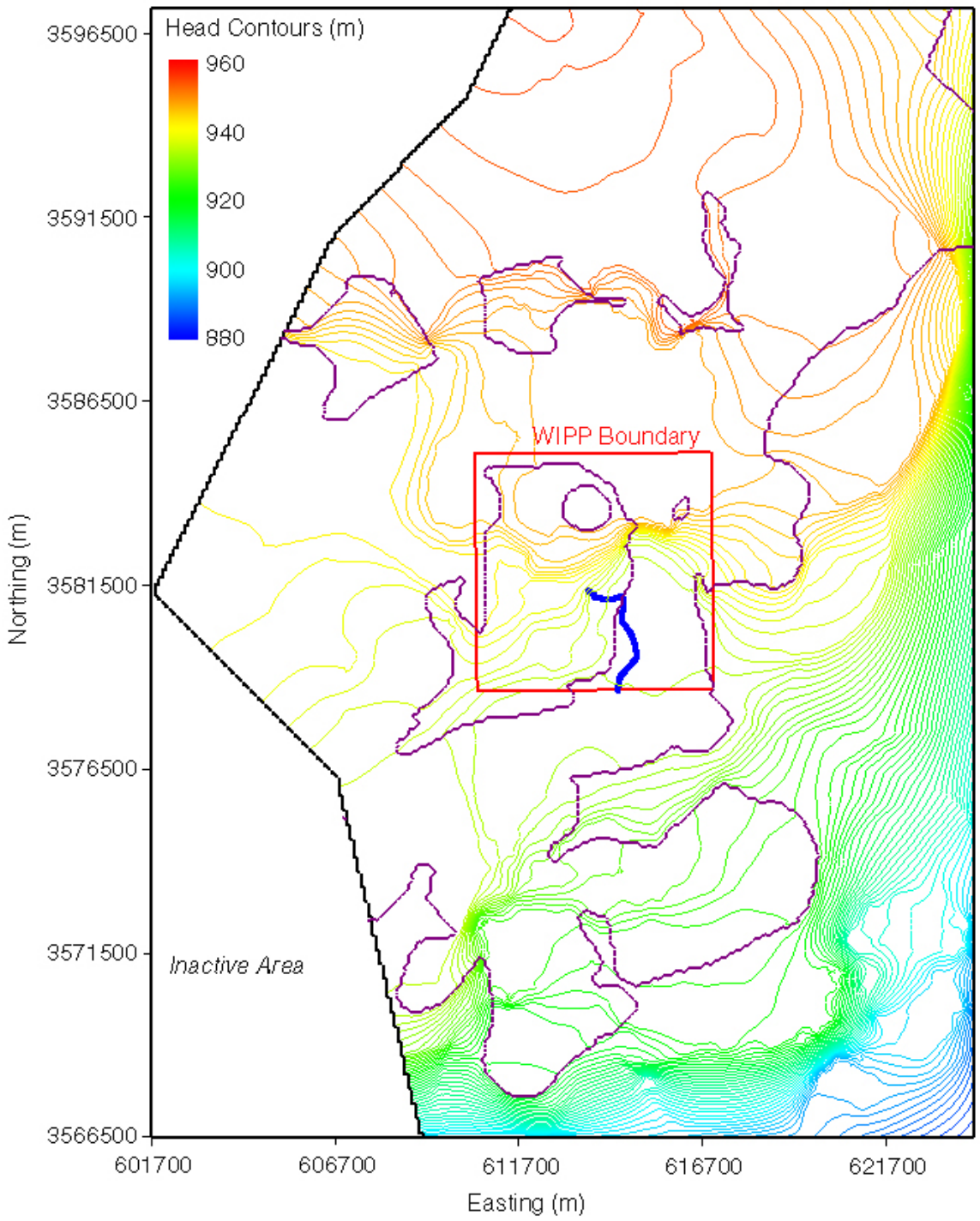


Figure TFIELD-84. Head Contours and Particle Track for the Minimum-Travel-Time T Field (d03r03-R3) for the Full-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

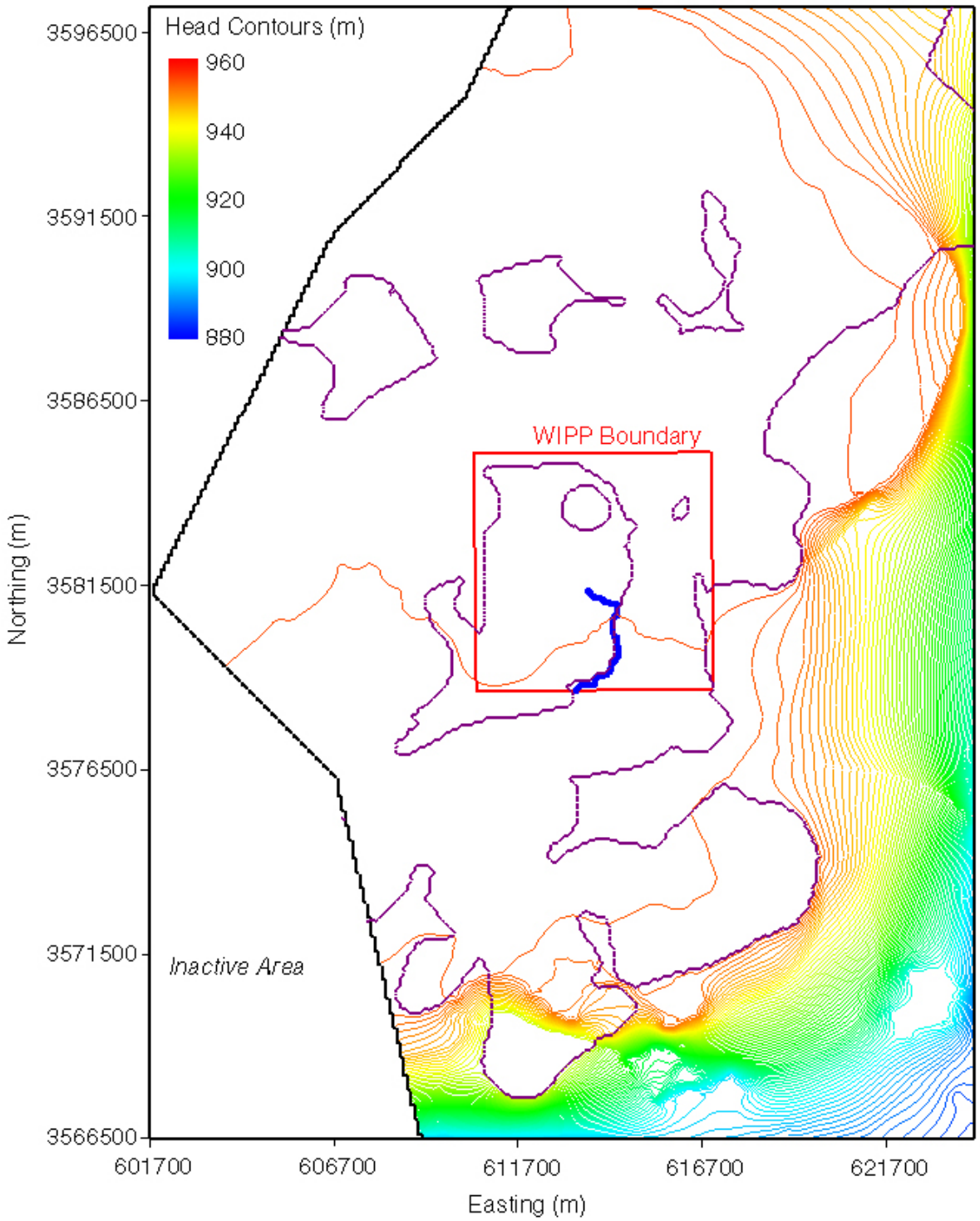


Figure TFIELD-85. Head Contours and Particle Track for the Median-Travel-Time T Field (d12r08-R3) for the Full-Mining Case. The WIPP LWB is the Red Box in the Center of the Figure and the Particle Track is the Blue Track Originating from the Approximate Center of the WIPP.

TFIELD-10.0 Summary

Observed Culebra transmissivity has been related to three deterministic factors: the thickness of overburden above the Culebra, the presence or absence of dissolution of the upper Salado, and the presence or absence of halite in units above and below the Culebra. Culebra transmissivity is also related to the occurrence of open, interconnected fractures, which cannot be mapped as easily as the other three factors and must be treated stochastically. A linear-regression model for Culebra transmissivity has been developed based on these factors that provides an excellent match to the observed data, and can be tested through the collection of additional data. This model was used to create 500 stochastic realizations of the distribution of Culebra transmissivity ("base" T fields) in the vicinity of the WIPP site.

A MODFLOW-2000 modeling domain was defined extending 30.7 km (19.1 mi) north-south and 22.4 km (13.9 mi) east-west, roughly centered on the WIPP site. This domain was discretized into 68,768 uniform 100-m (328-ft) by 100-m (328-ft) cells. Water-level measurements made in 37 wells in late 2000 were used to define "steady-state" head conditions and constant-head boundary conditions on the northern, eastern, and southern extremes of the model domain. No-flow boundaries down the arms of Nash Draw, representing flow lines, were used on the western side of the model domain, reducing the number of active cells to 53,769.

MODFLOW-2000 and PEST were used to calibrate 146 of the base T fields to steady-state heads and transient drawdown responses to seven large-scale pumping tests. This calibration was done by using 100 pilot points to adjust the transmissivity values within the model domain to improve the fit to the observed heads. The pilot points were used to adjust a residual T field that was combined with a previously created base T field to yield the final calibrated T field. Of the 146 T fields, 121 were judged to be adequately calibrated for use in WIPP compliance calculations by virtue of being from a single population with respect to the CDF of travel times from a point above the center of the WIPP disposal panels to the LWB. From these 121 T fields, the 100 having the best objective fit measures were selected for further use.

The EPA requires that the potential effects of future potash mining be taken into account when evaluating the performance of the WIPP disposal system. Accordingly, transmissivities in the areas within the model domain where current or future mining might affect the Culebra were scaled by a random multiplier between 1 and 1,000 obtained from LHS. A single multiplier was used for each T field, applied first to the areas outside the WIPP LWB that might be mined to create a partial-mining T field, and then to the areas both inside and outside the LWB that might be mined to create a full-mining T field. The LHS was performed three times to create three replicates of T fields, leading to a total of 600 T fields. The MODFLOW-2000 water "budget" files from forward runs of these 600 T fields provided the input to radionuclide-transport calculations using SECOTP2D.

In all cases (no mining, partial mining, and full mining), the particle tracks on the T fields show travel times that are longer than those calculated for the T fields used in the CCA. In the case of the T fields unaltered for the effects of mining, the longer travel times are caused by a shift of relatively high-T from the southeastern to the southwestern portion of the WIPP site relative to the CCA T fields. In the case of the T fields altered for full and partial mining, the longer travel times are the combined result of the westward shift of high-T discussed above and a change in

the definition of the areas to be mined that resulted in less water entering the Culebra on the WIPP site.

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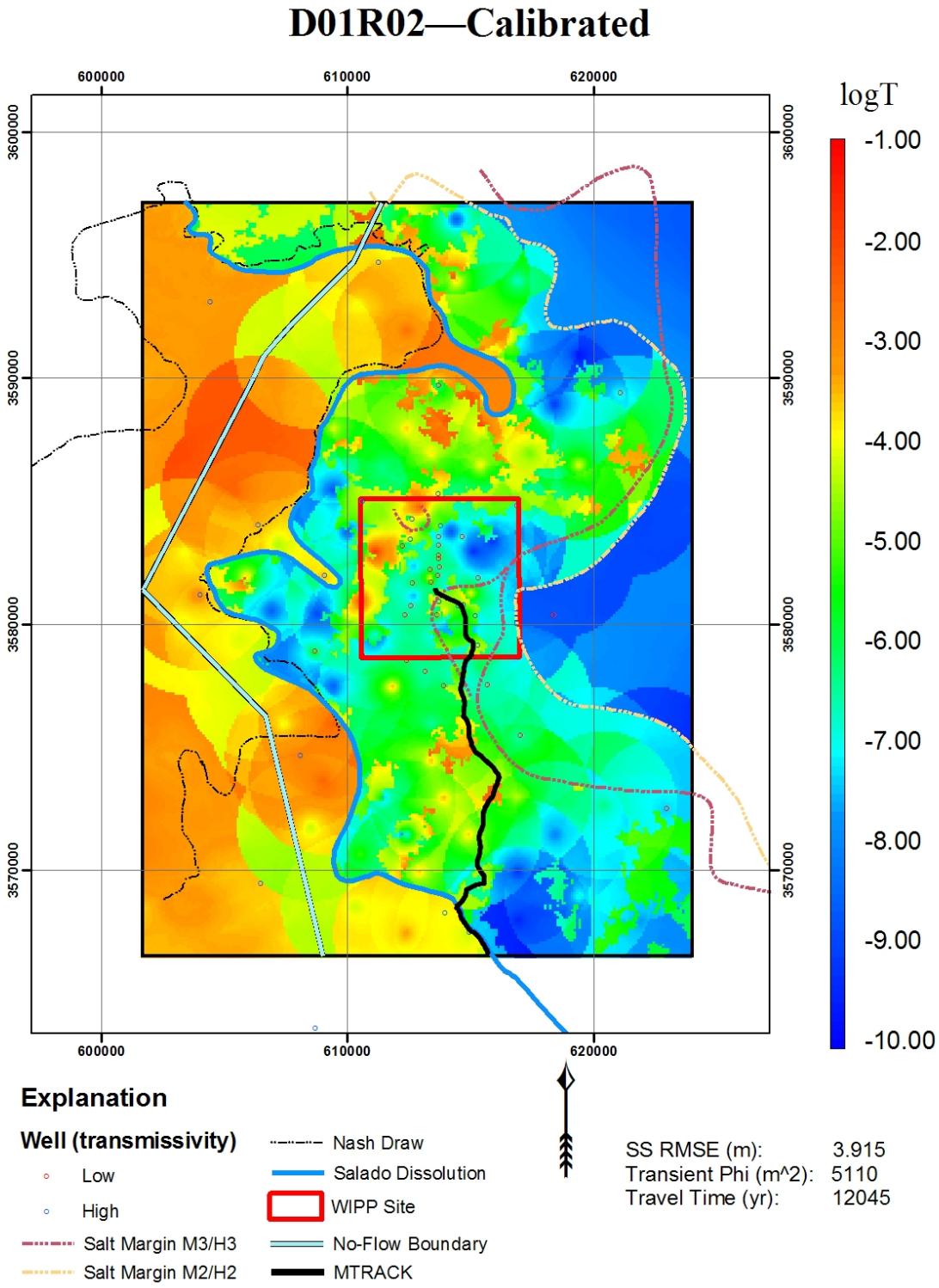
Title 40 CFR Part 191
Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Attachment A: TFIELD Visualization

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Attachment A: TFIELD Visualization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Explanation
Well (transmissivity)
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High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
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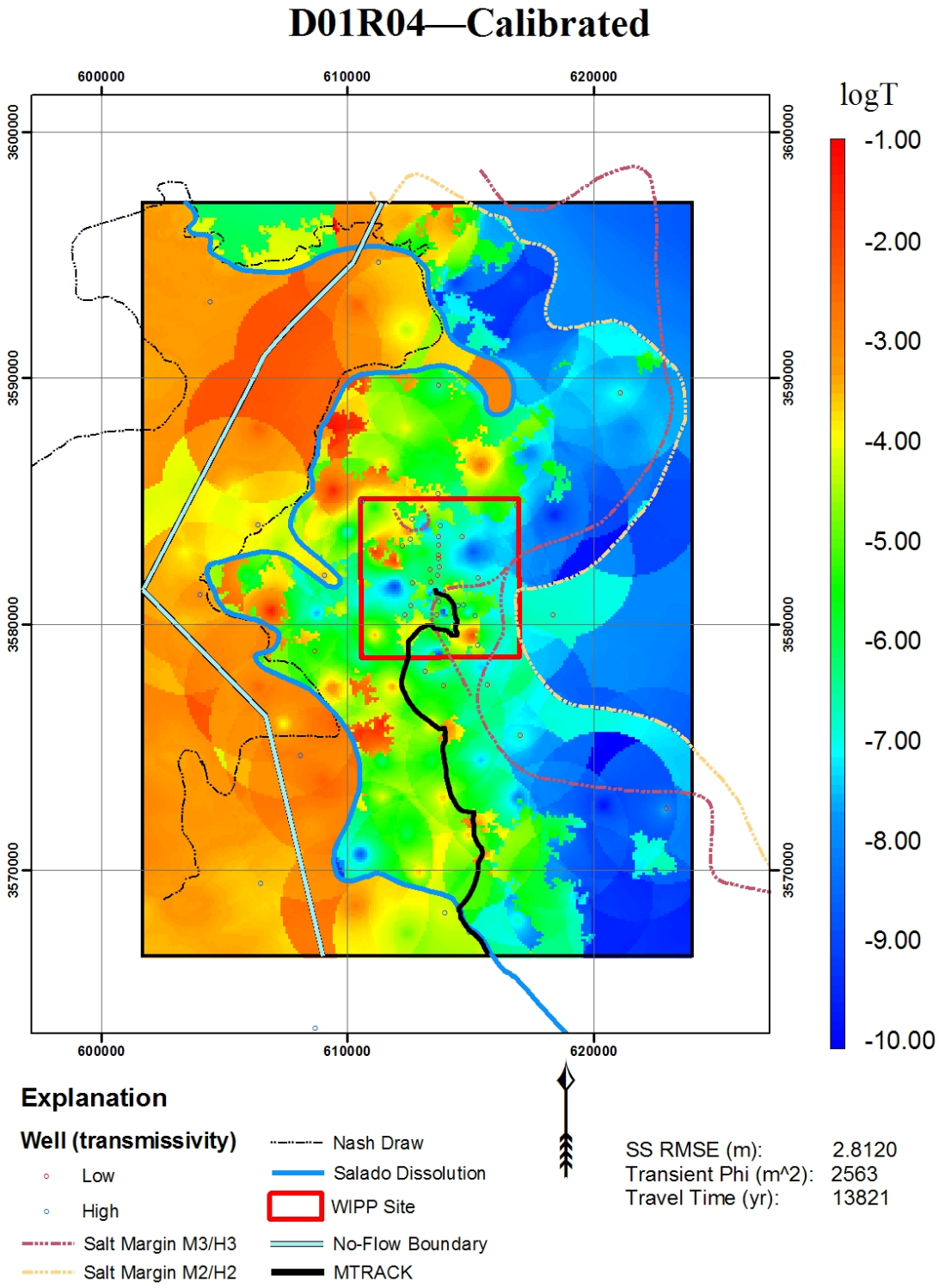
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Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
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MTRACK
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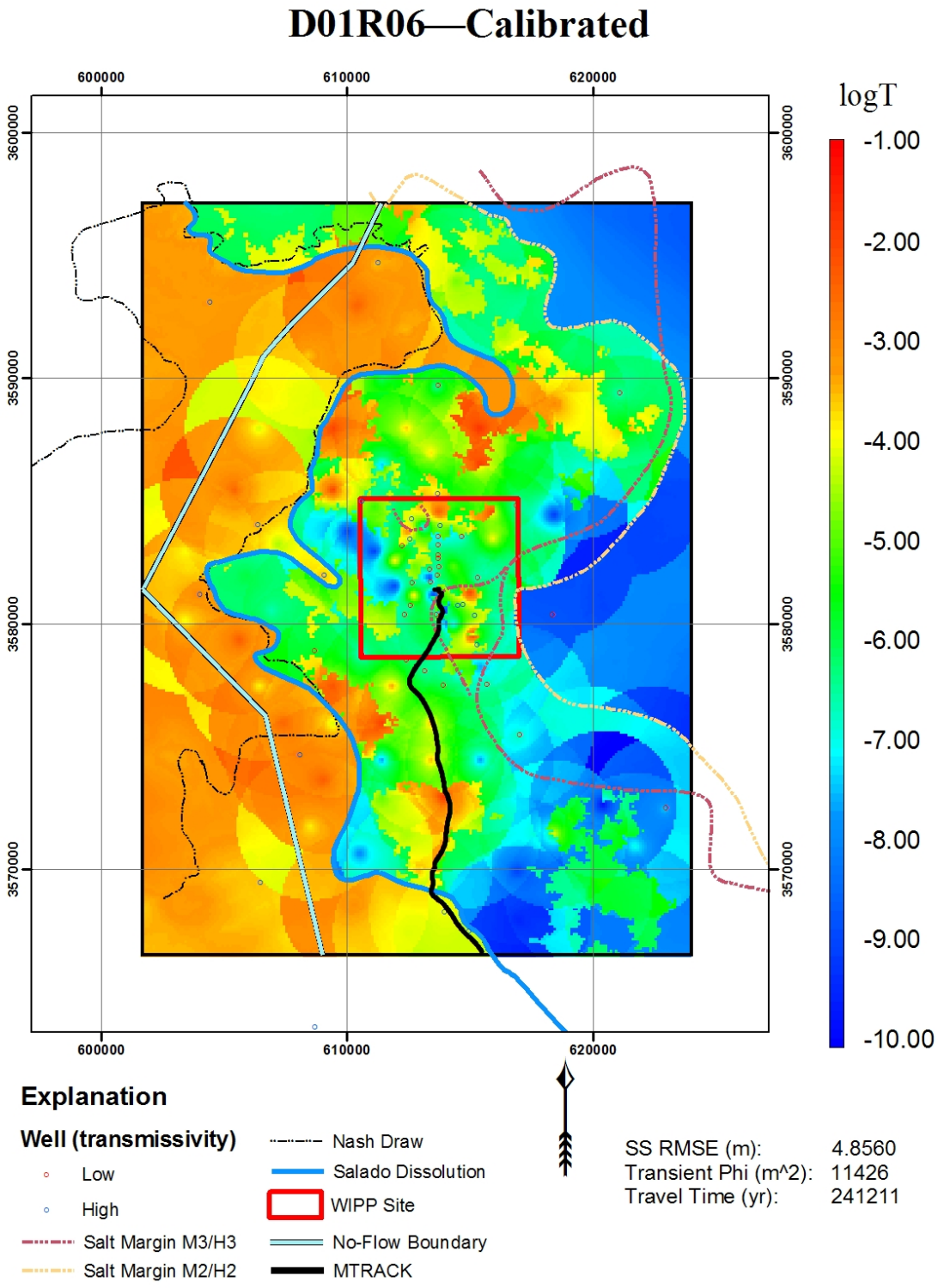
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High
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Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
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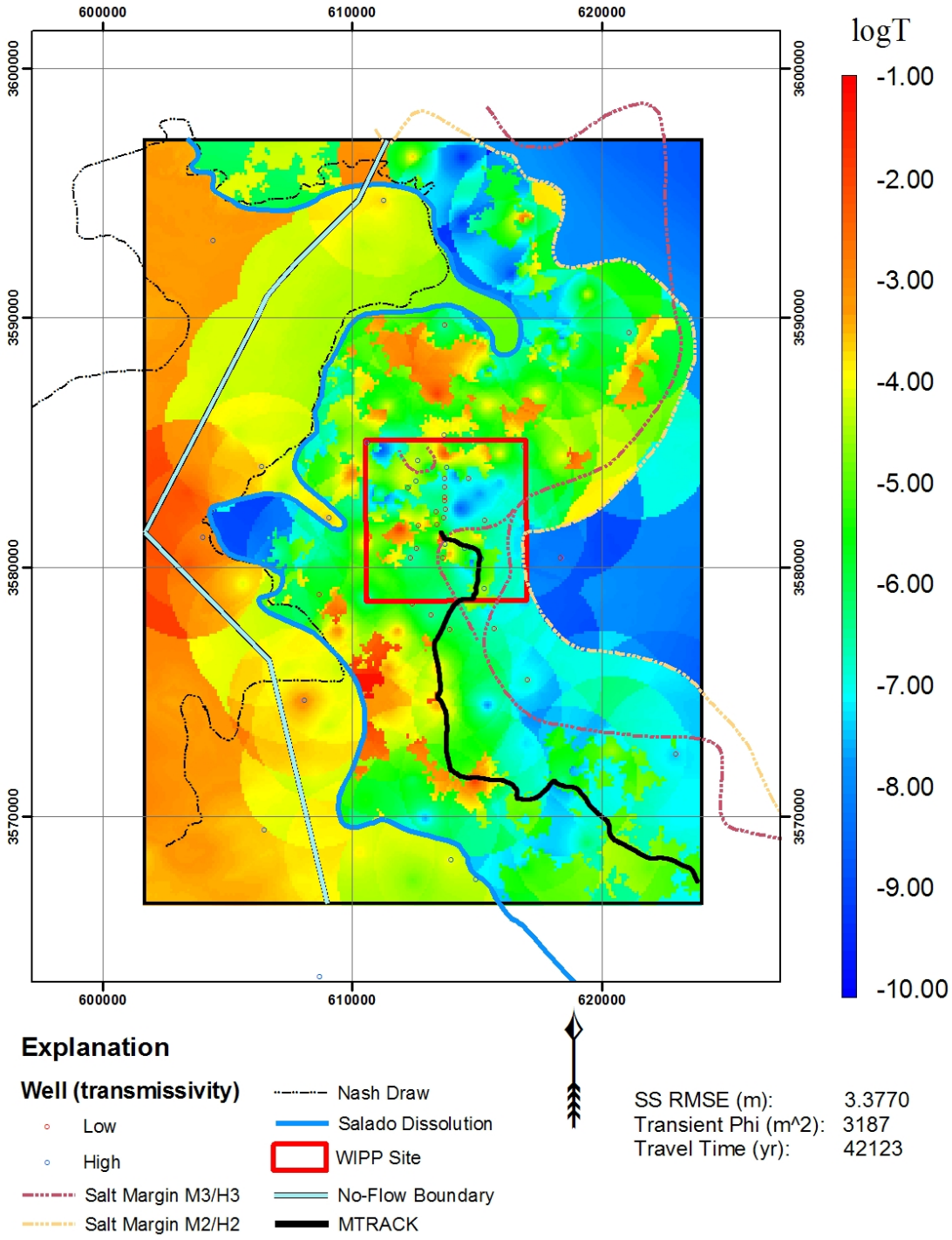

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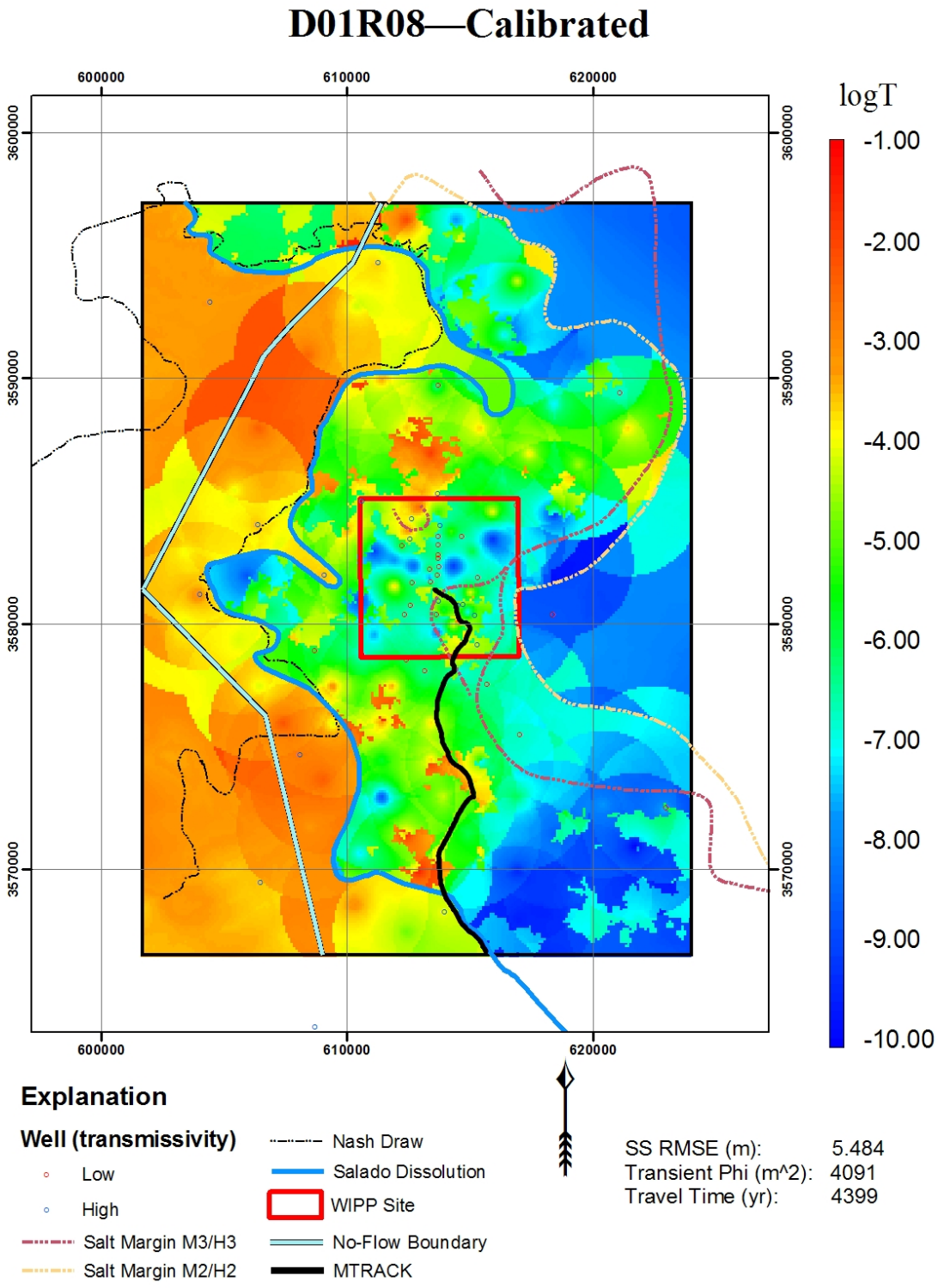
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-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
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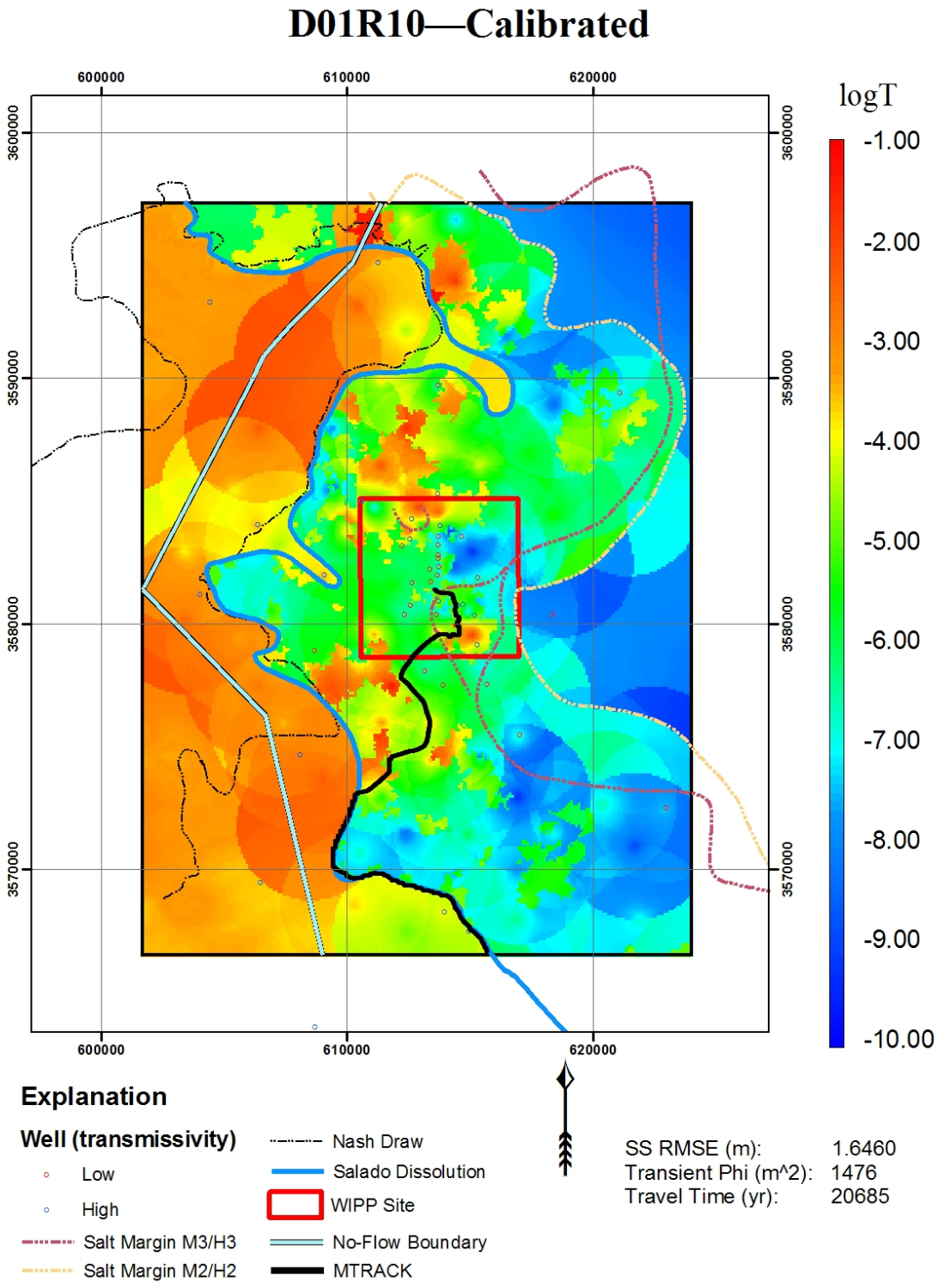
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-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
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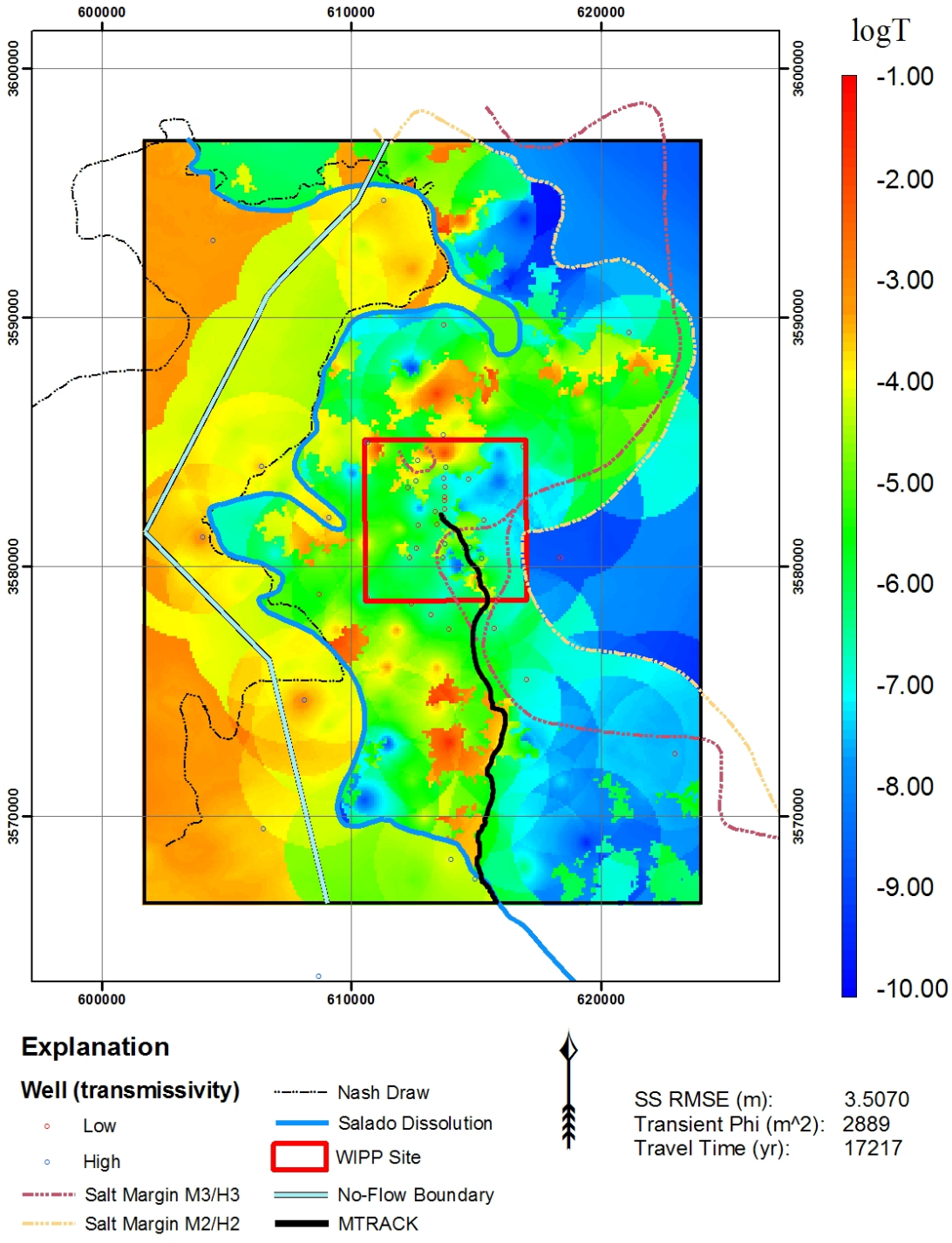

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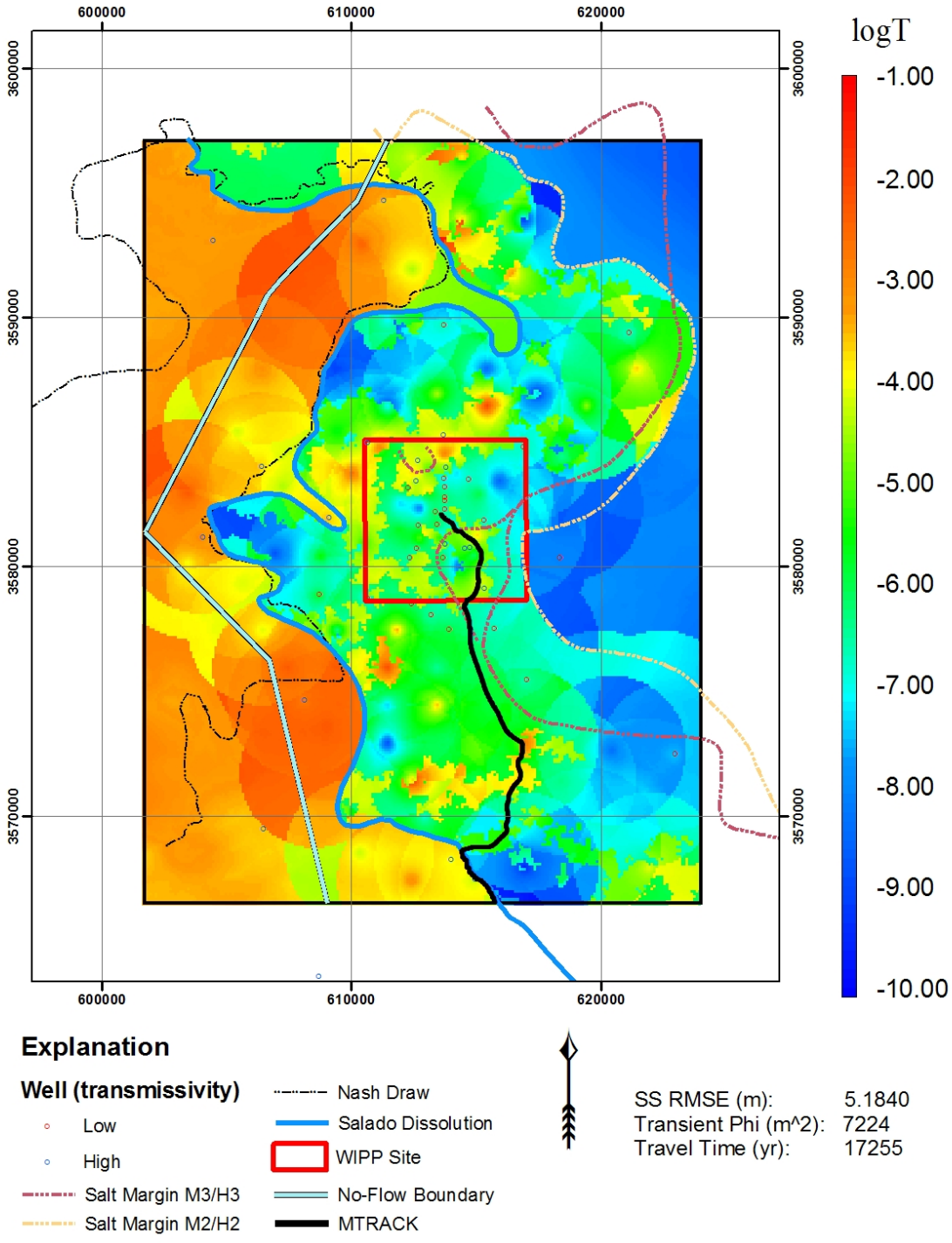

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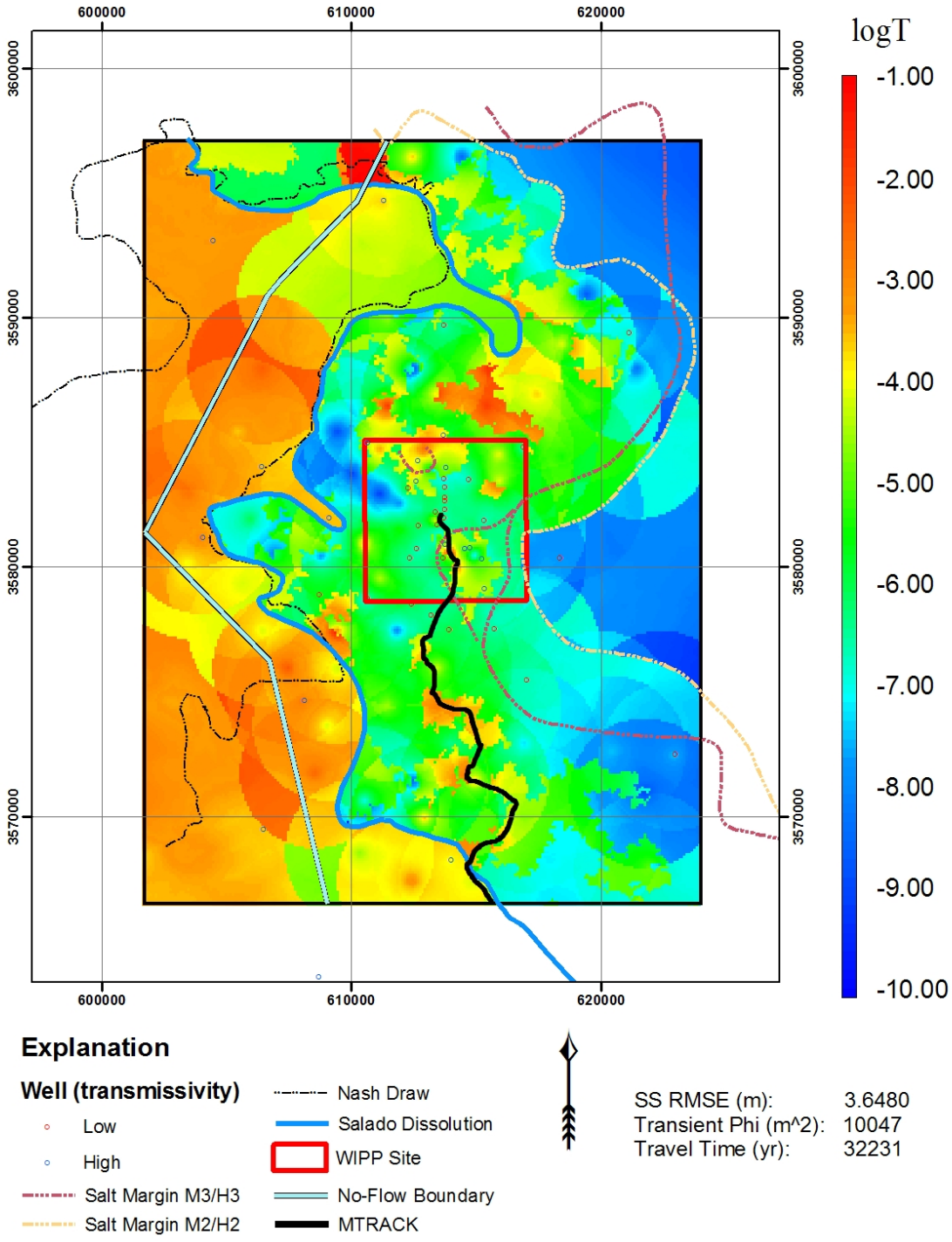

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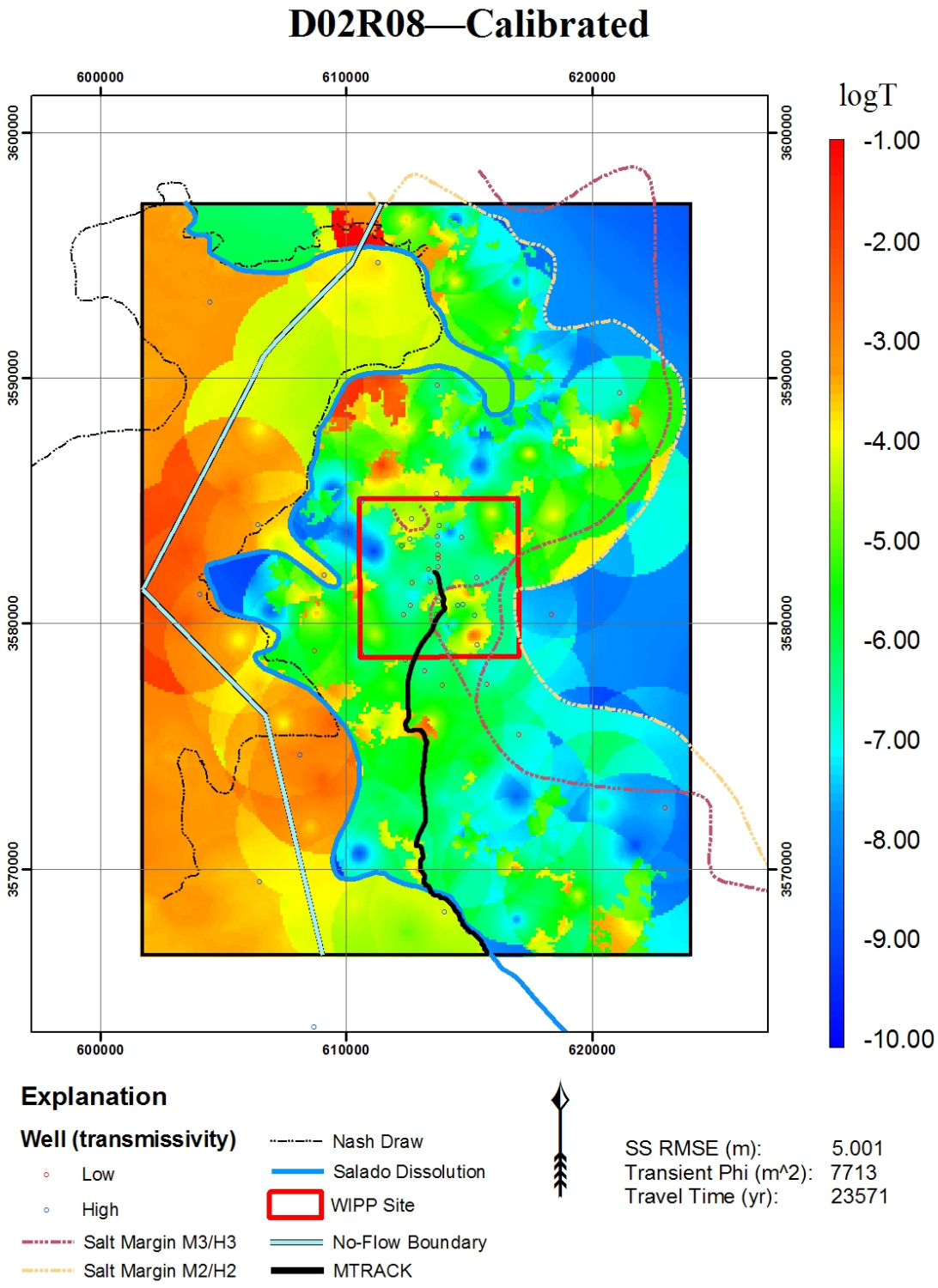
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-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
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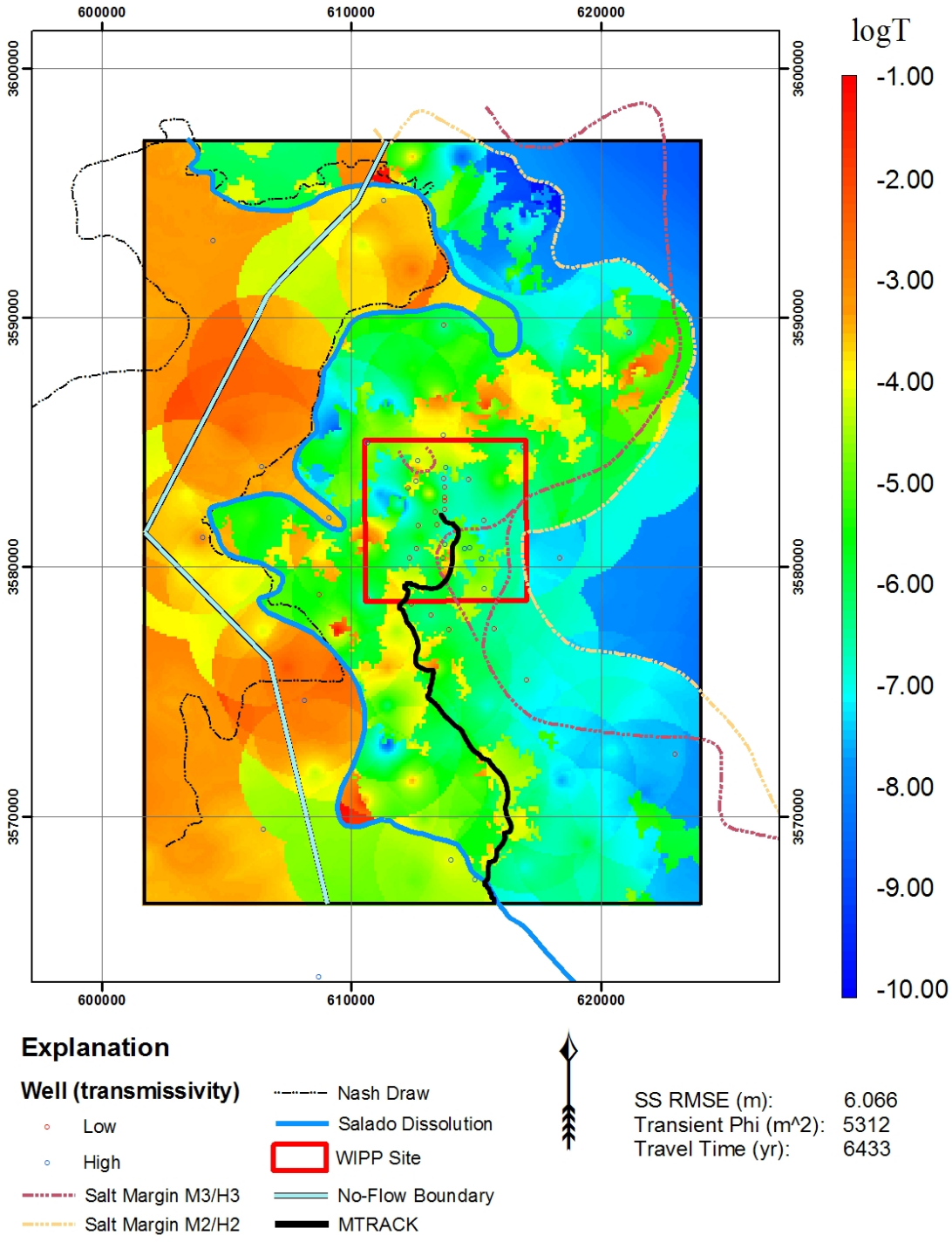

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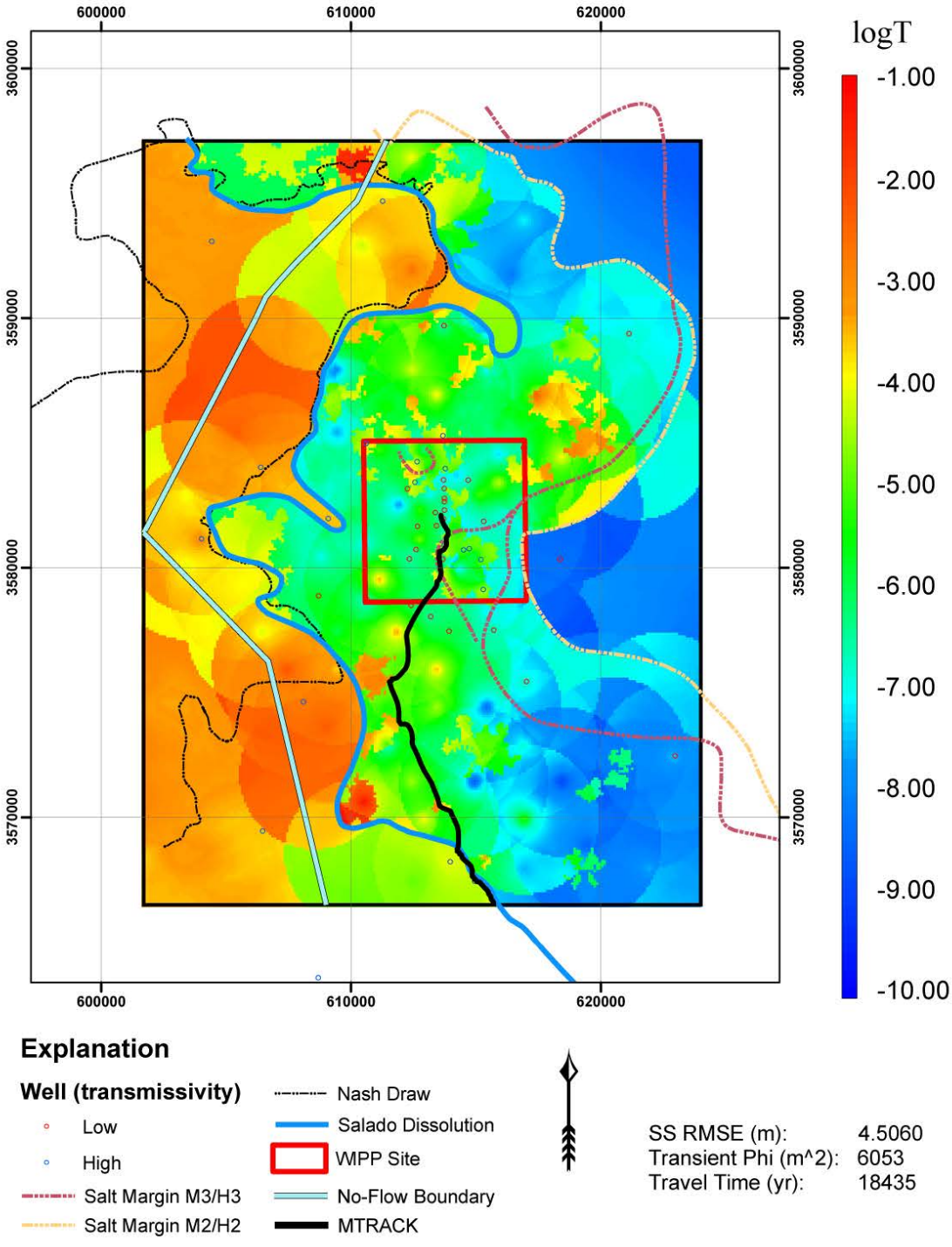

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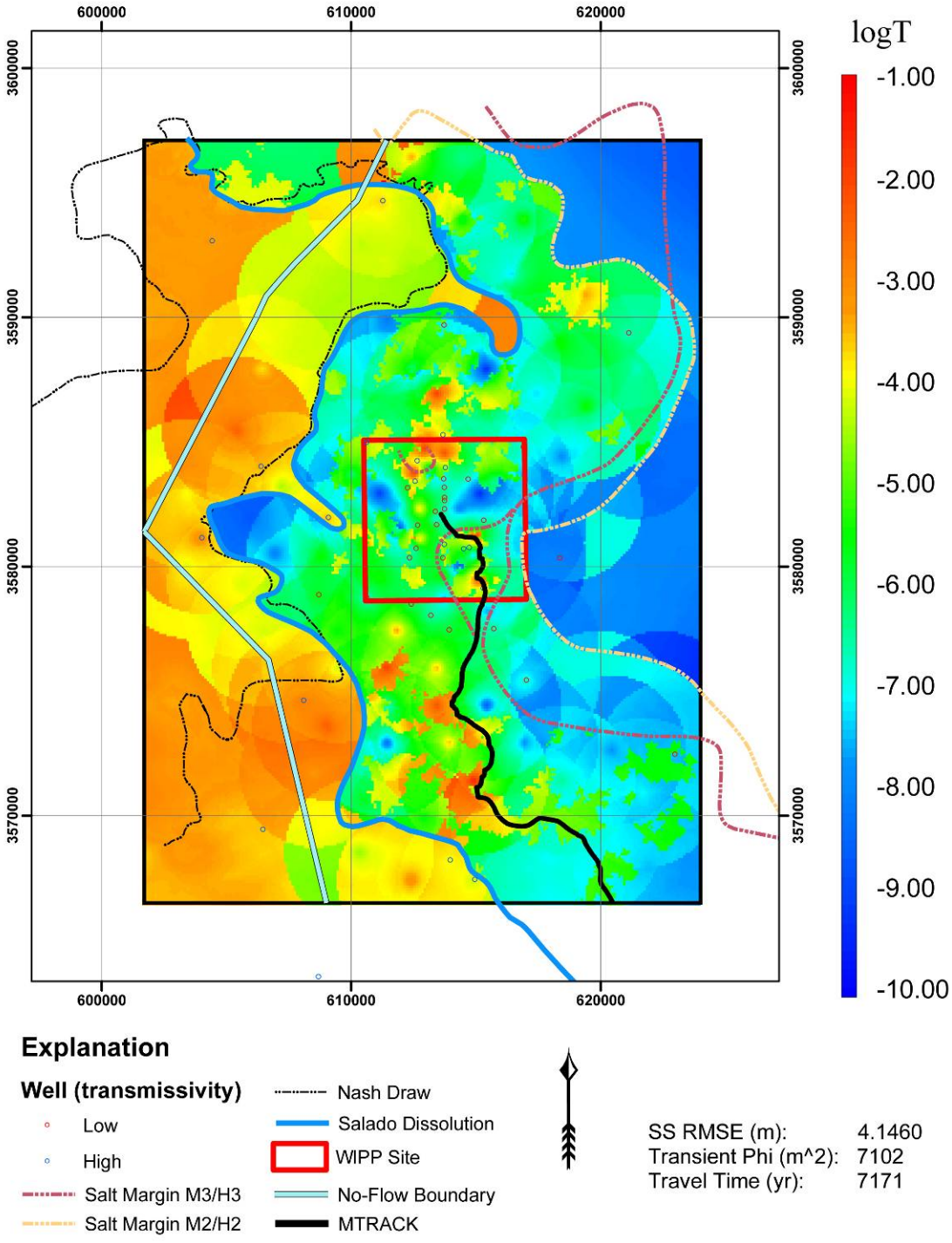
D03R03—Calibrated



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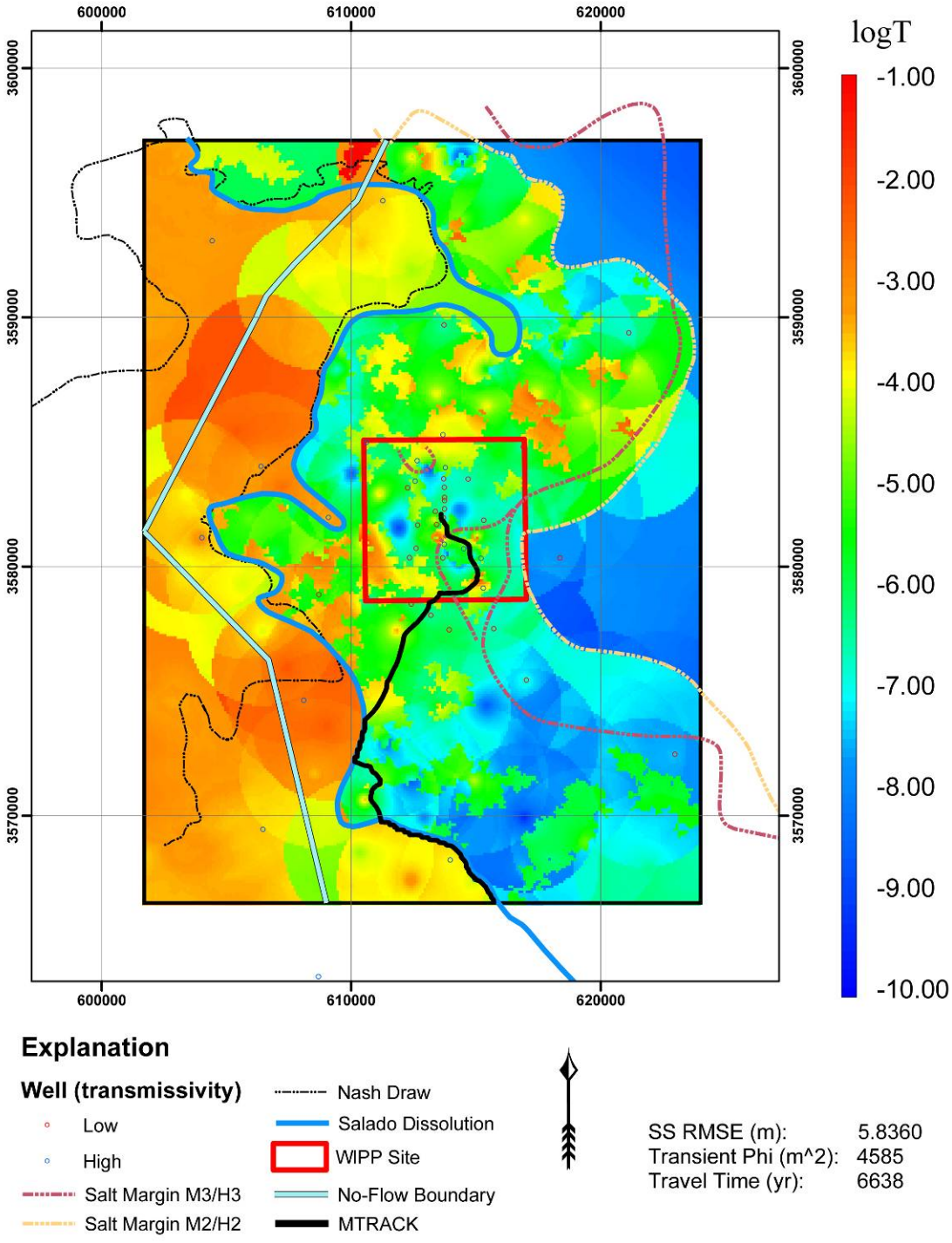

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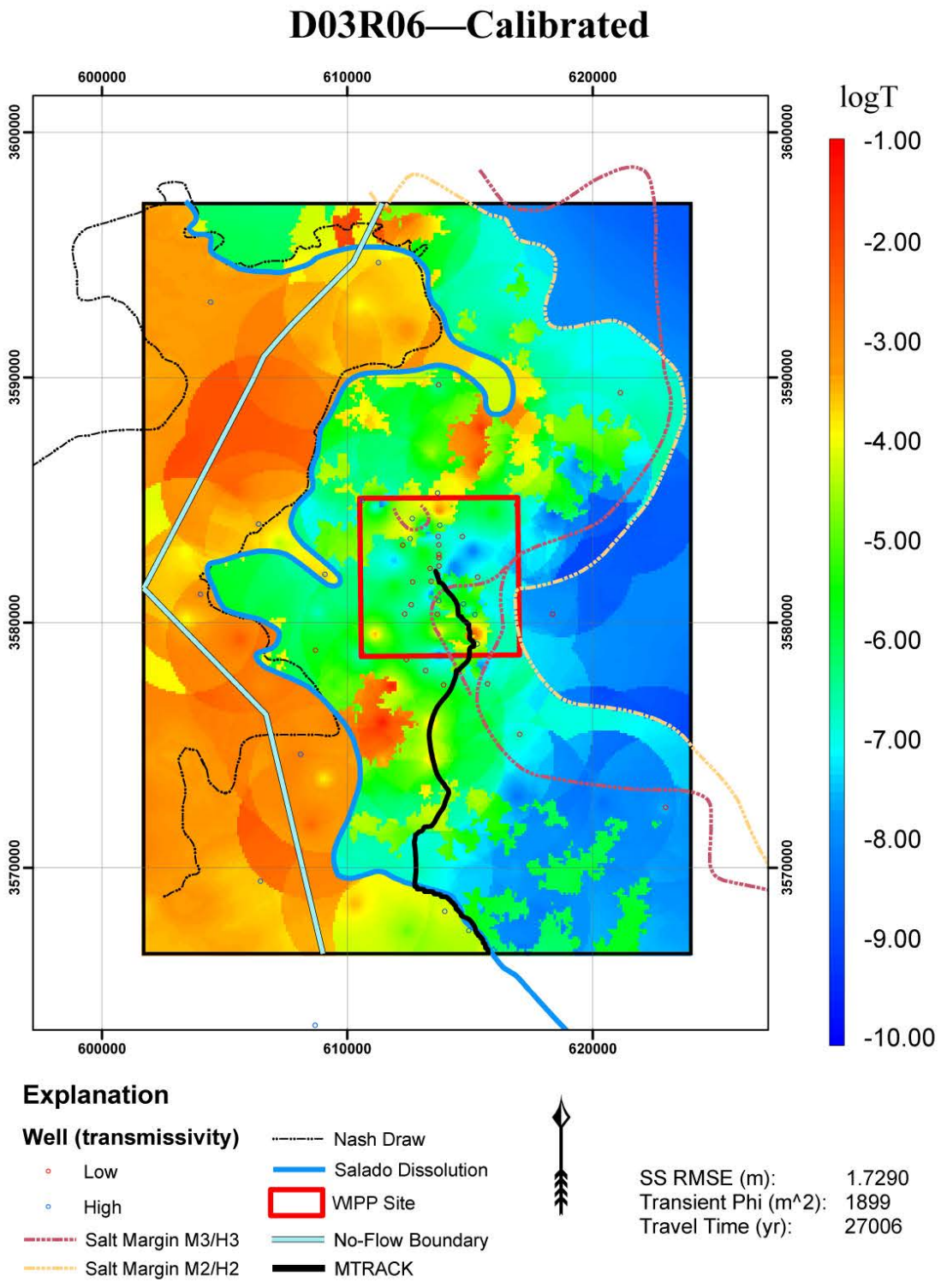
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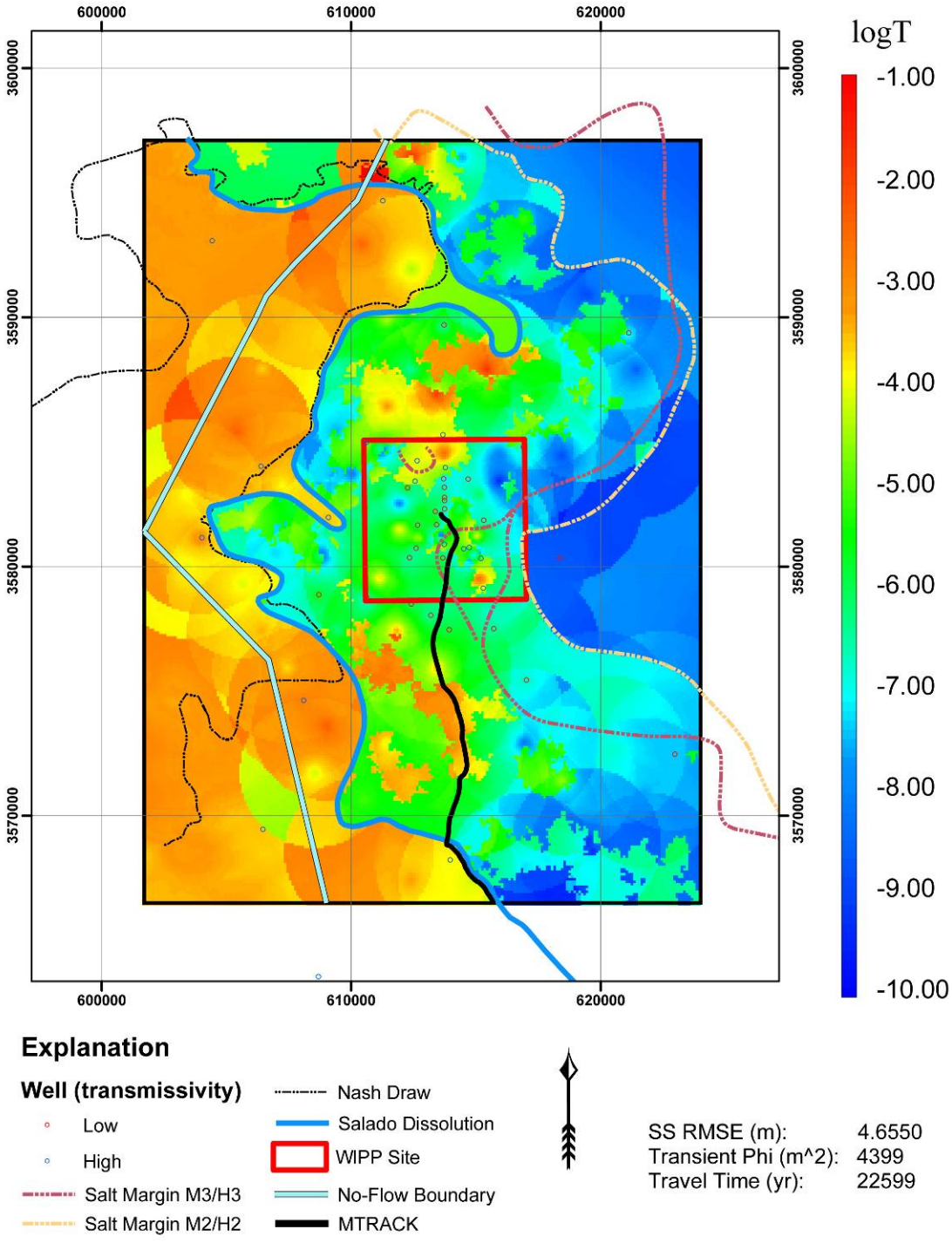
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.7290
Transient Phi (m^2): 1899
Travel Time (yr): 27006

1

D03R07—Calibrated



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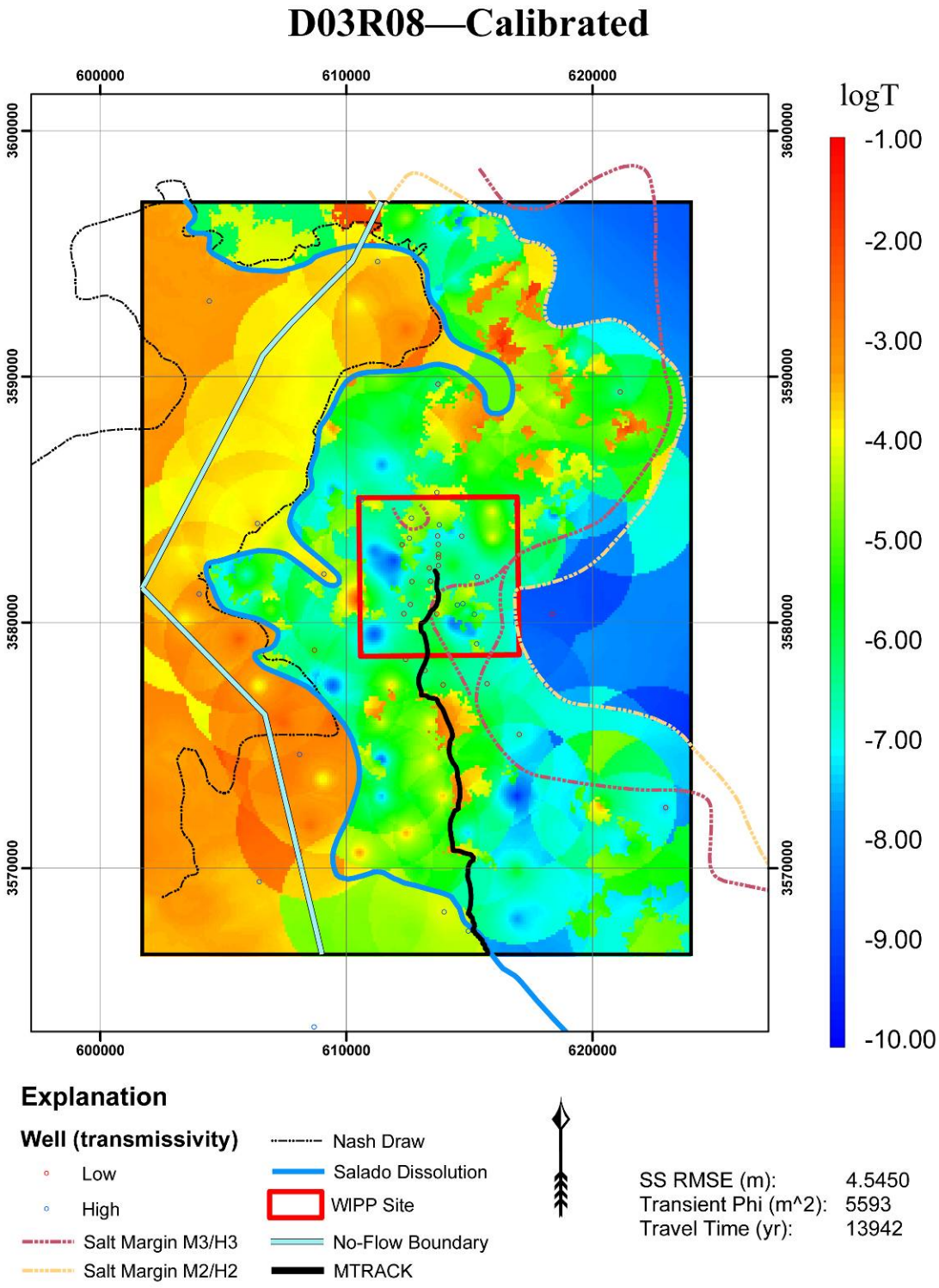
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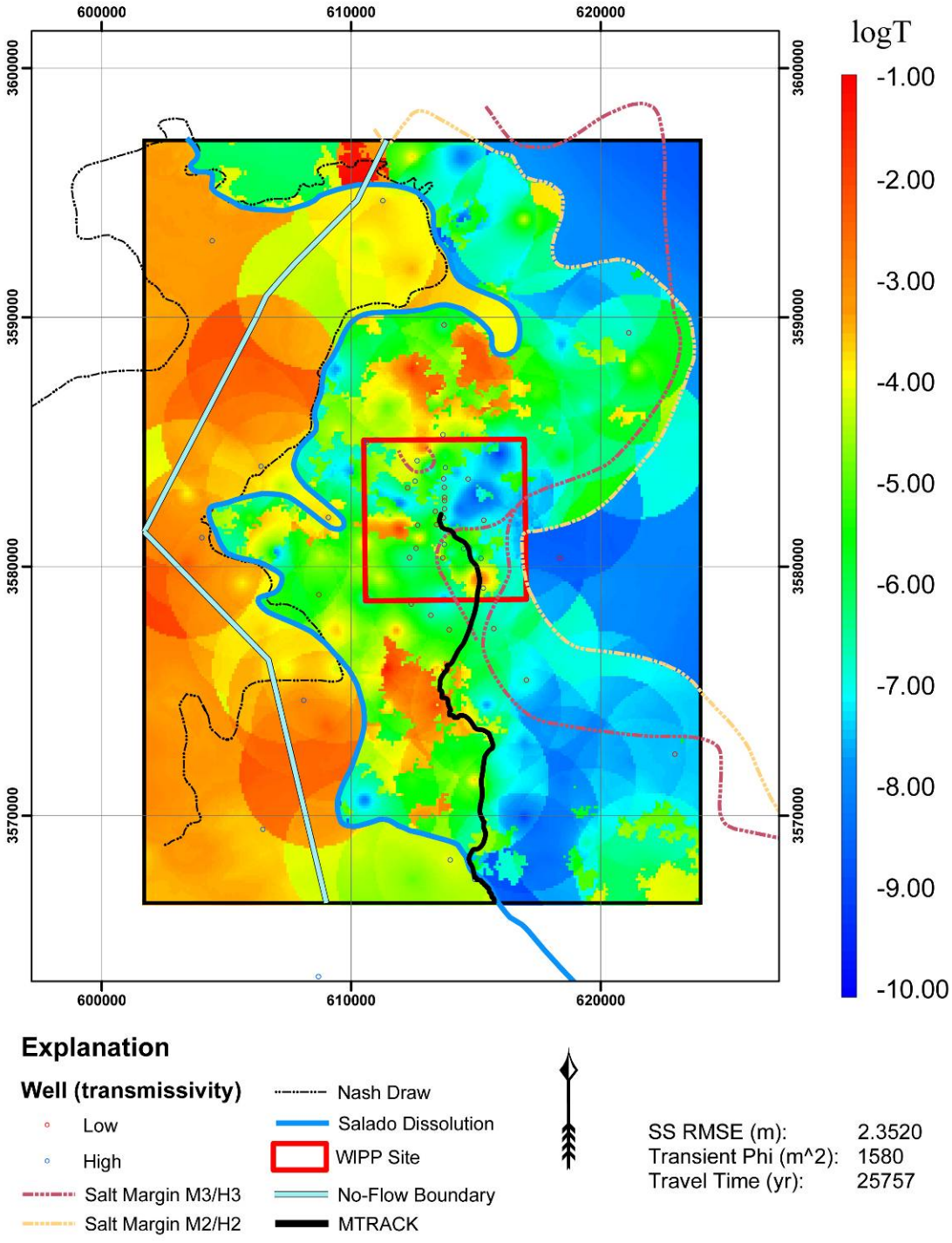
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 4.5450
Transient Phi (m^2): 5593
Travel Time (yr): 13942

1

D03R09—Calibrated



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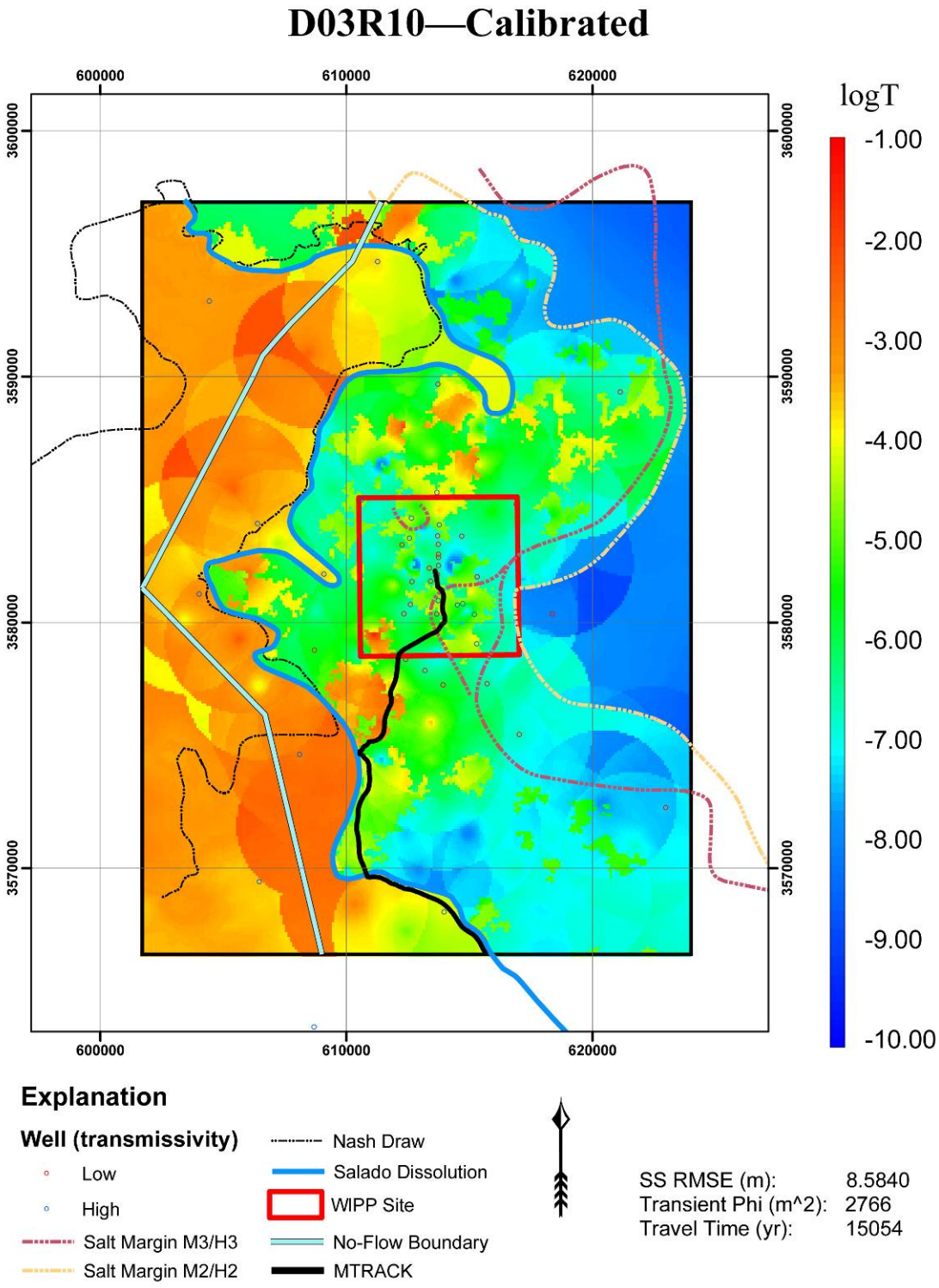
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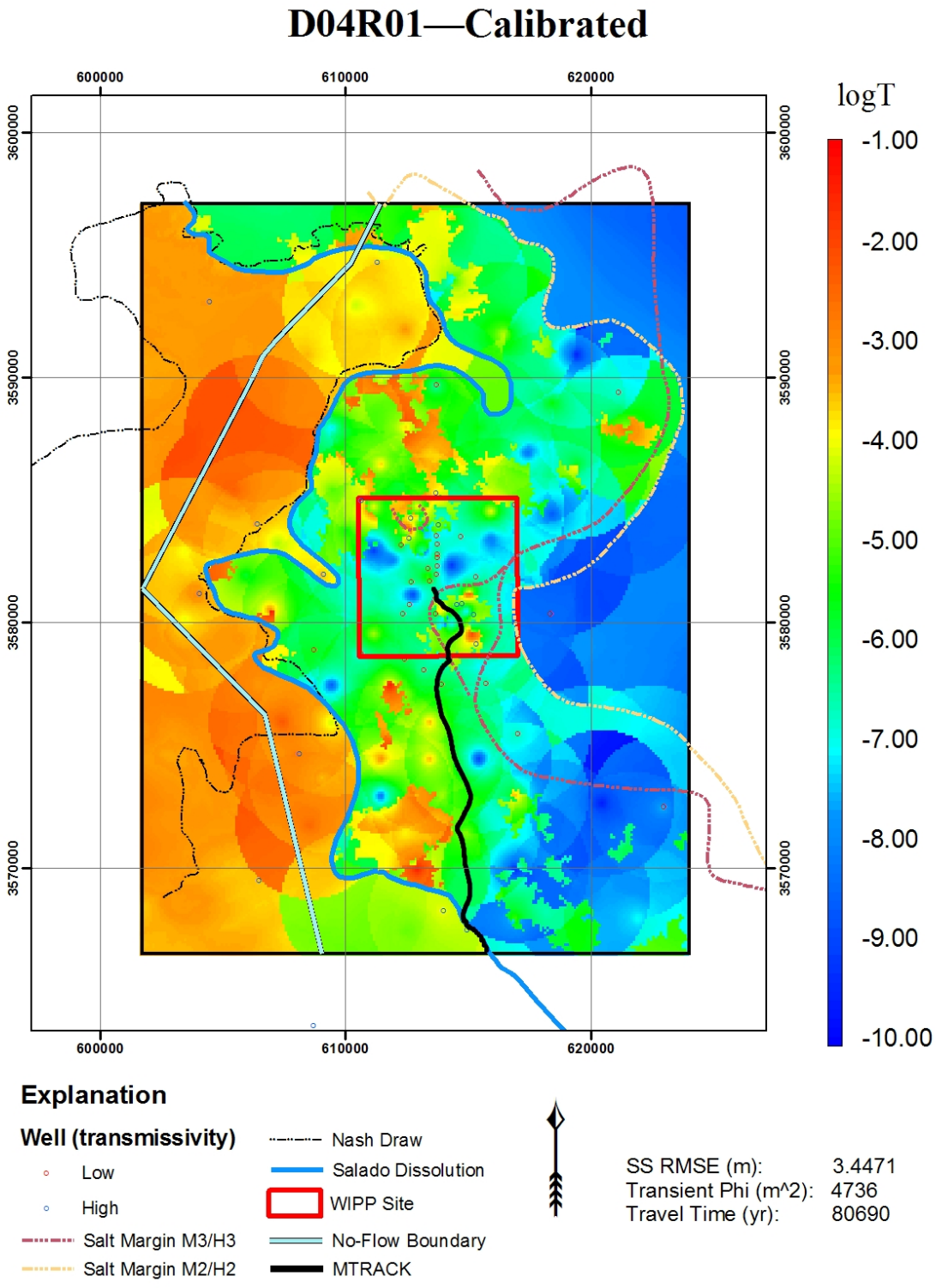
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 8.5840
Transient Phi (m^2): 2766
Travel Time (yr): 15054

1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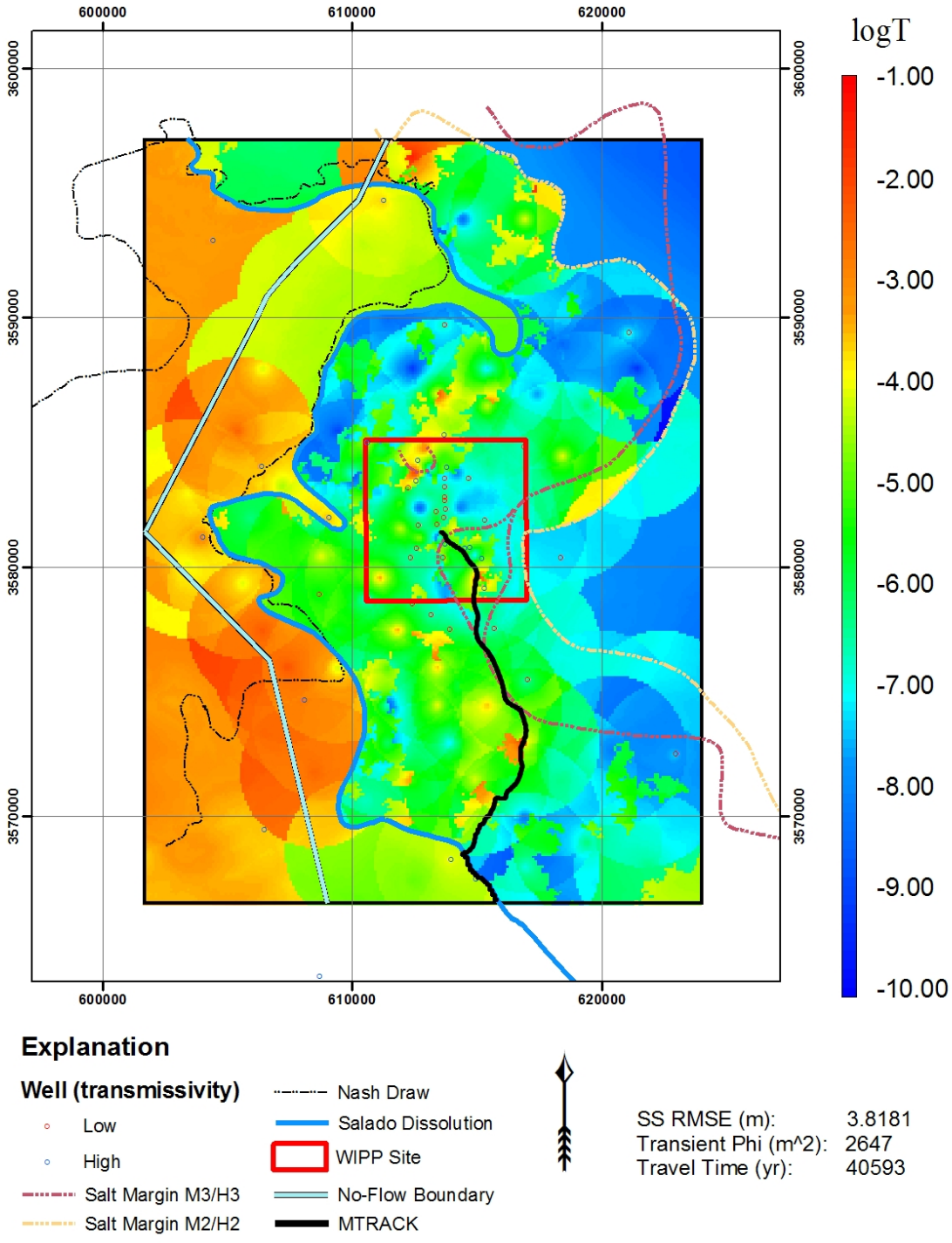
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.4471
Transient Phi (m^2): 4736
Travel Time (yr): 80690

1

D04R02—Calibrated



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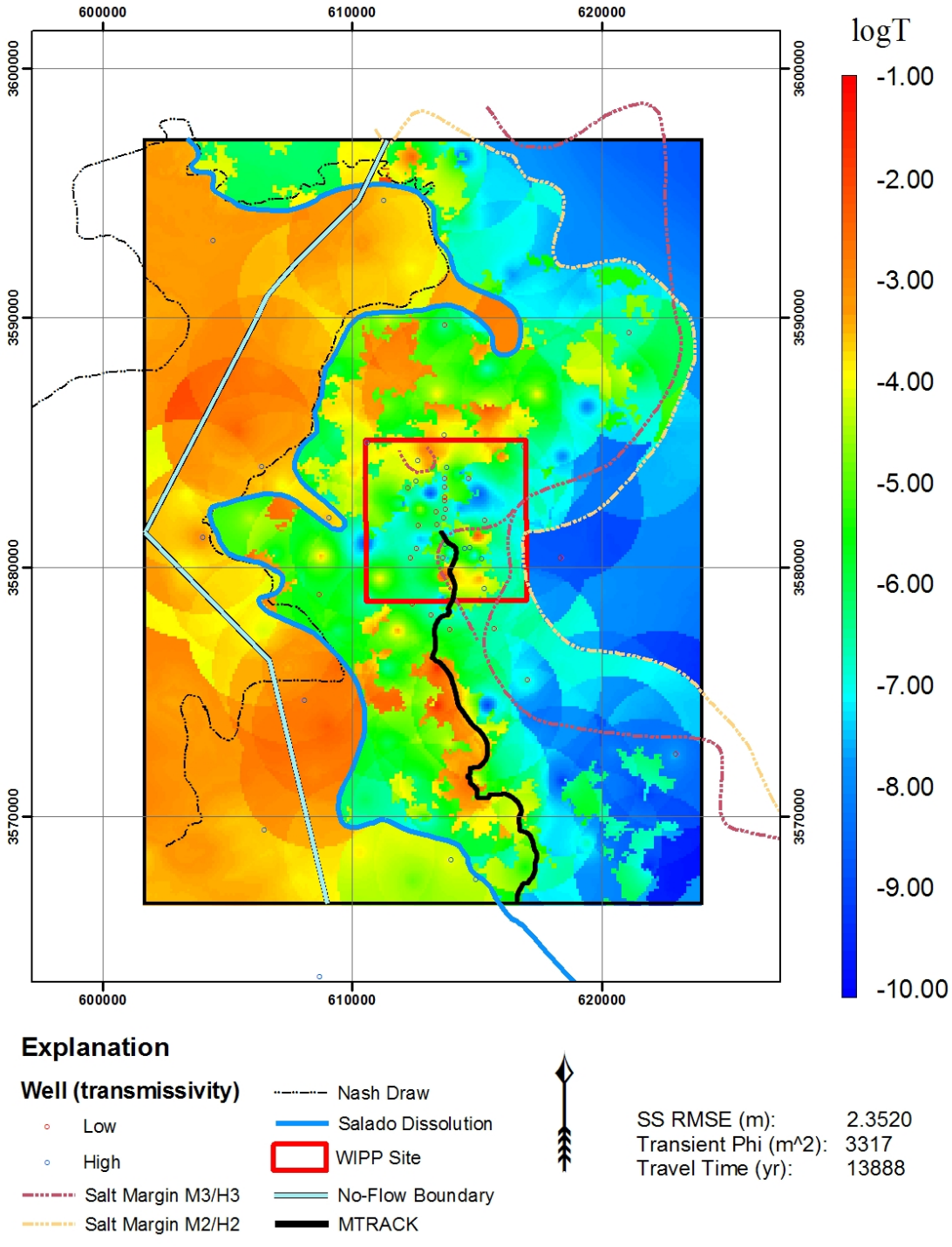

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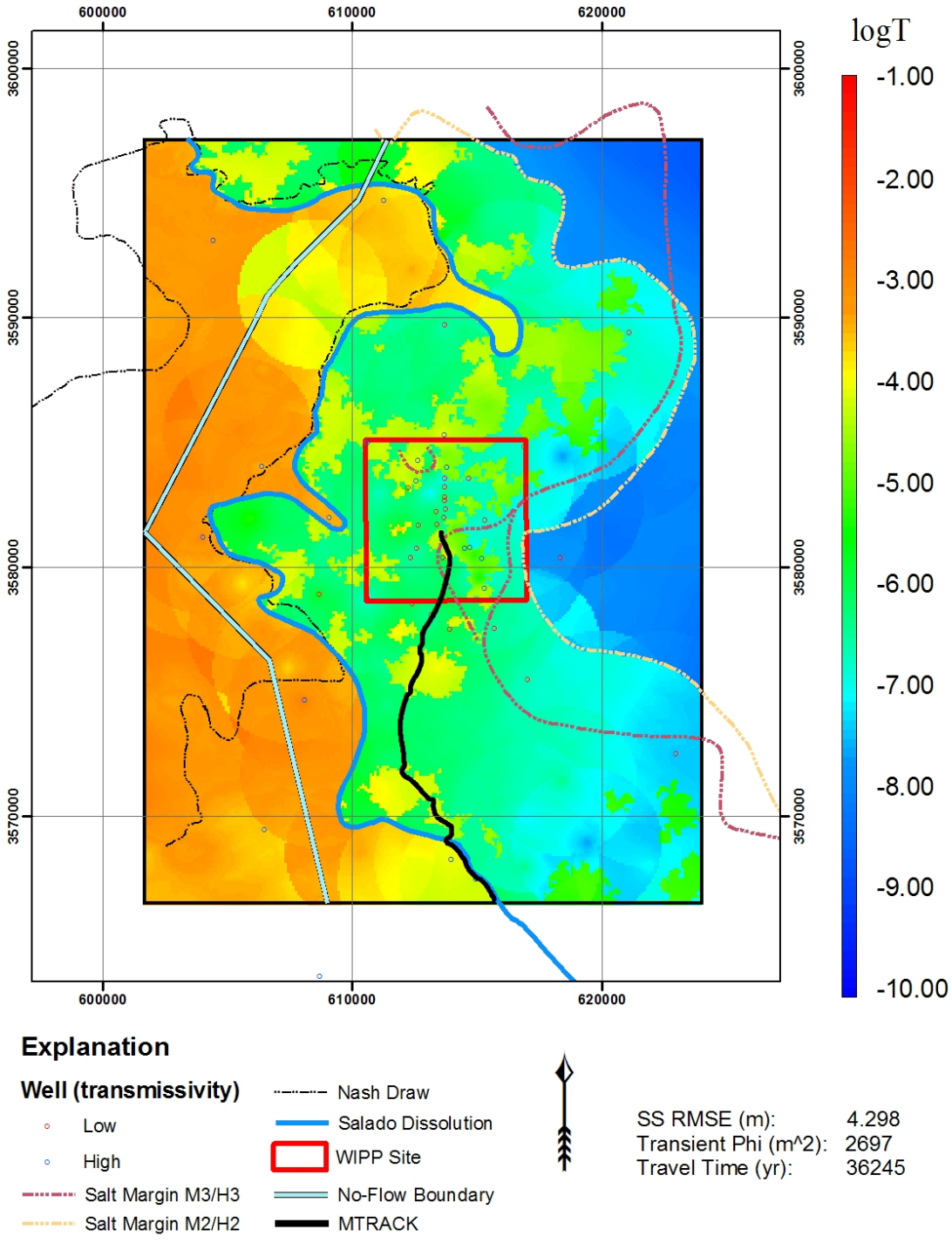

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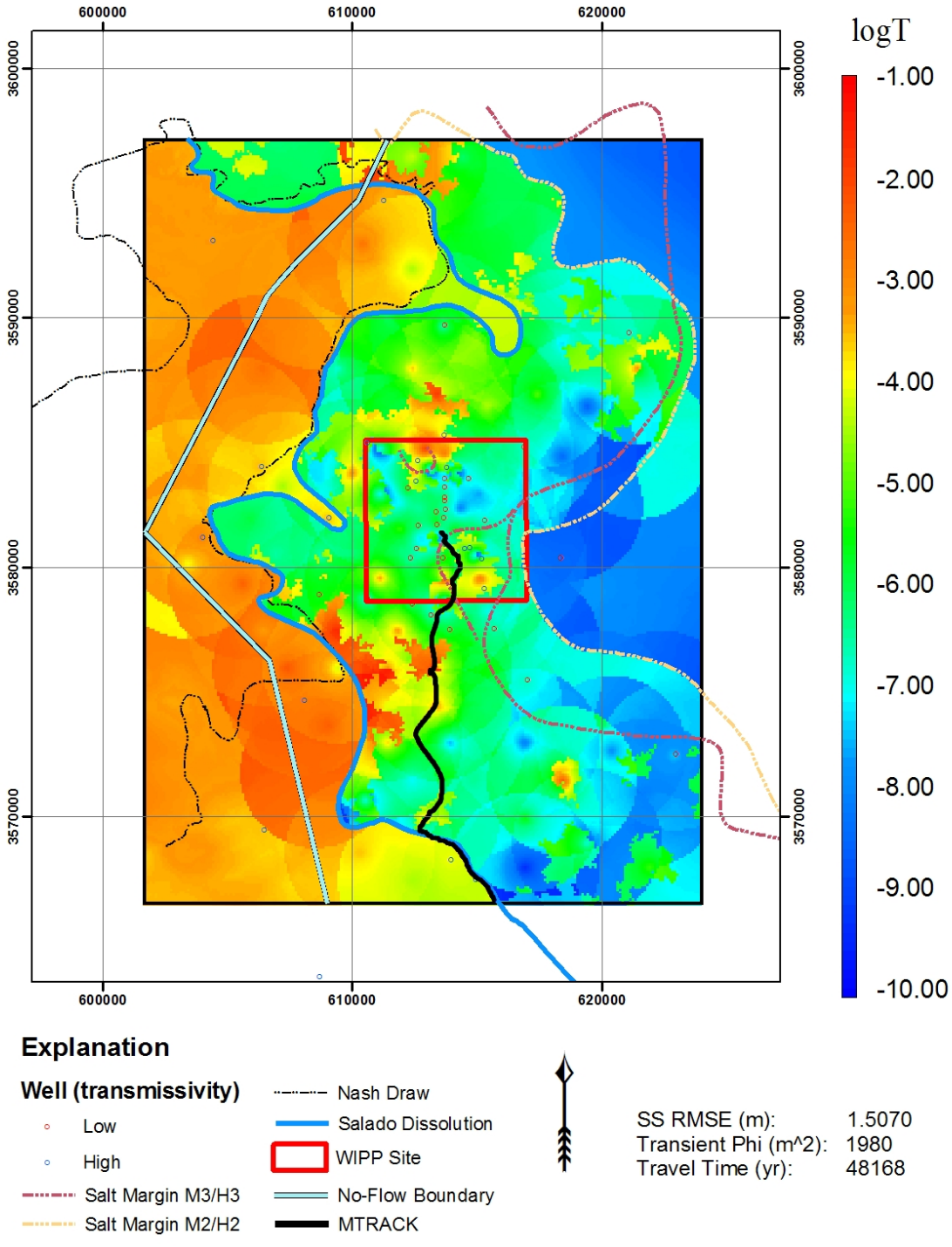

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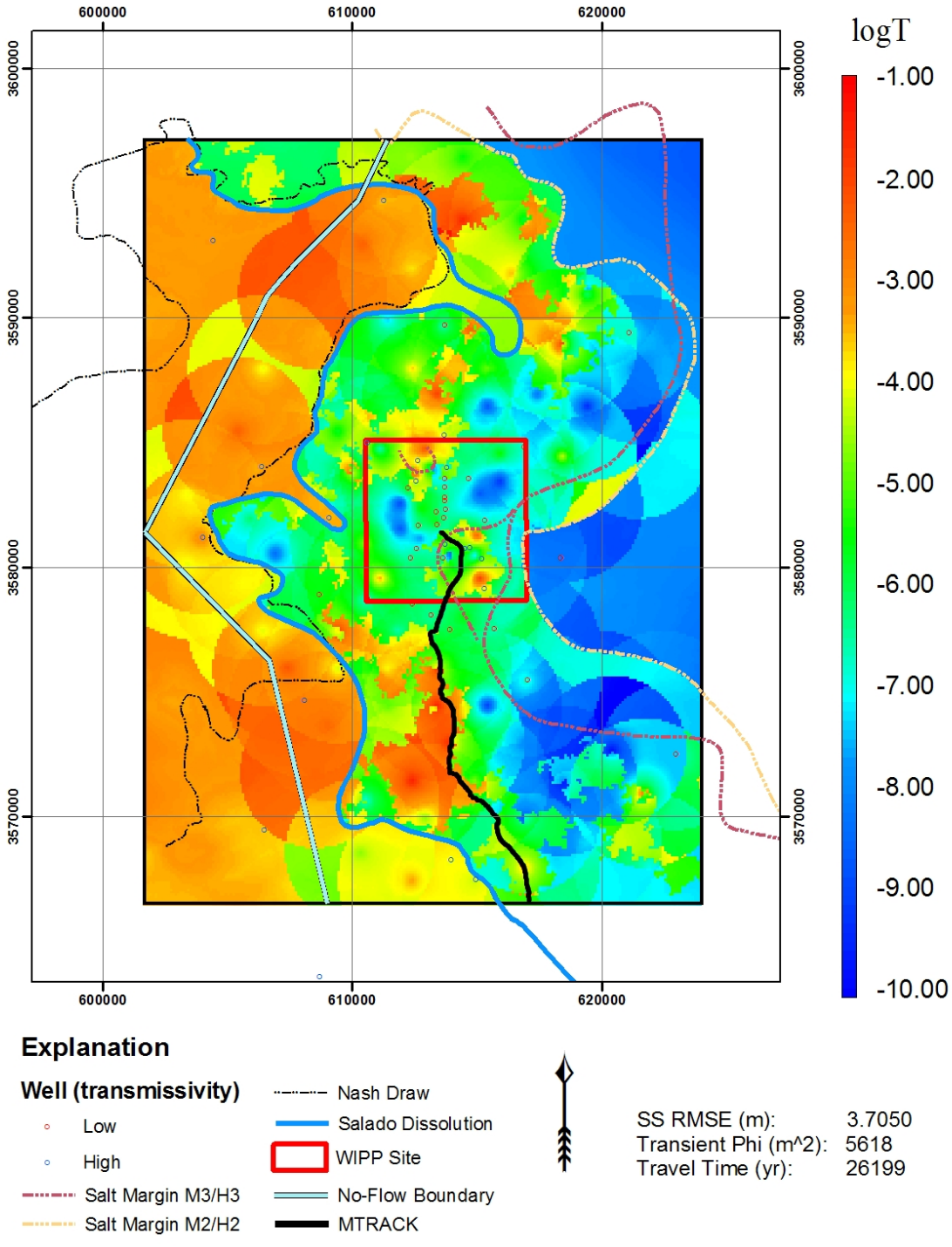
D04R06—Calibrated



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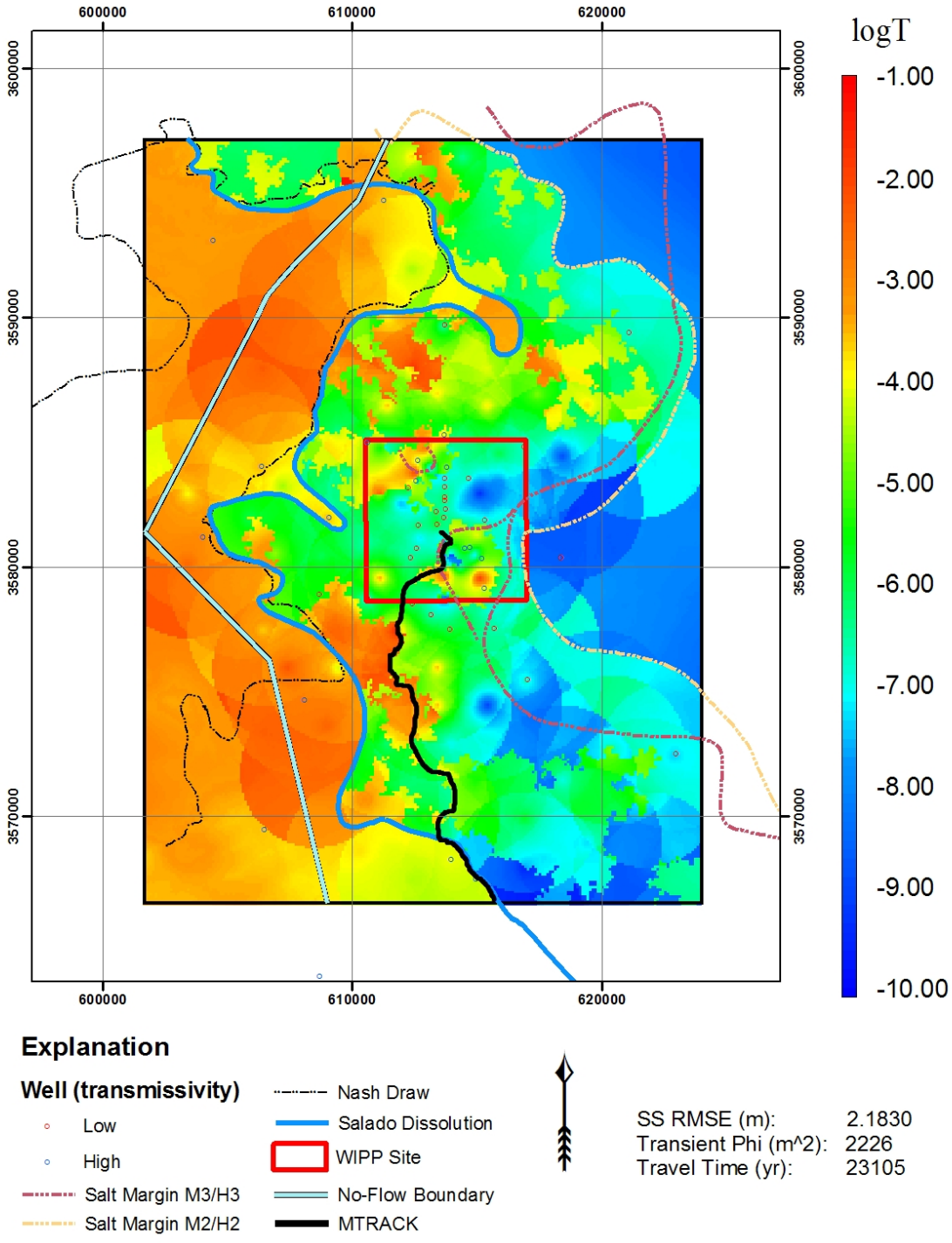
D04R07—Calibrated



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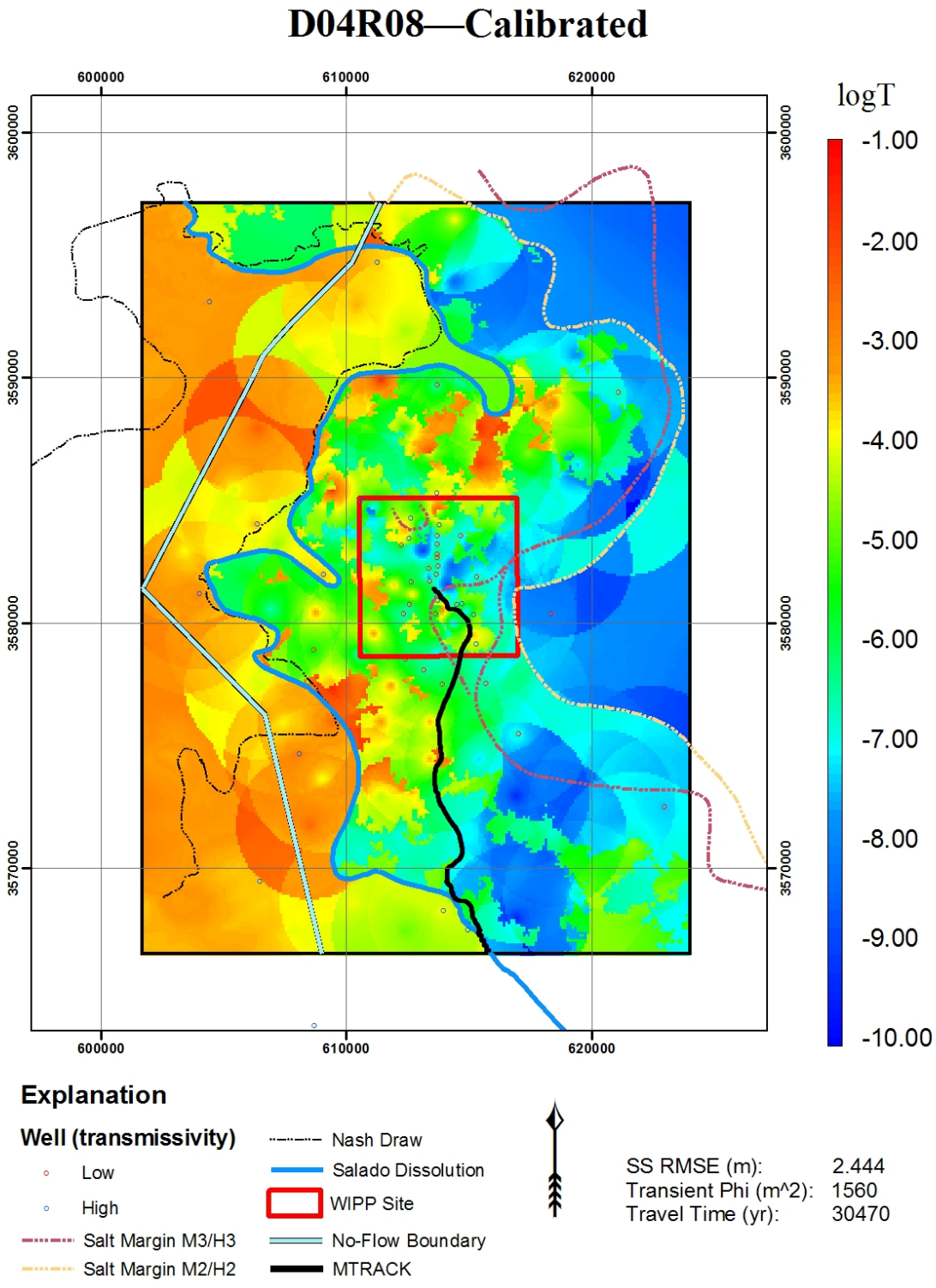
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-6.00
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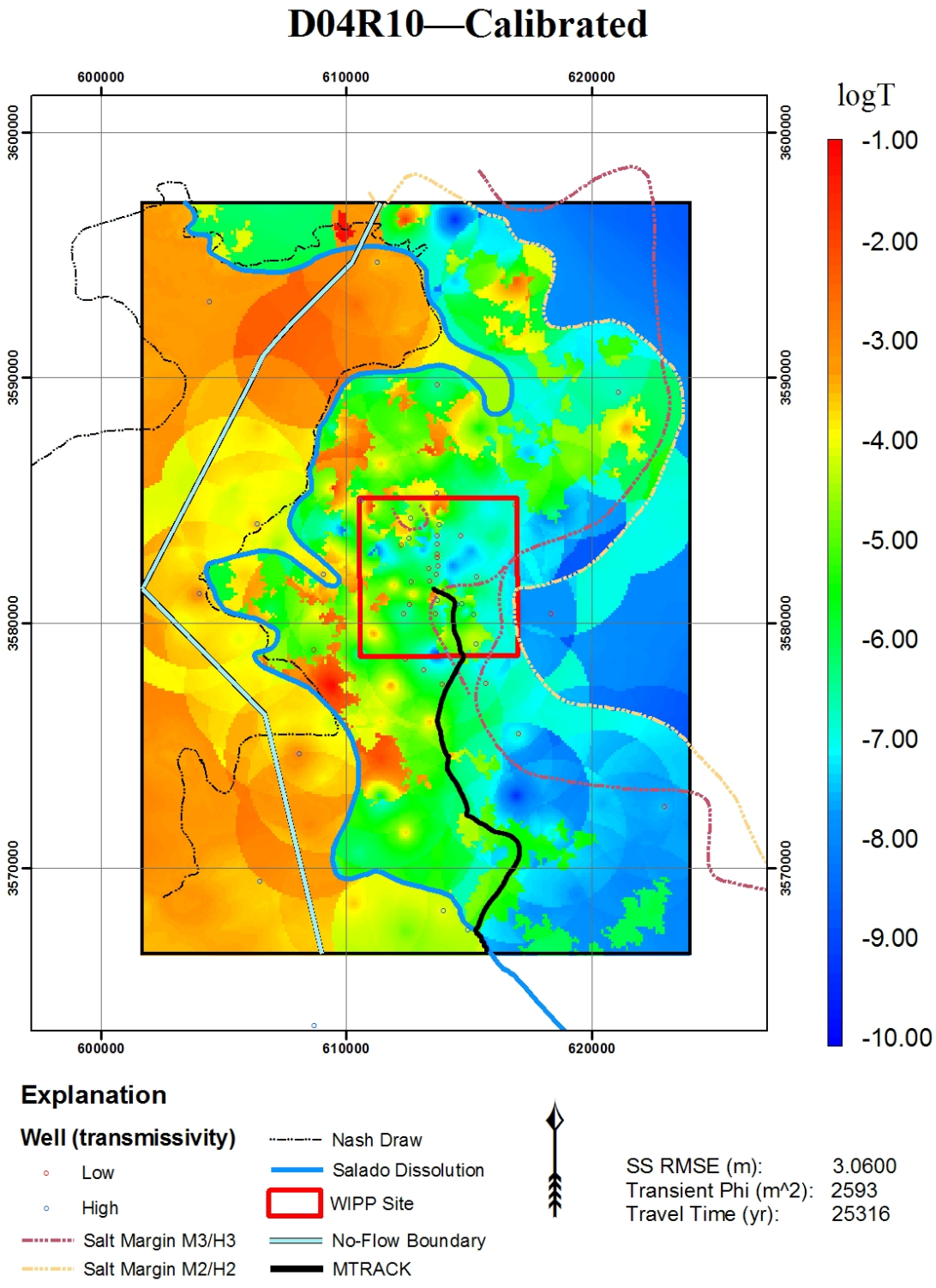
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.444
Transient Phi (m^2): 1560
Travel Time (yr): 30470

1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-6.00
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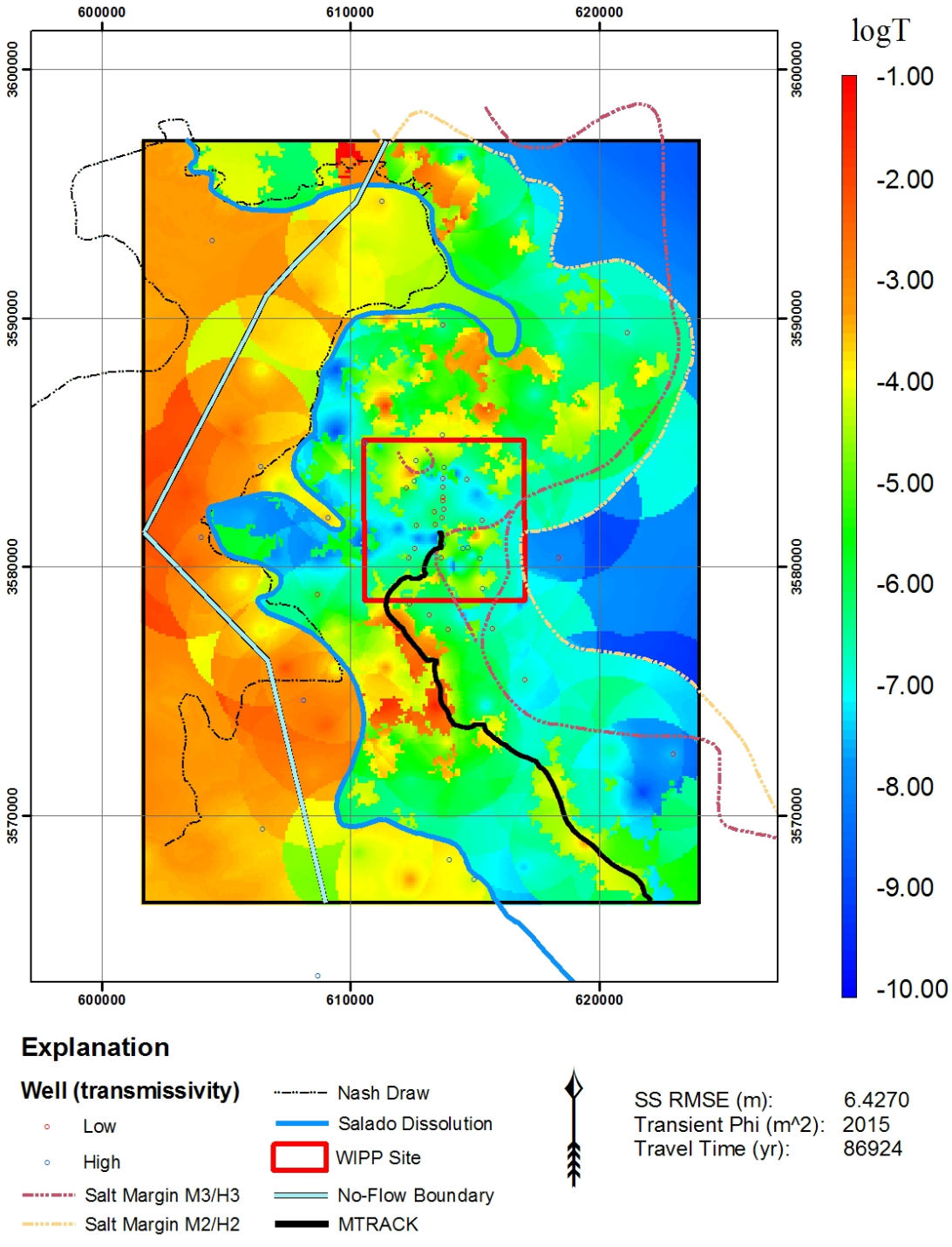
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.0600
Transient Phi (m^2): 2593
Travel Time (yr): 25316

1

D05R01—Calibrated



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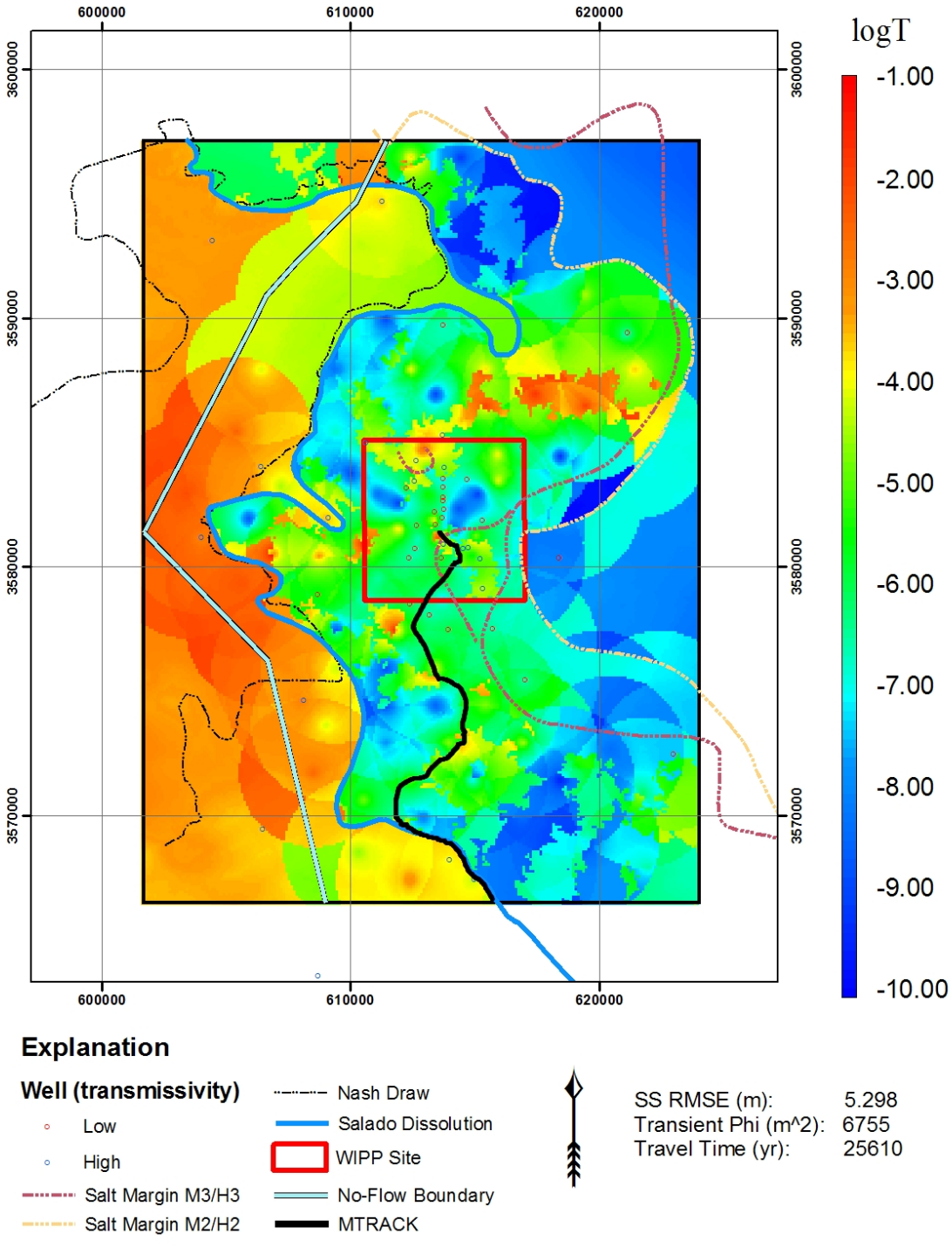
D05R02—Calibrated



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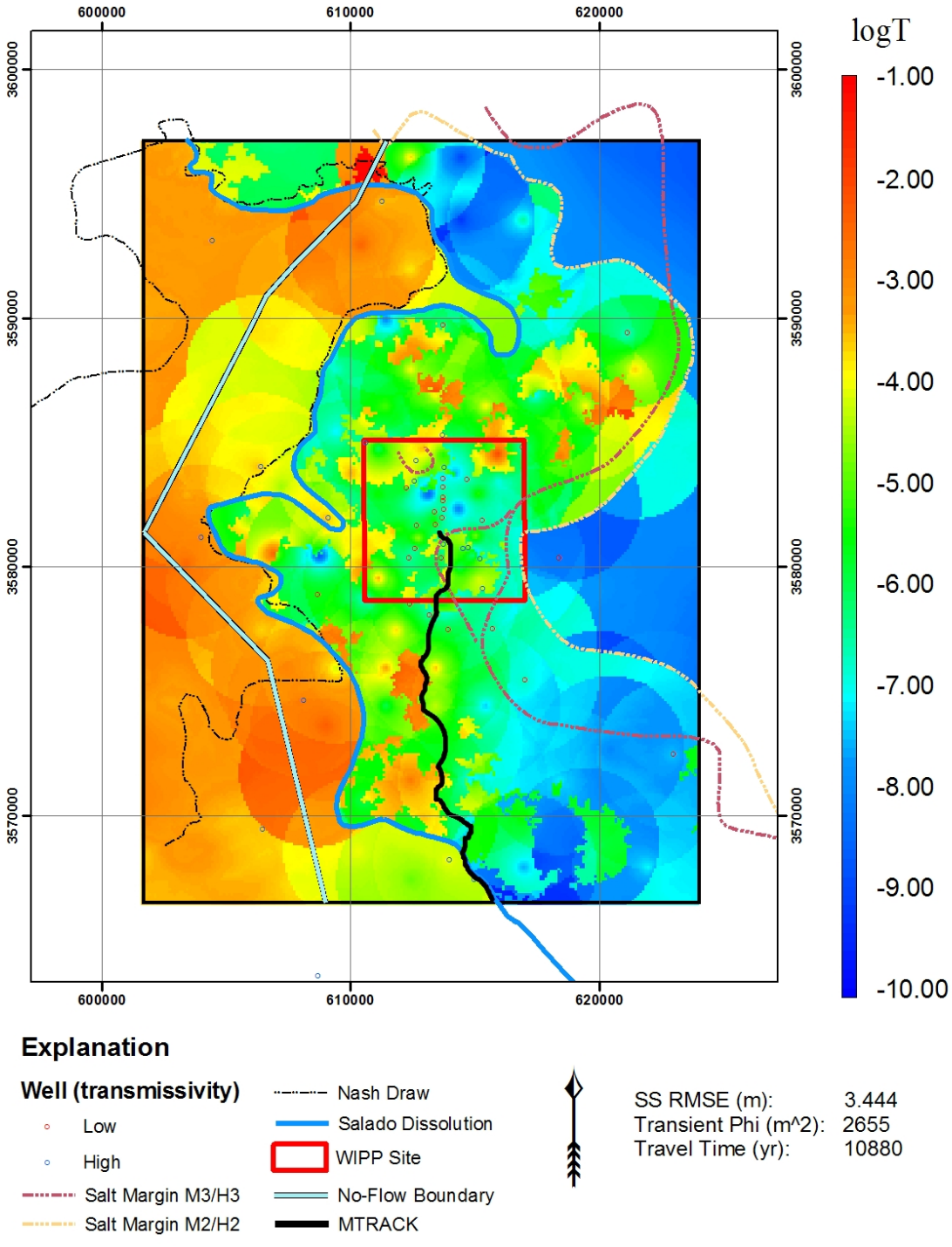
D05R03—Calibrated



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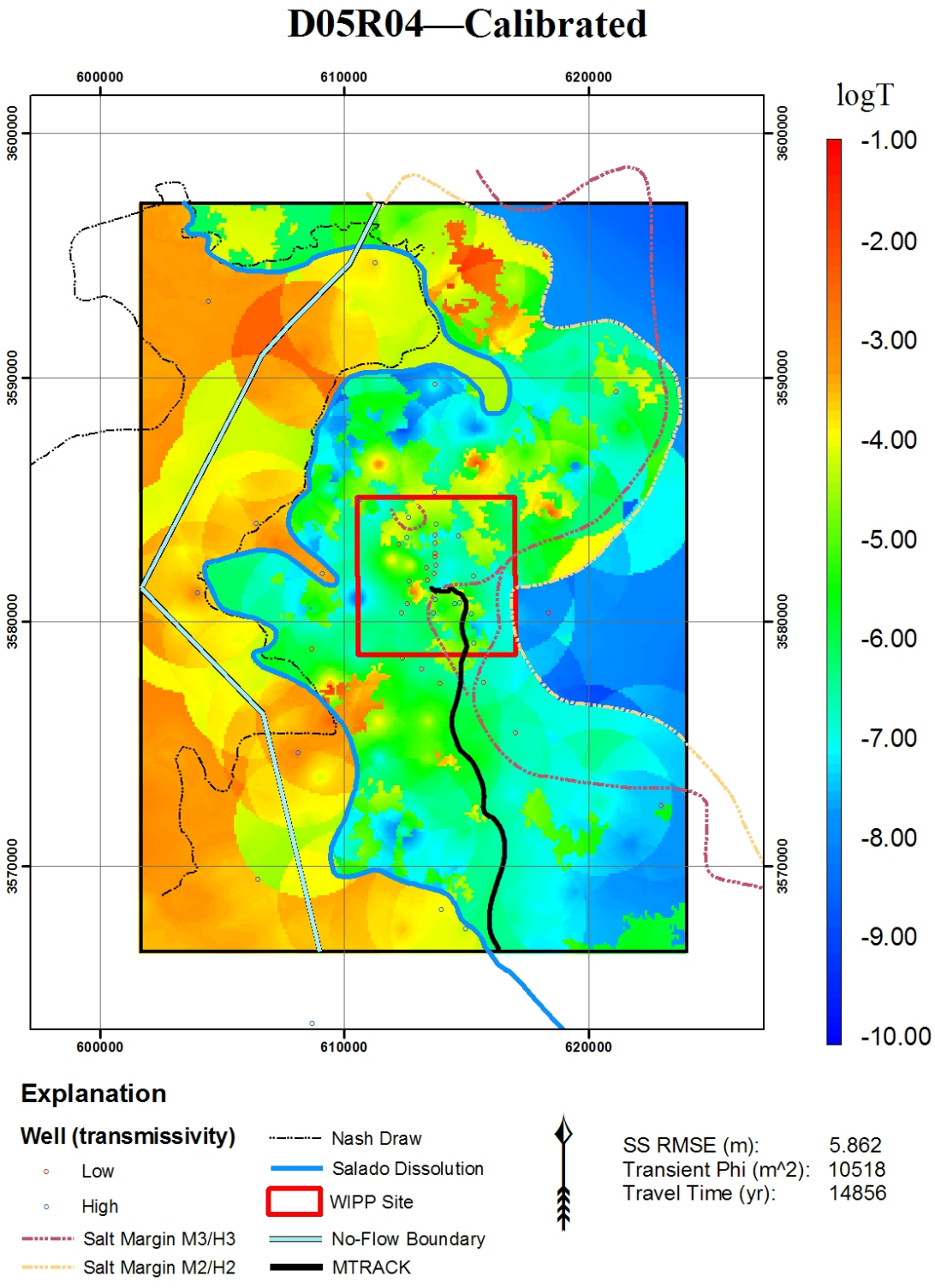
D05R04—Calibrated
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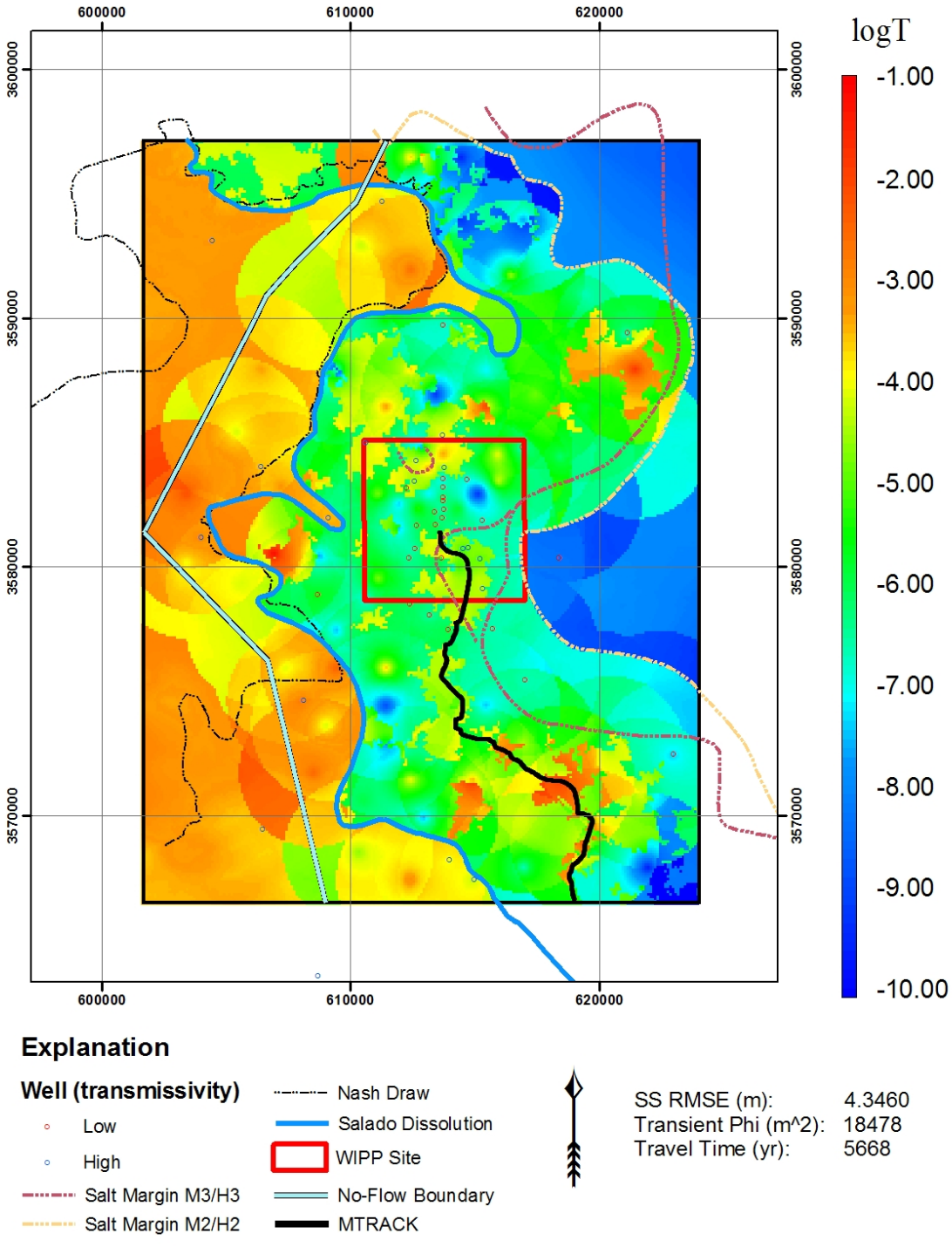
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.862
Transient Phi (m^2): 10518
Travel Time (yr): 14856

1

D05R05—Calibrated



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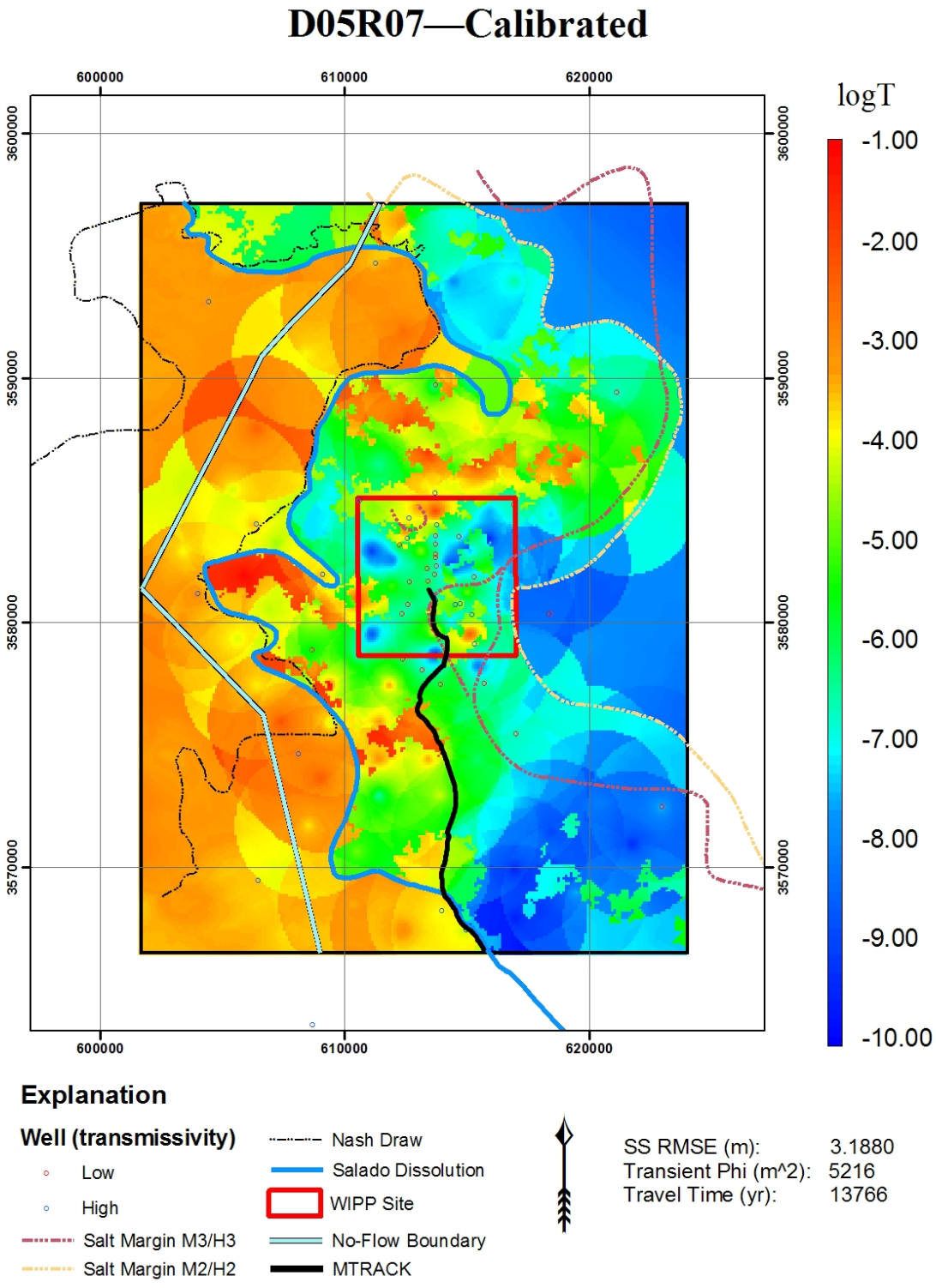
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-2.00
-3.00
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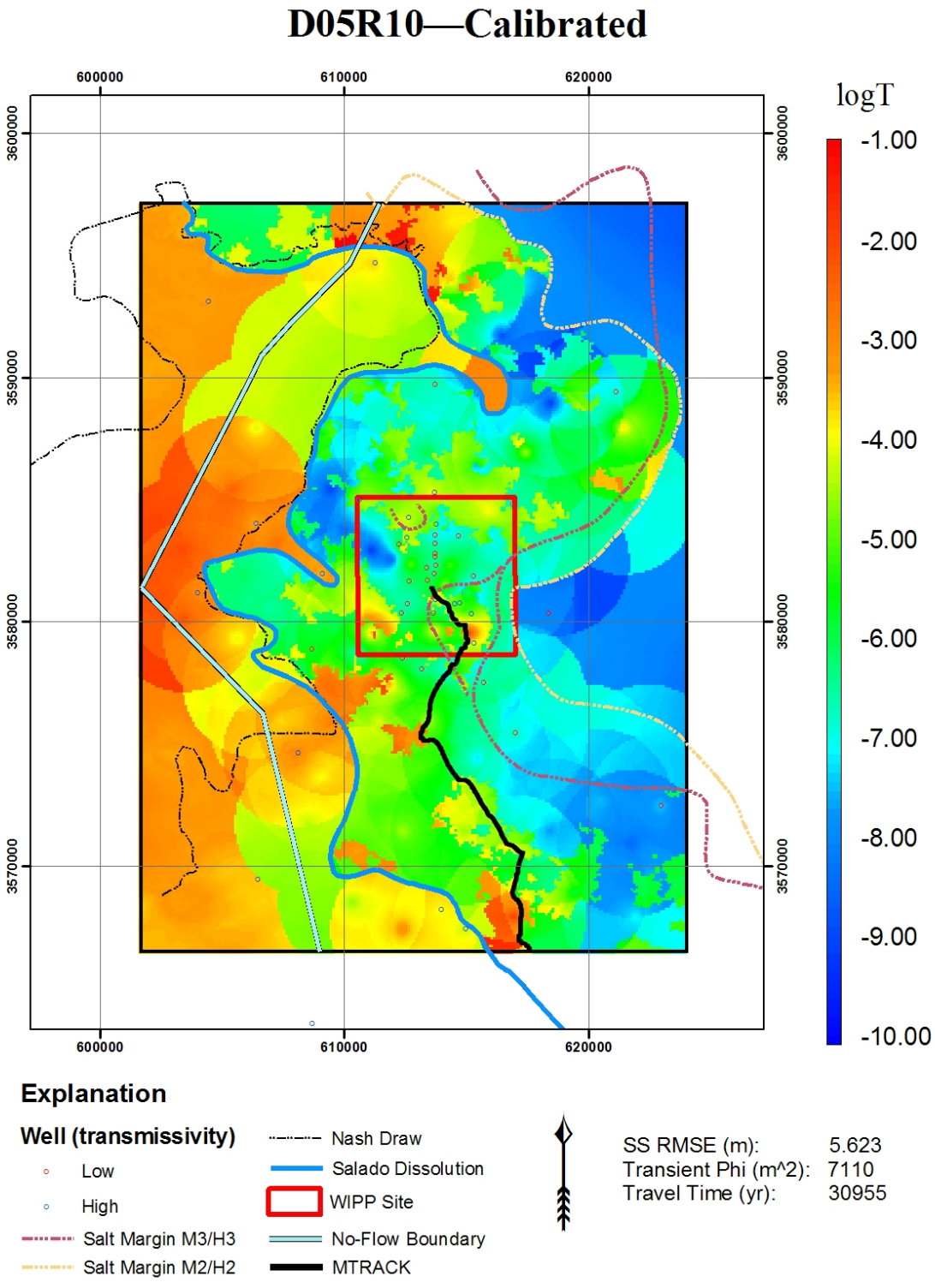
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.1880
Transient Phi (m^2): 5216
Travel Time (yr): 13766

1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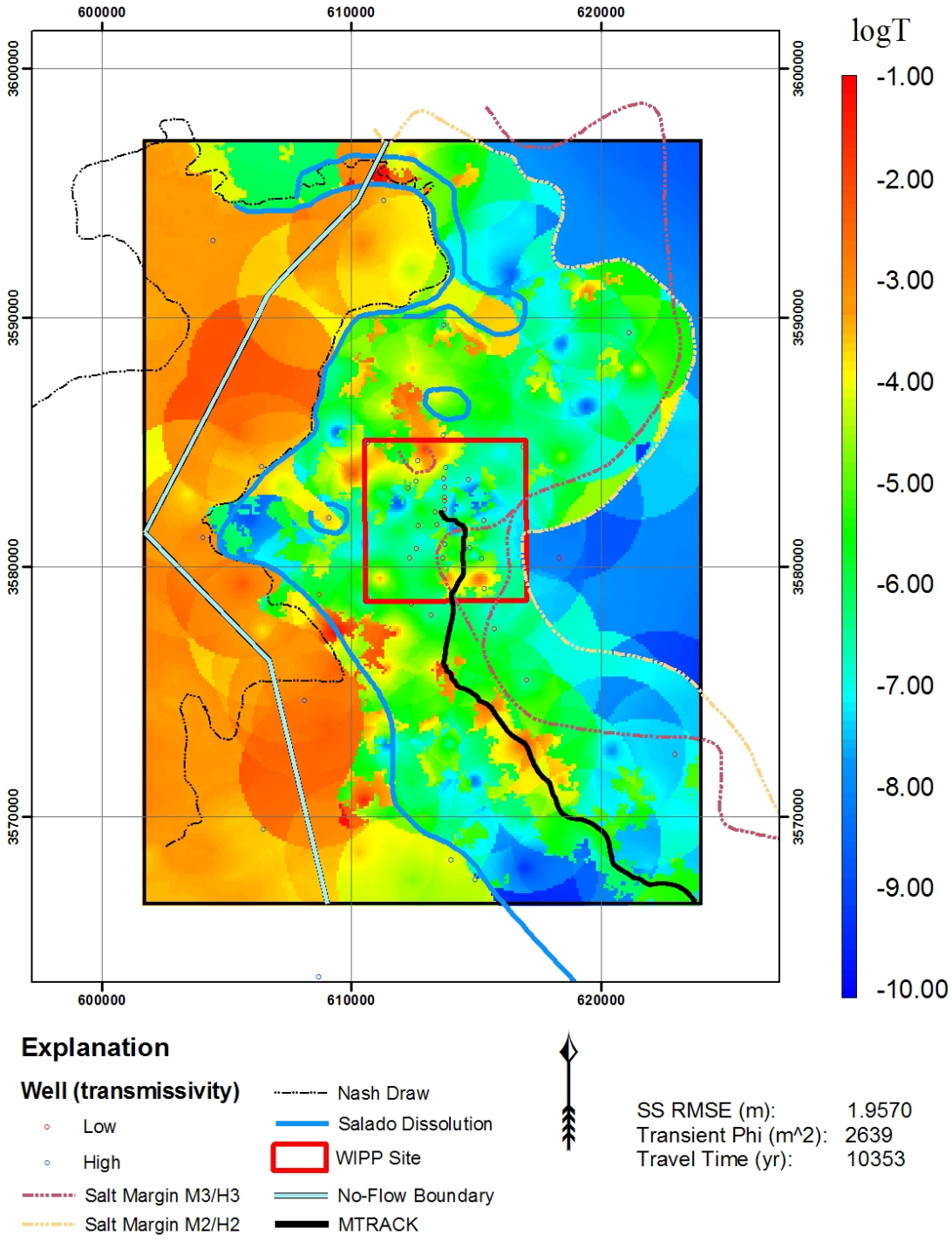
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.623
Transient Phi (m^2): 7110
Travel Time (yr): 30955

1

D06R02—Calibrated



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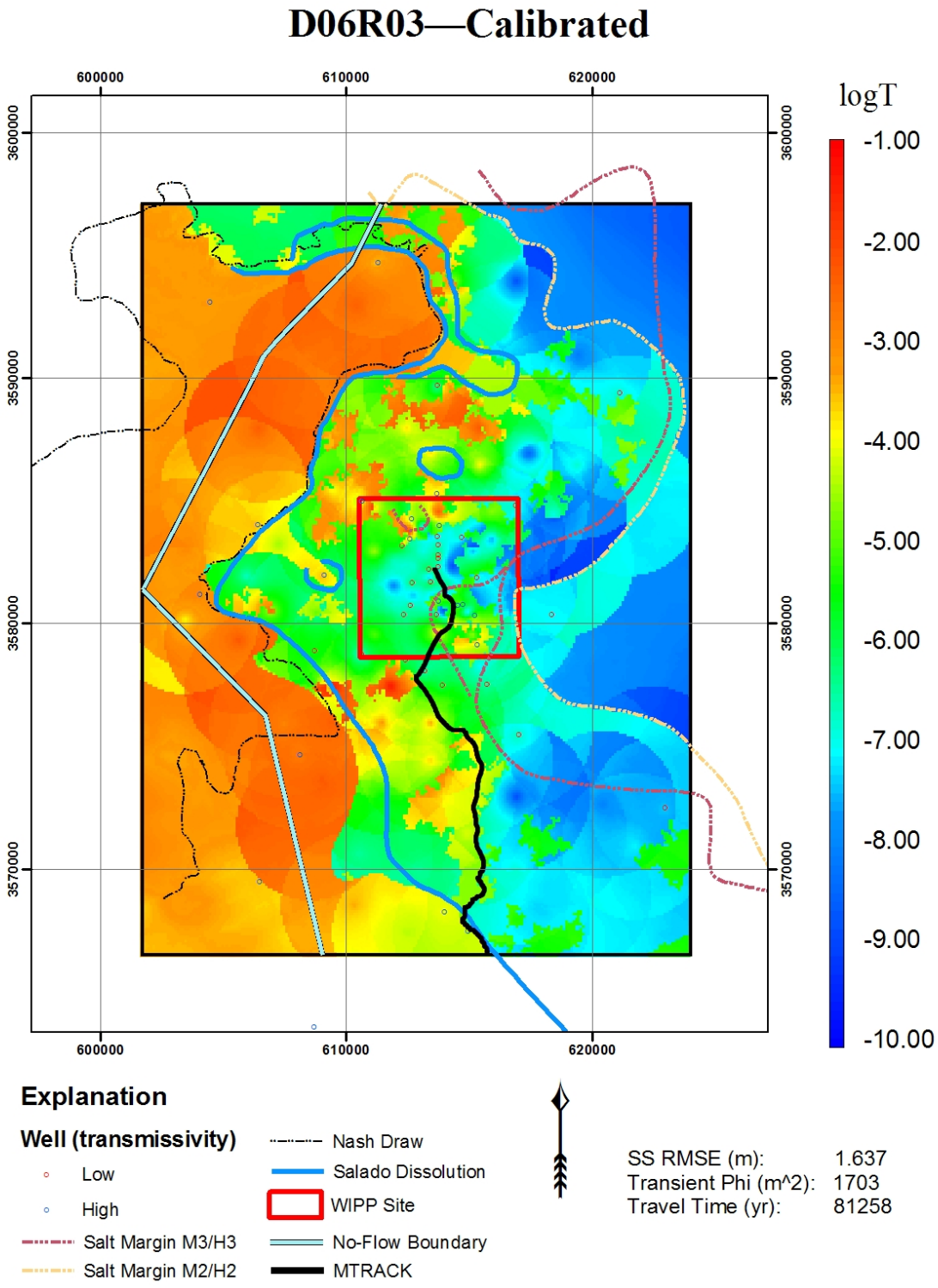
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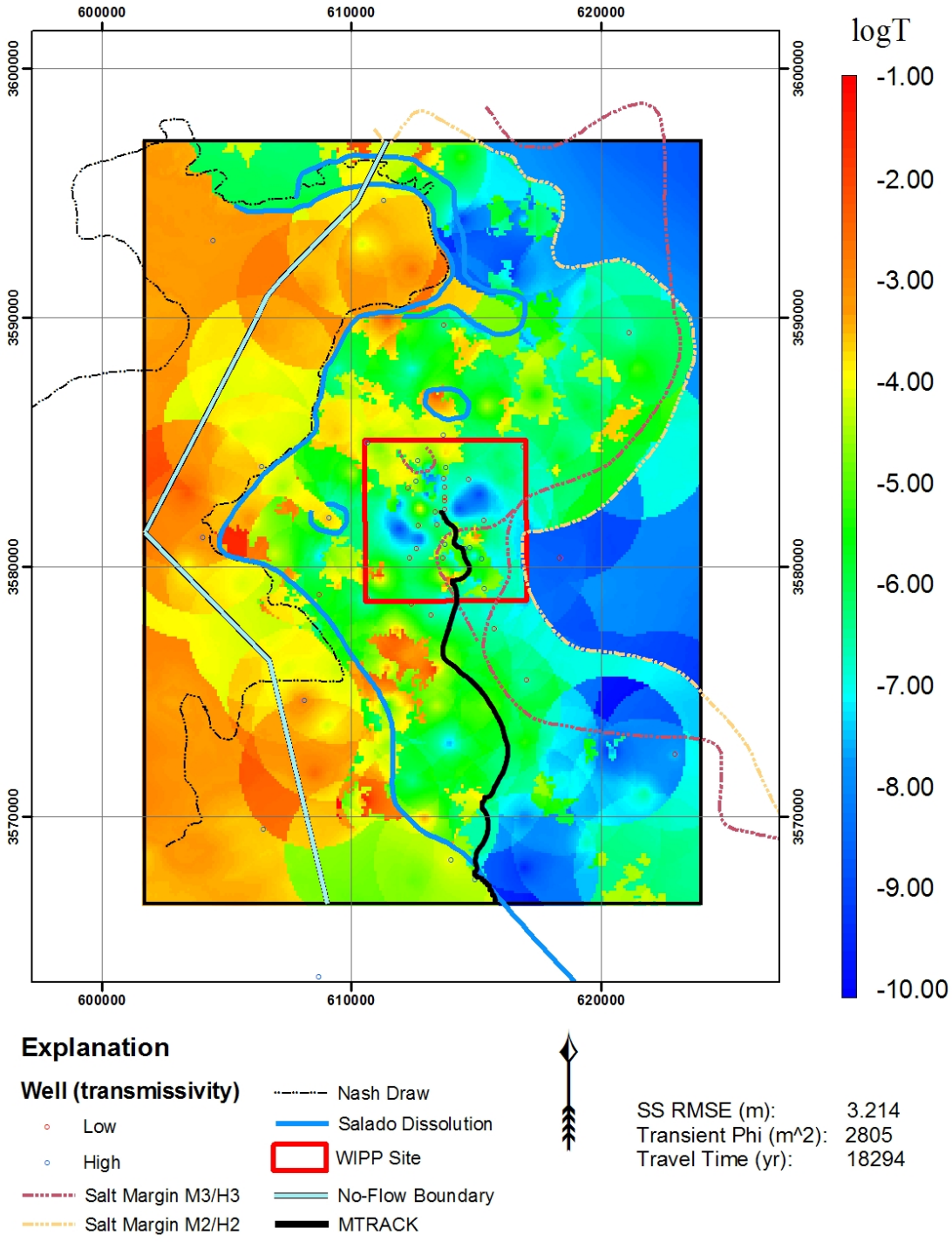
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.637
Transient Phi (m^2): 1703
Travel Time (yr): 81258

1

D06R04—Calibrated



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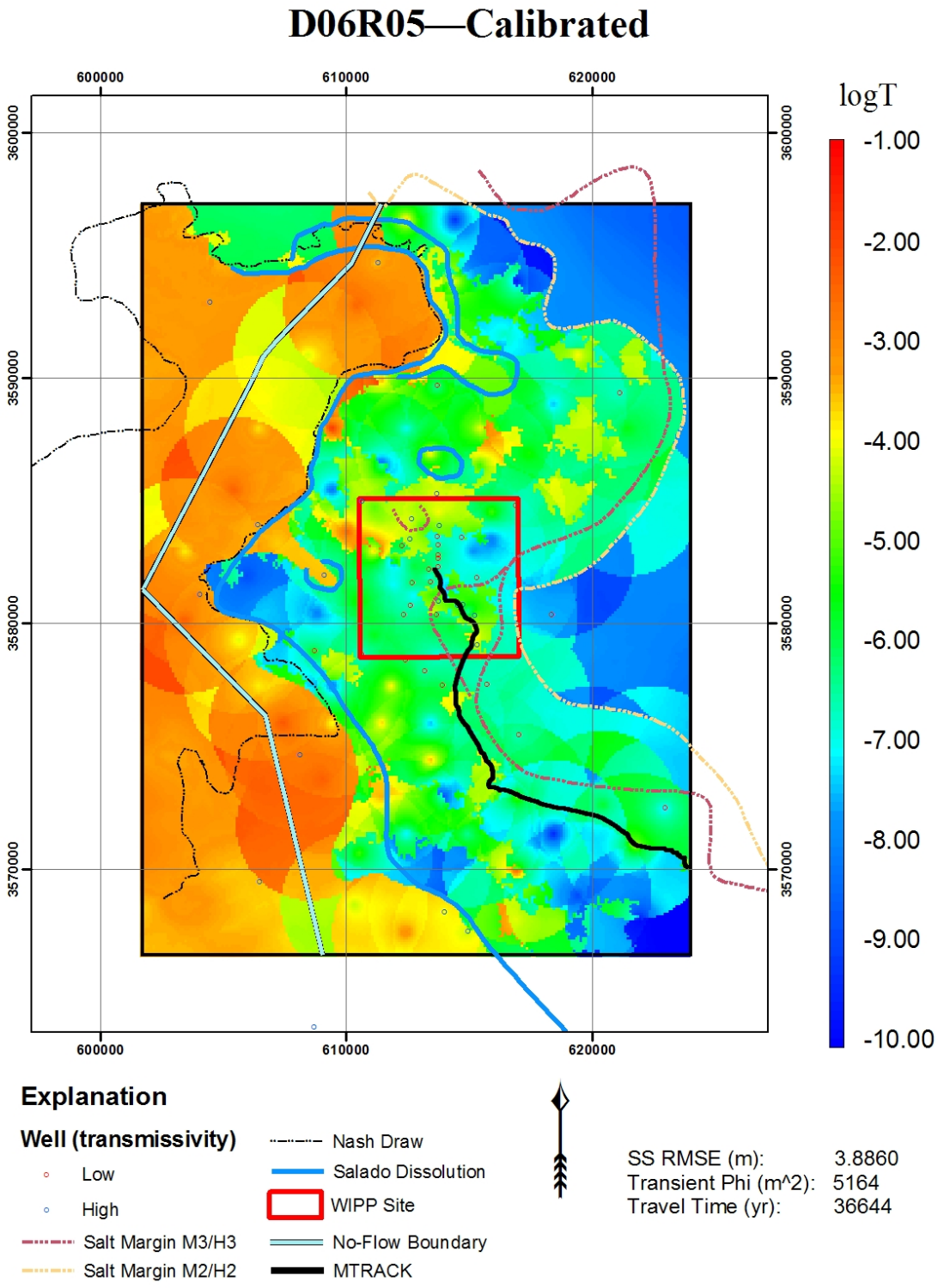
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-3.00
-4.00
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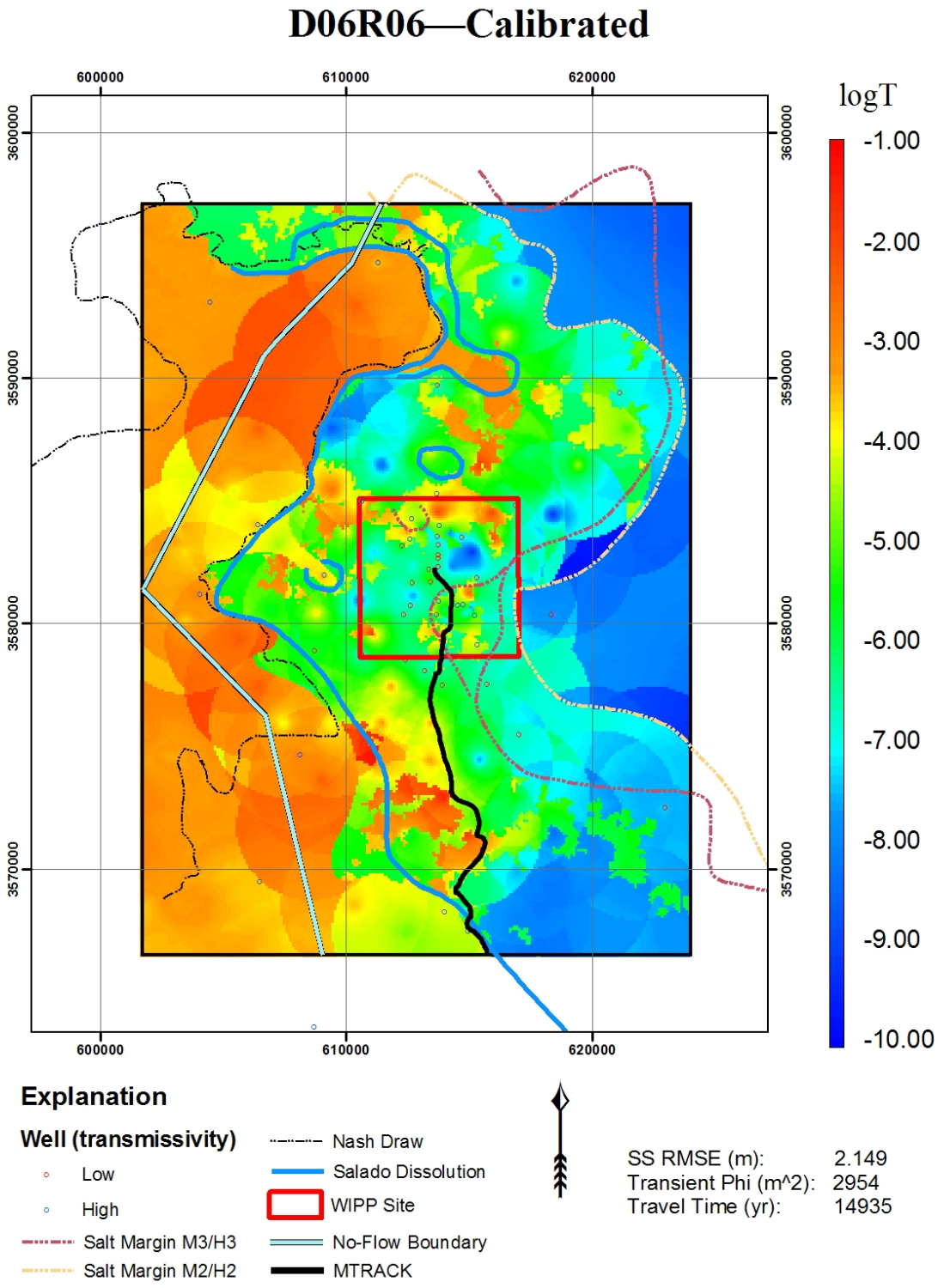
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.8860
Transient Phi (m^2): 5164
Travel Time (yr): 36644

1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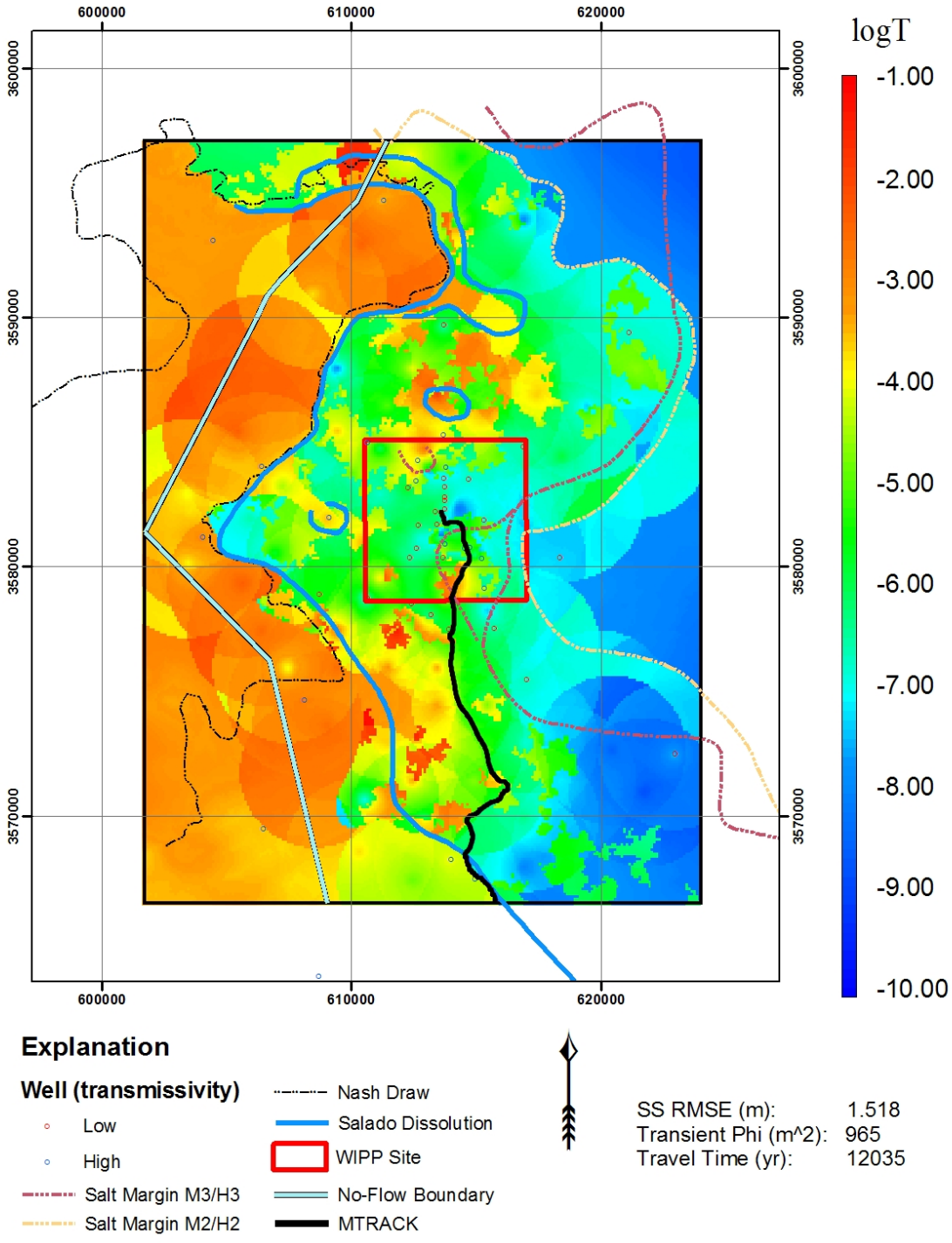
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.149
Transient Phi (m^2): 2954
Travel Time (yr): 14935

1

D06R07—Calibrated



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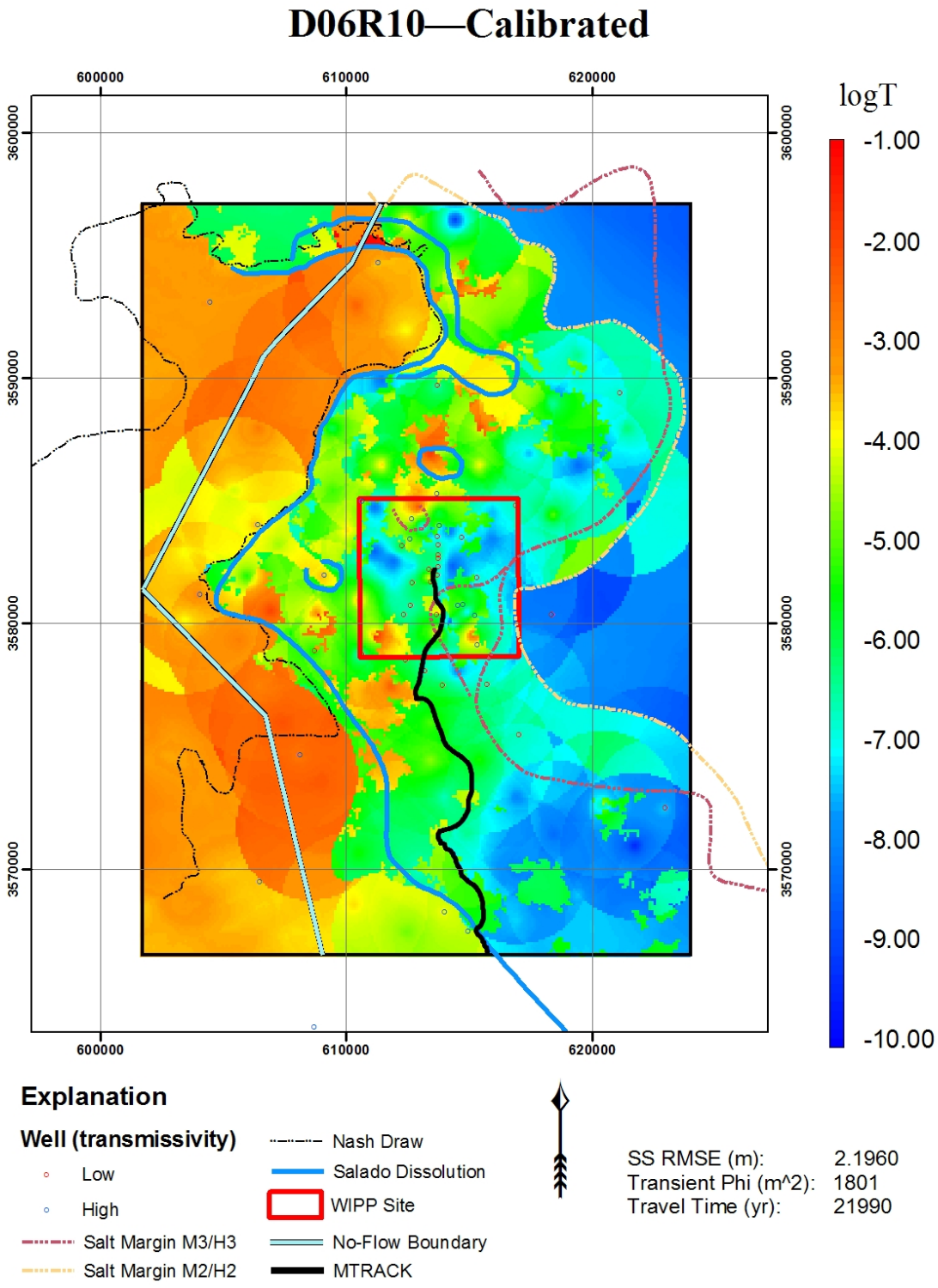
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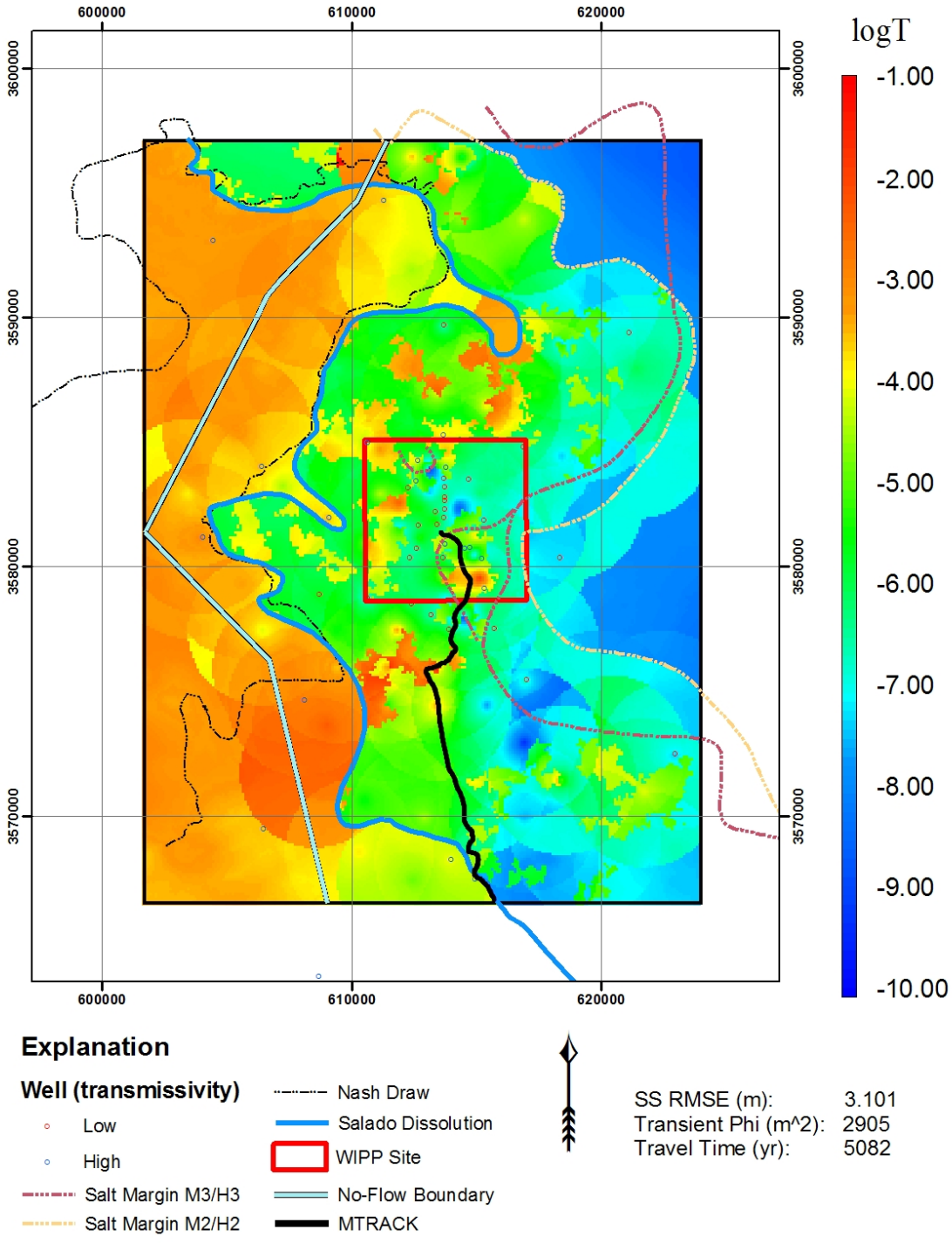
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.1960
Transient Phi (m^2): 1801
Travel Time (yr): 21990

1

D07R01—Calibrated



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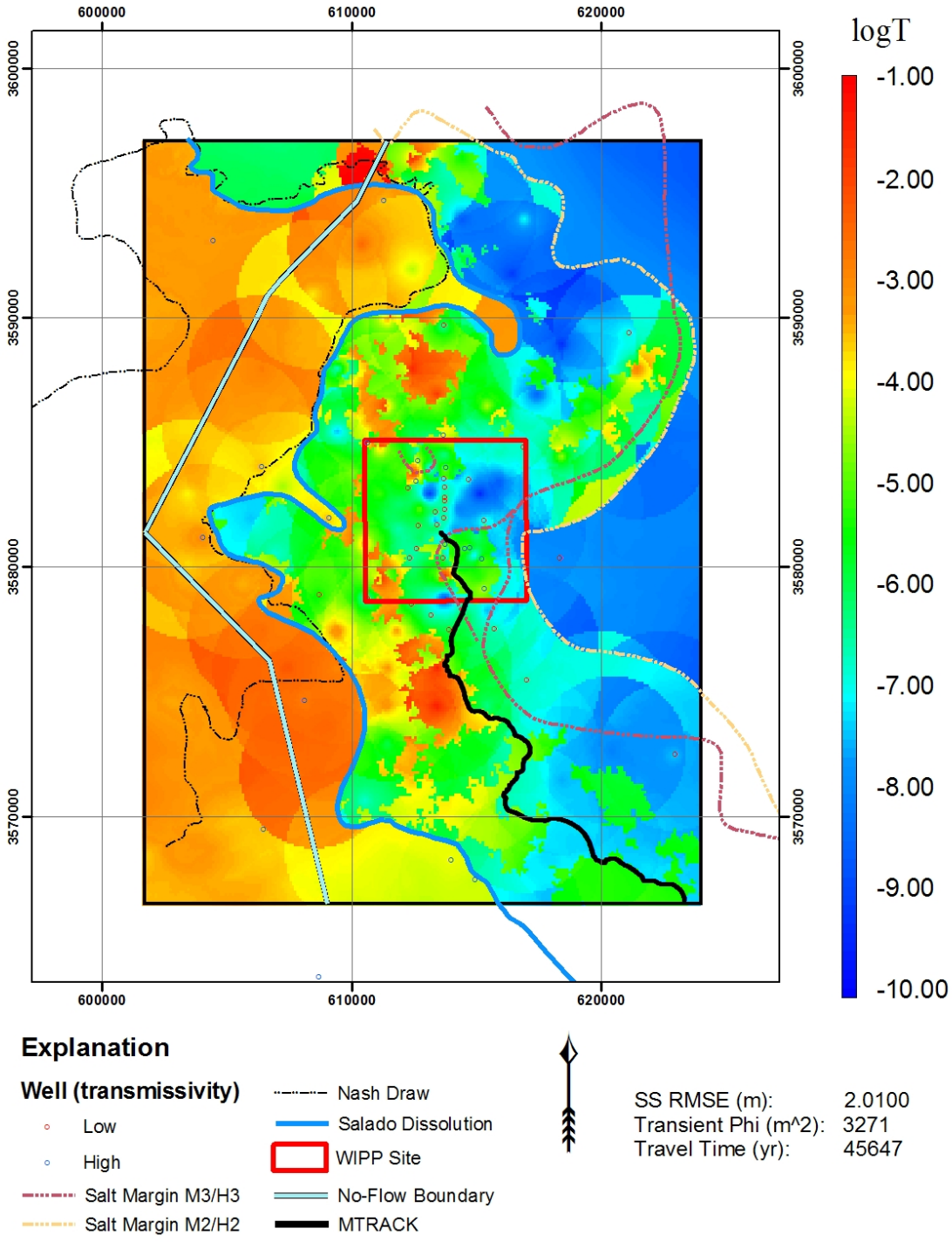

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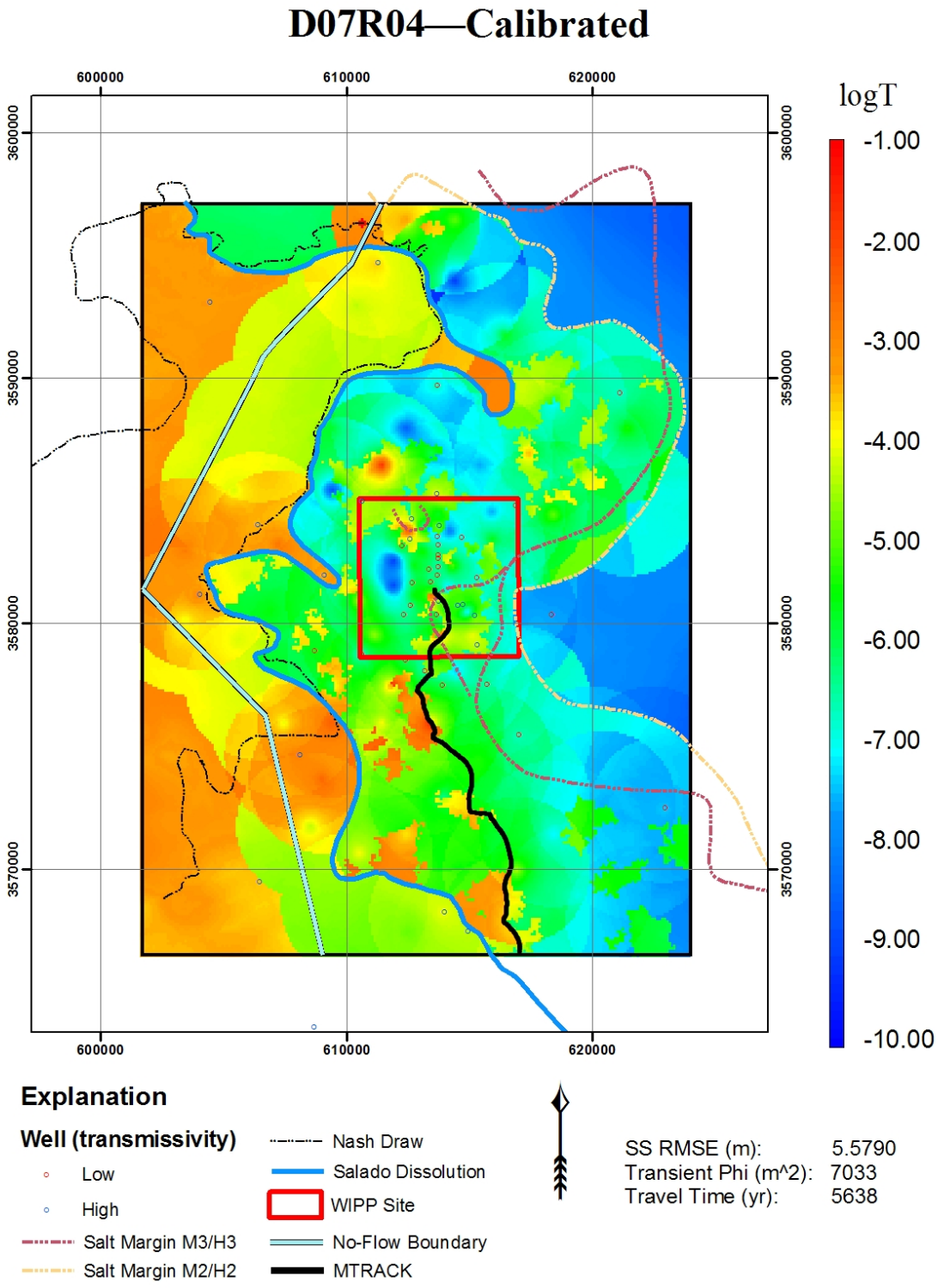
D07R04—Calibrated
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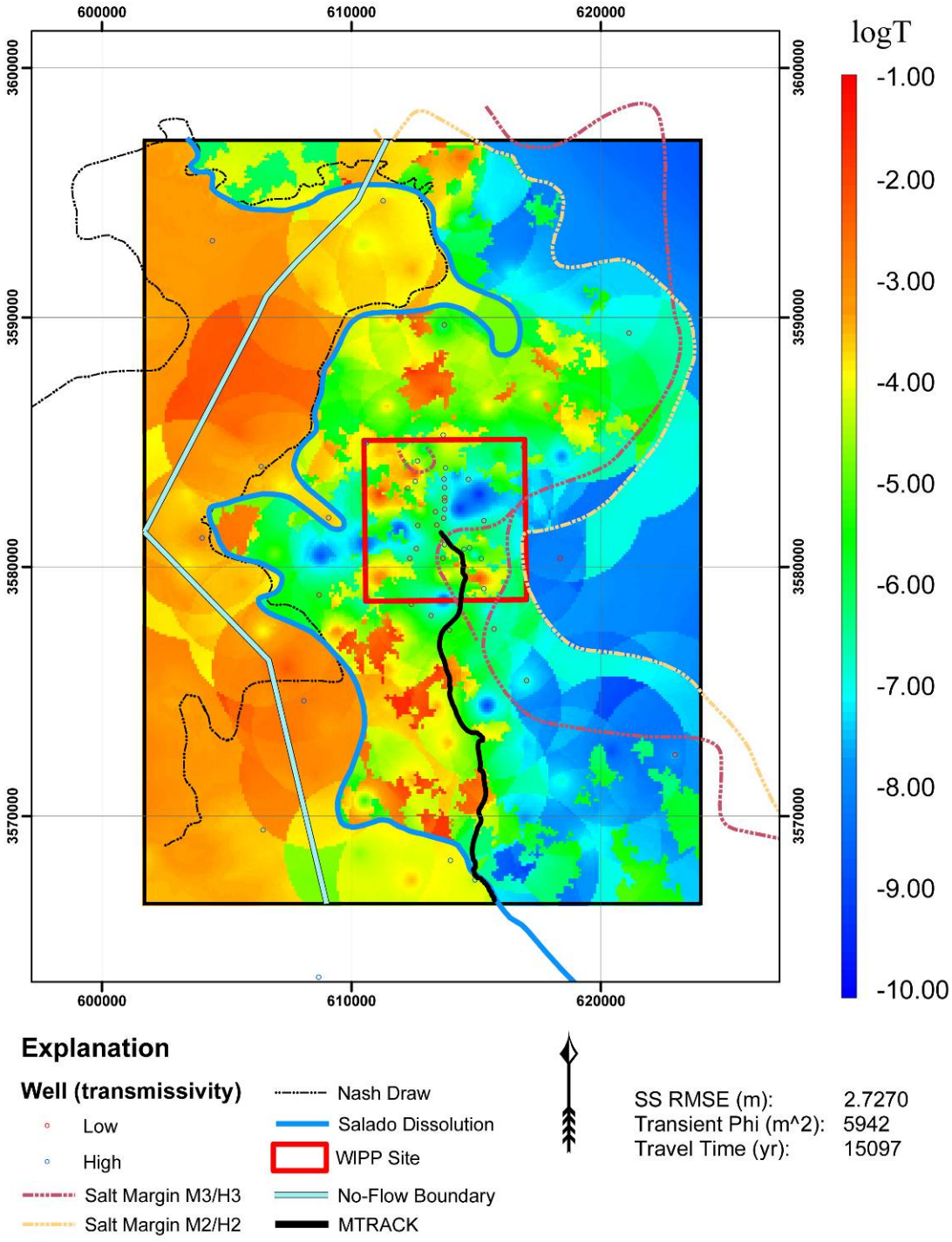
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.5790
Transient Phi (m^2): 7033
Travel Time (yr): 5638

1

D07R05—Calibrated



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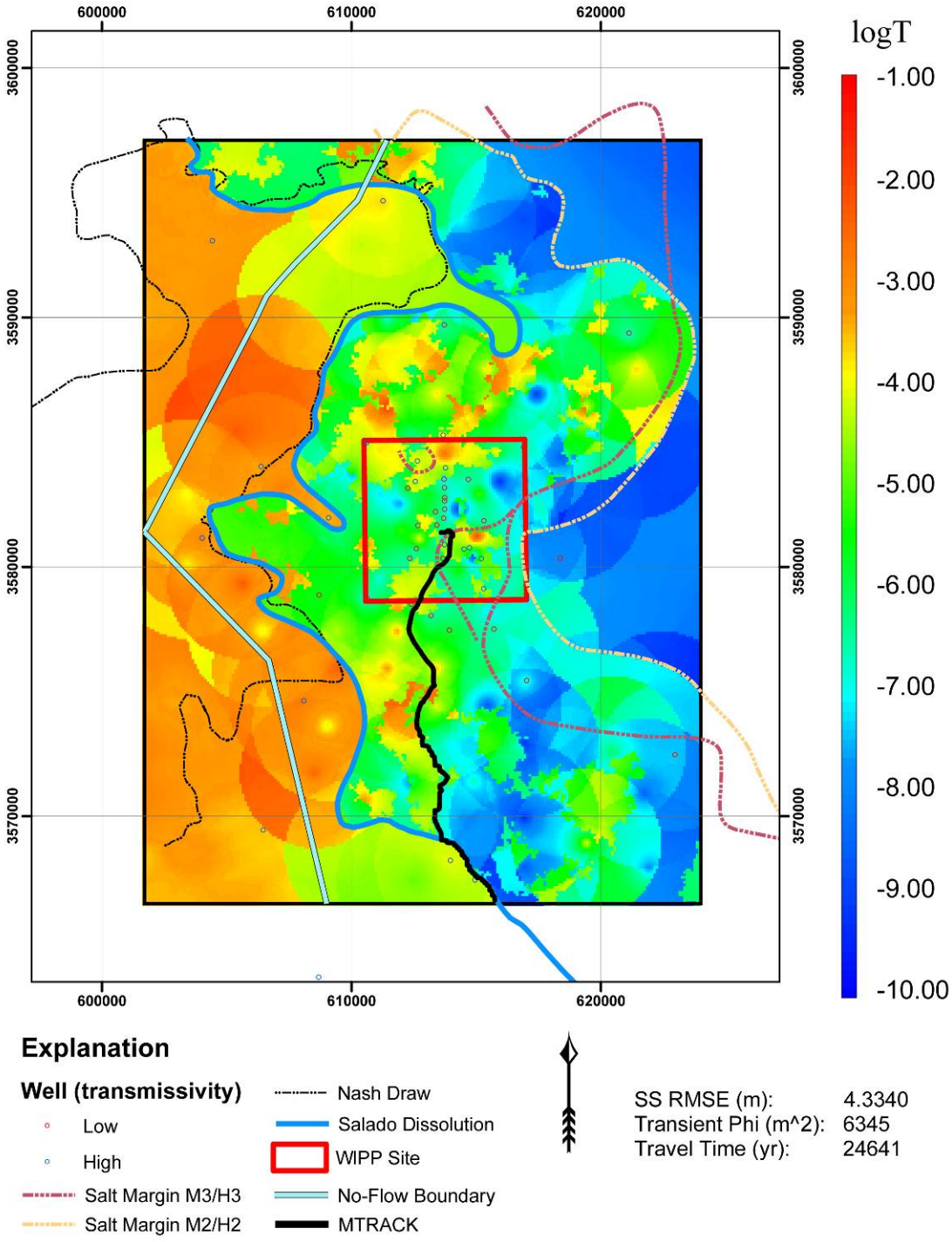
D07R06—Calibrated



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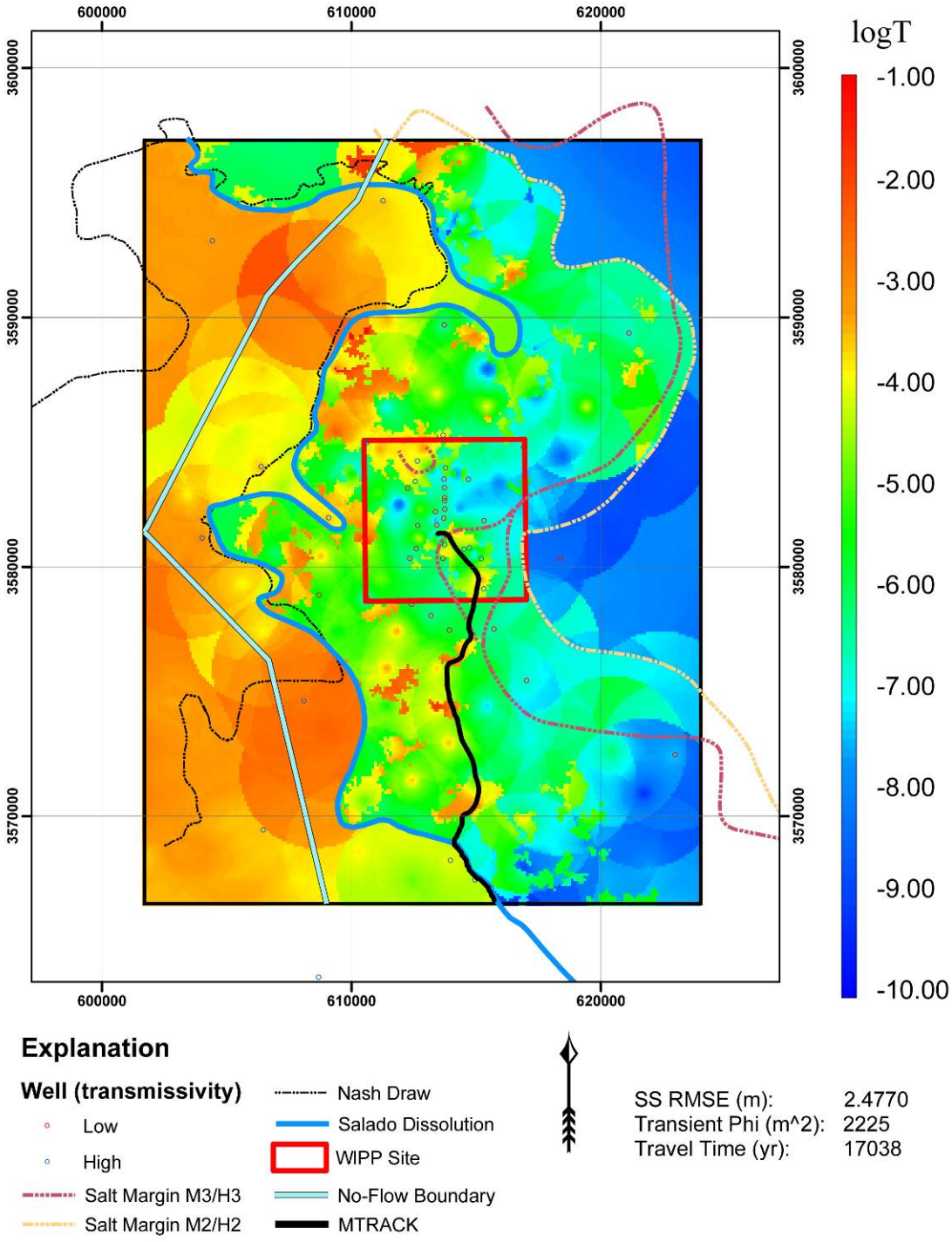
D07R07—Calibrated



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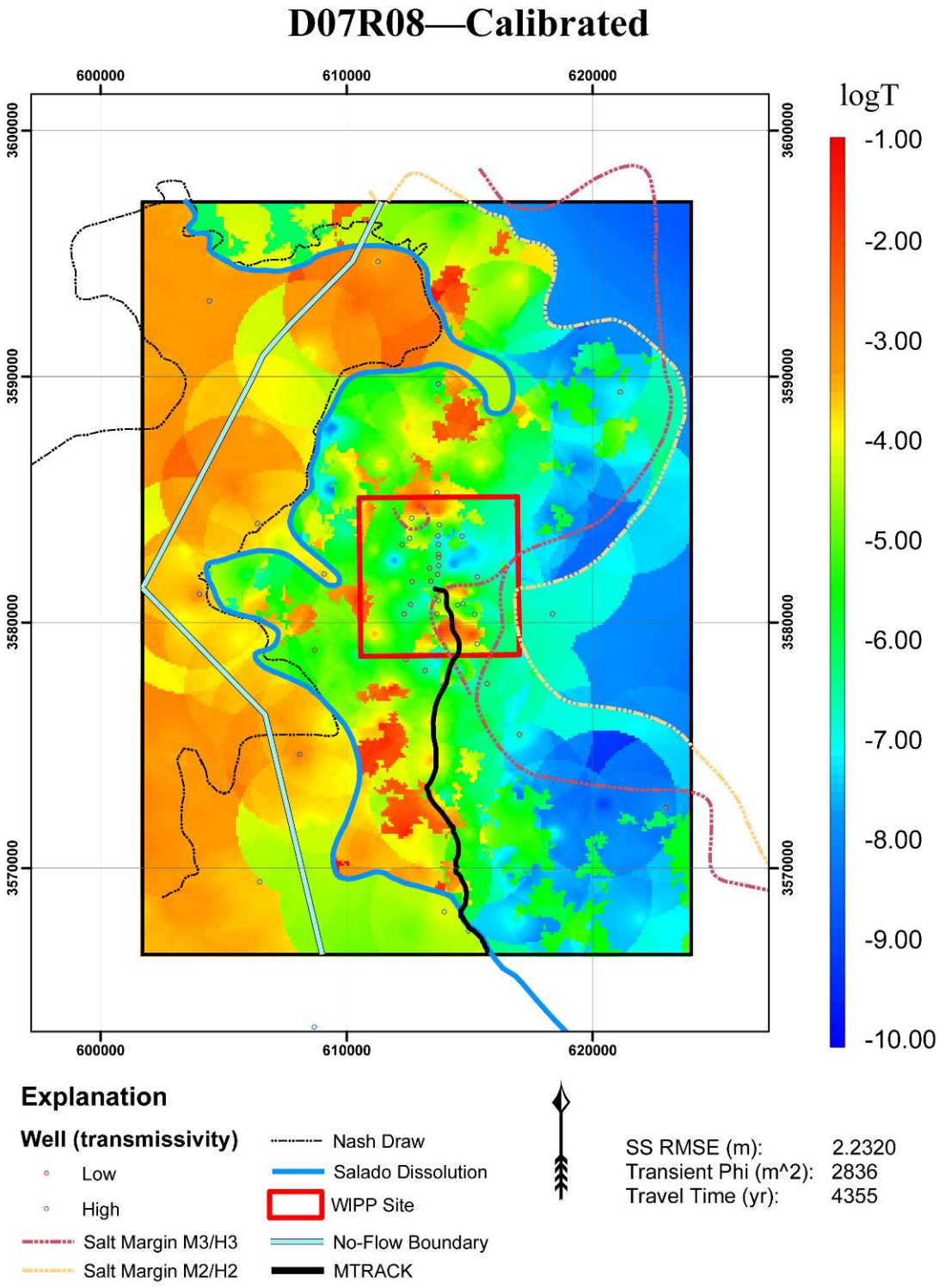
D07R08—Calibrated
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logT
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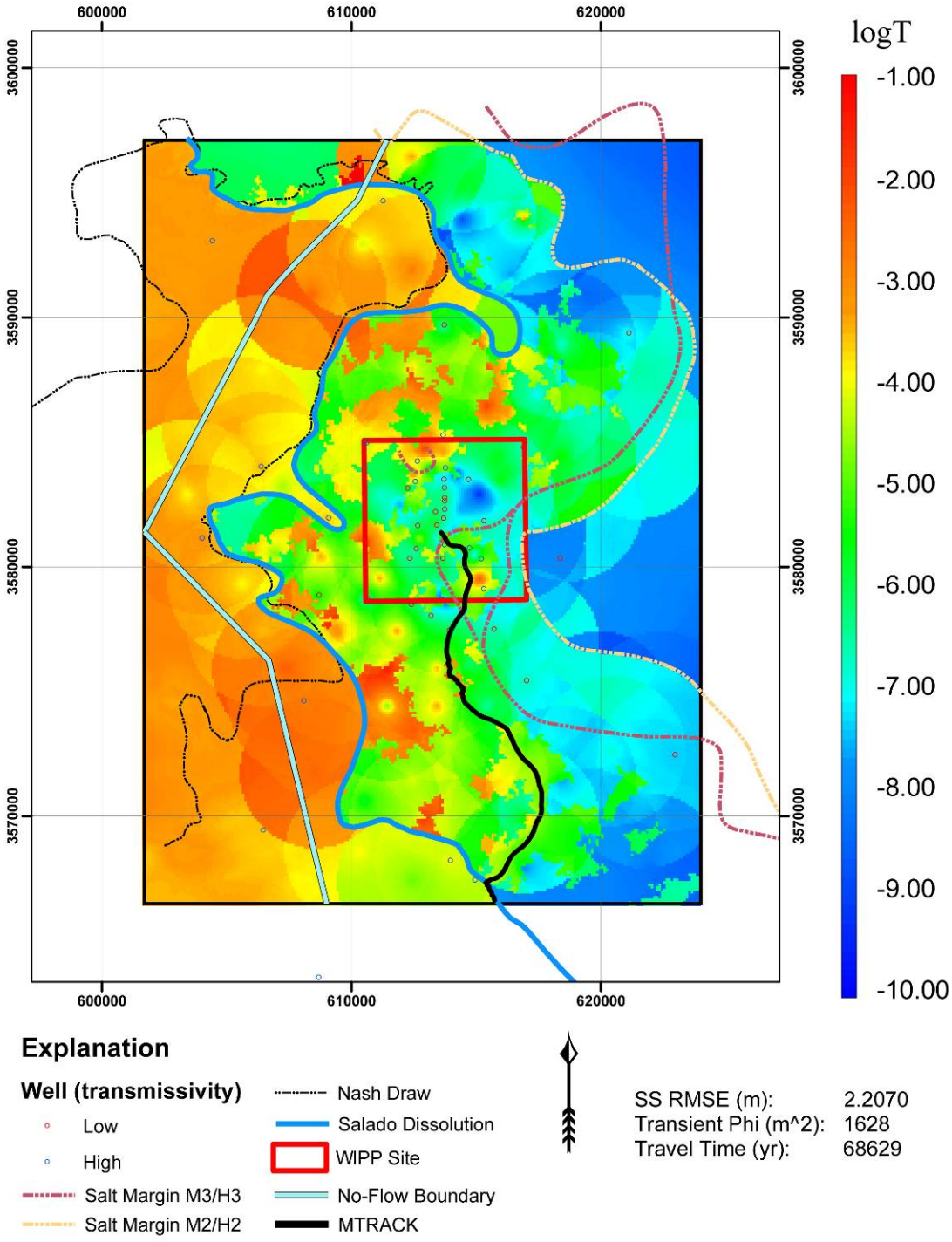
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.2320
Transient Phi (m^2): 2836
Travel Time (yr): 4355

1

D07R09—Calibrated



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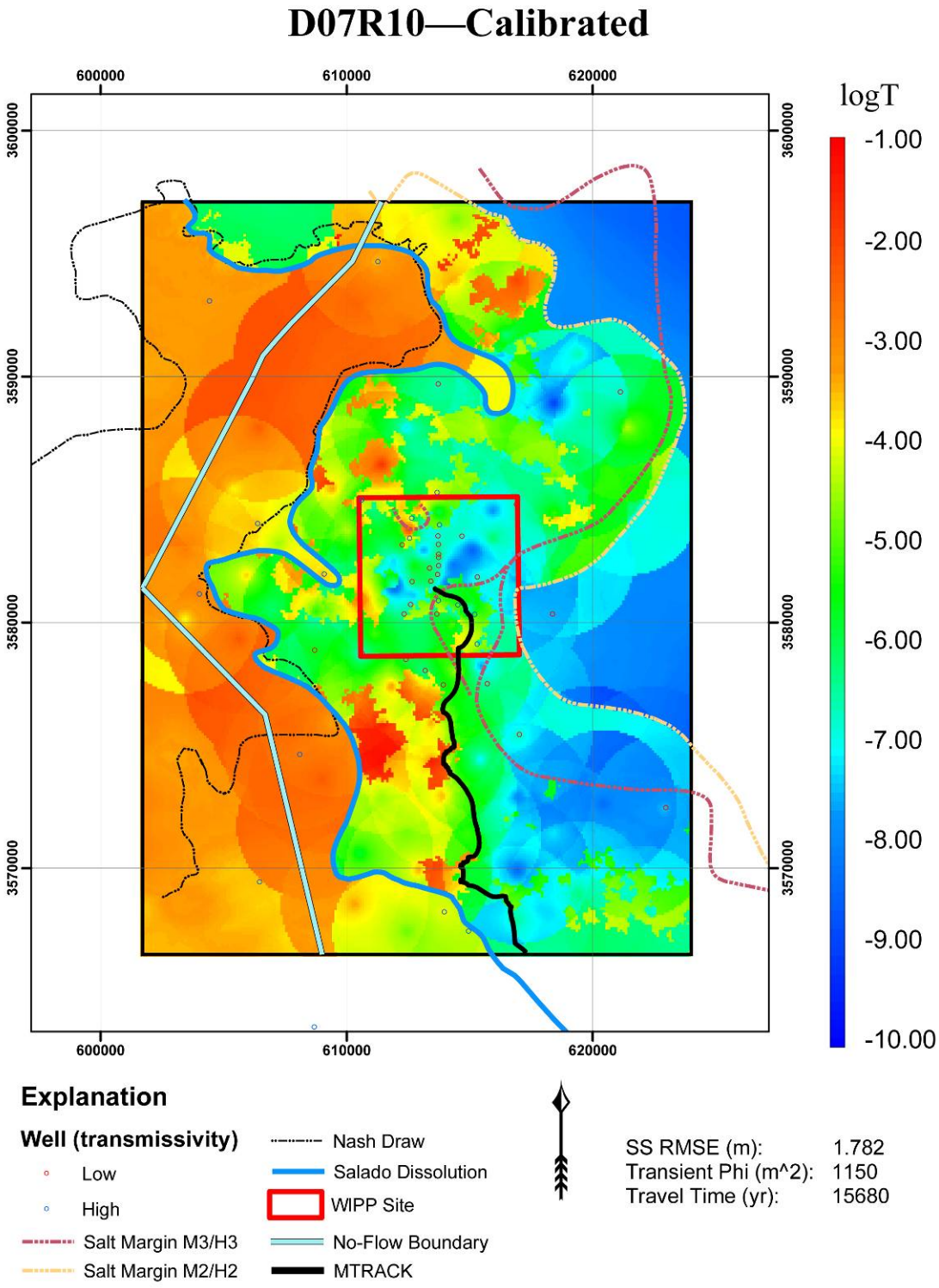
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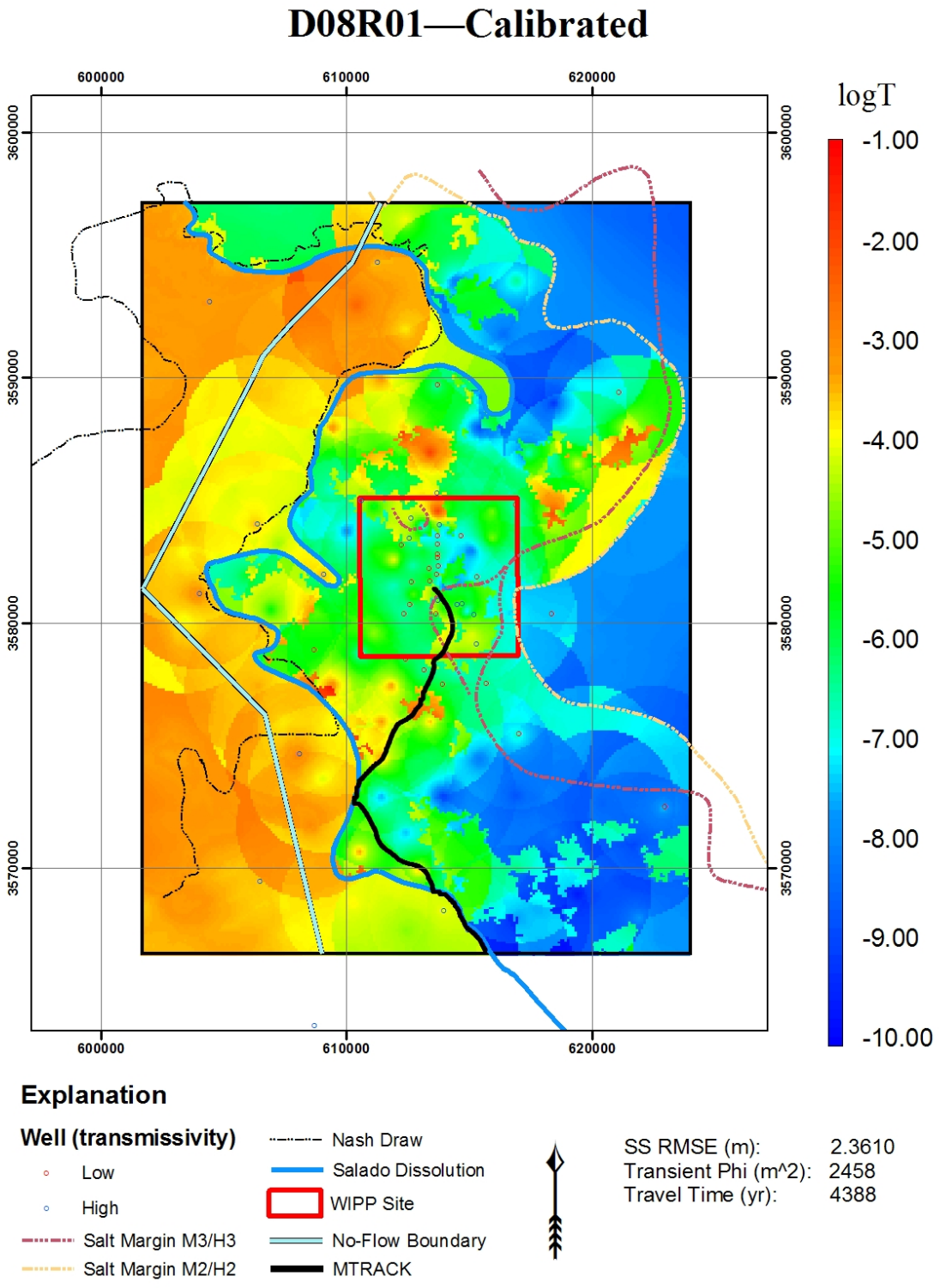
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.782
Transient Phi (m^2): 1150
Travel Time (yr): 15680

1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3570000
logT
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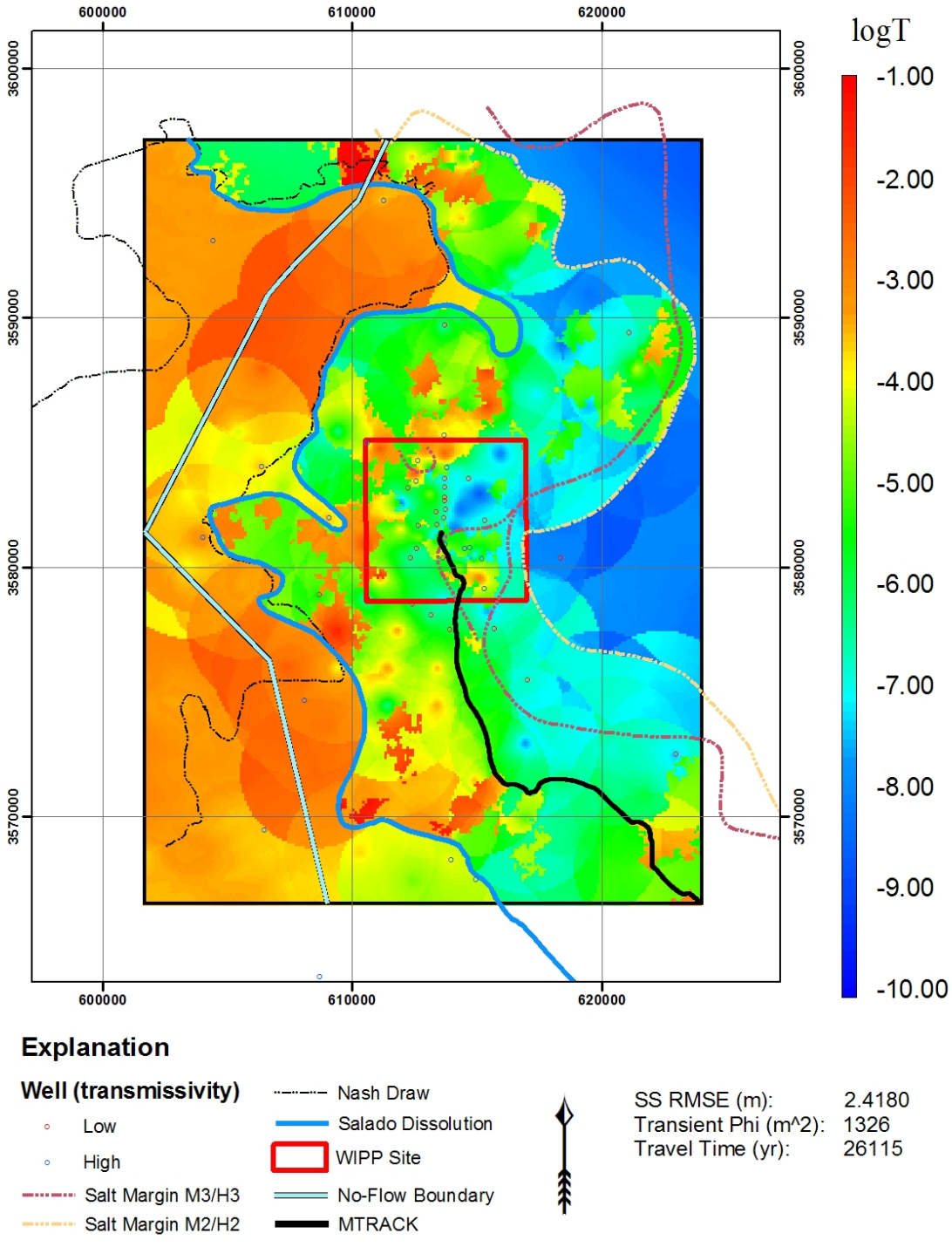
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.3610
Transient Phi (m^2): 2458
Travel Time (yr): 4388

1

D08R02—Calibrated



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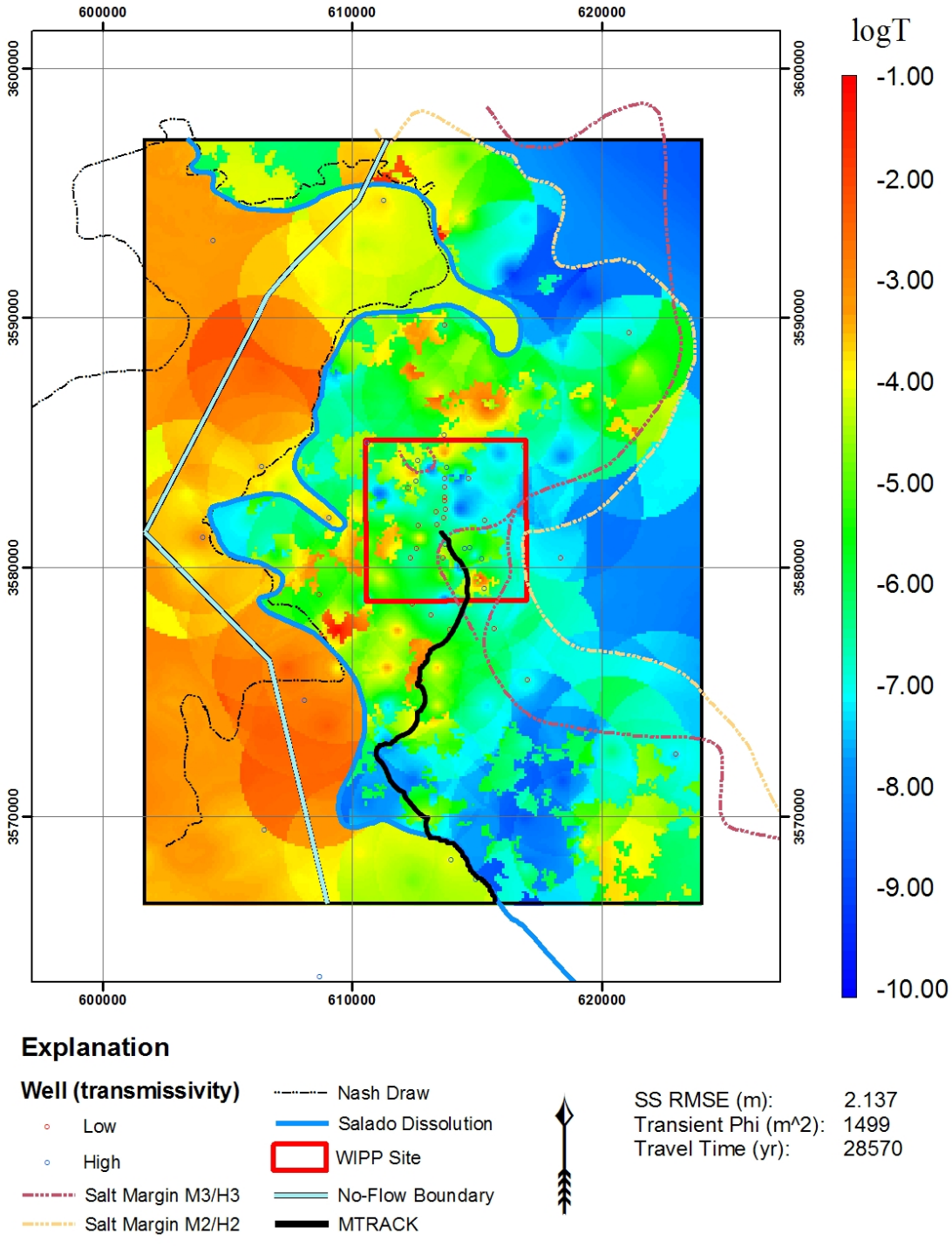
D08R03—Calibrated



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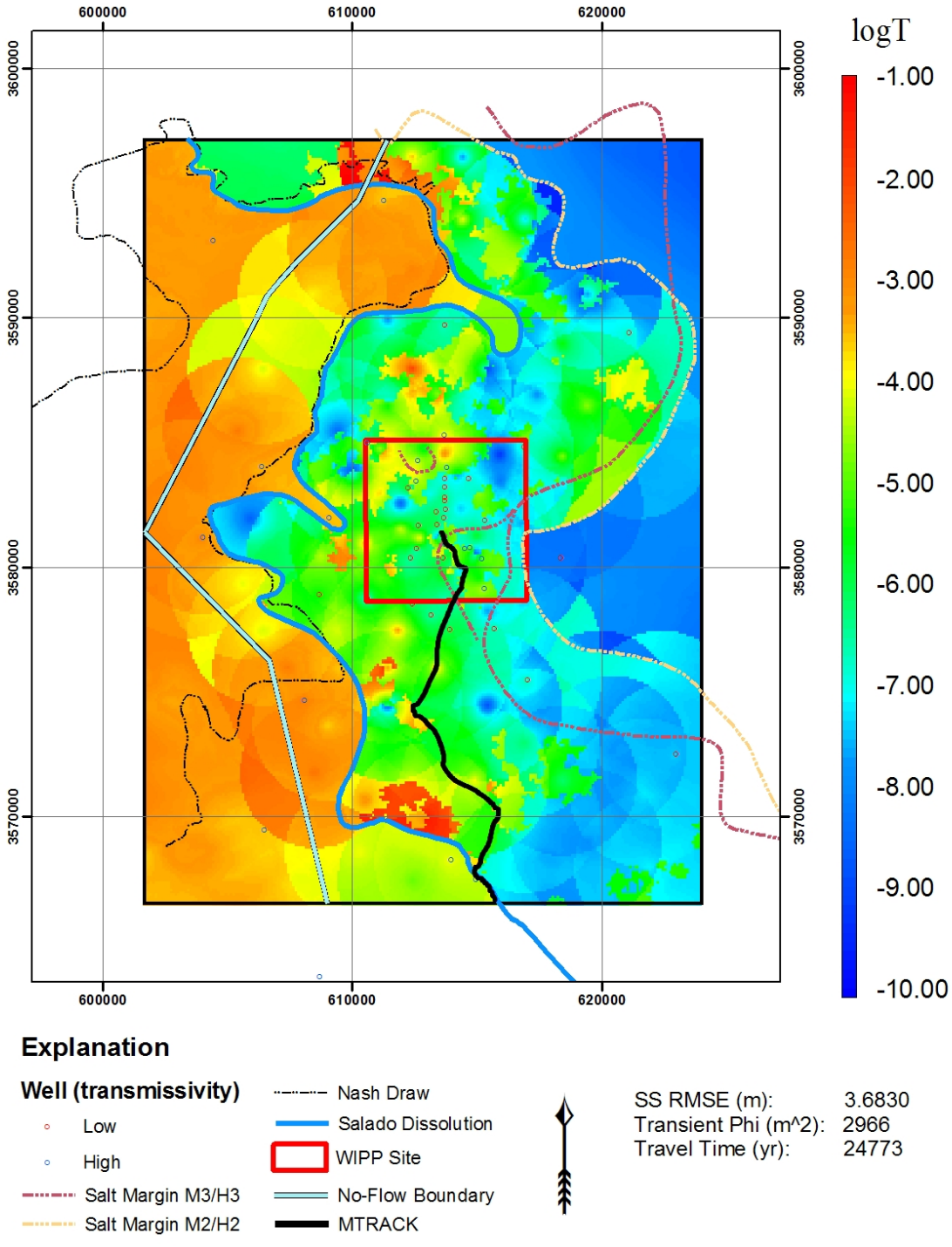
D08R04—Calibrated



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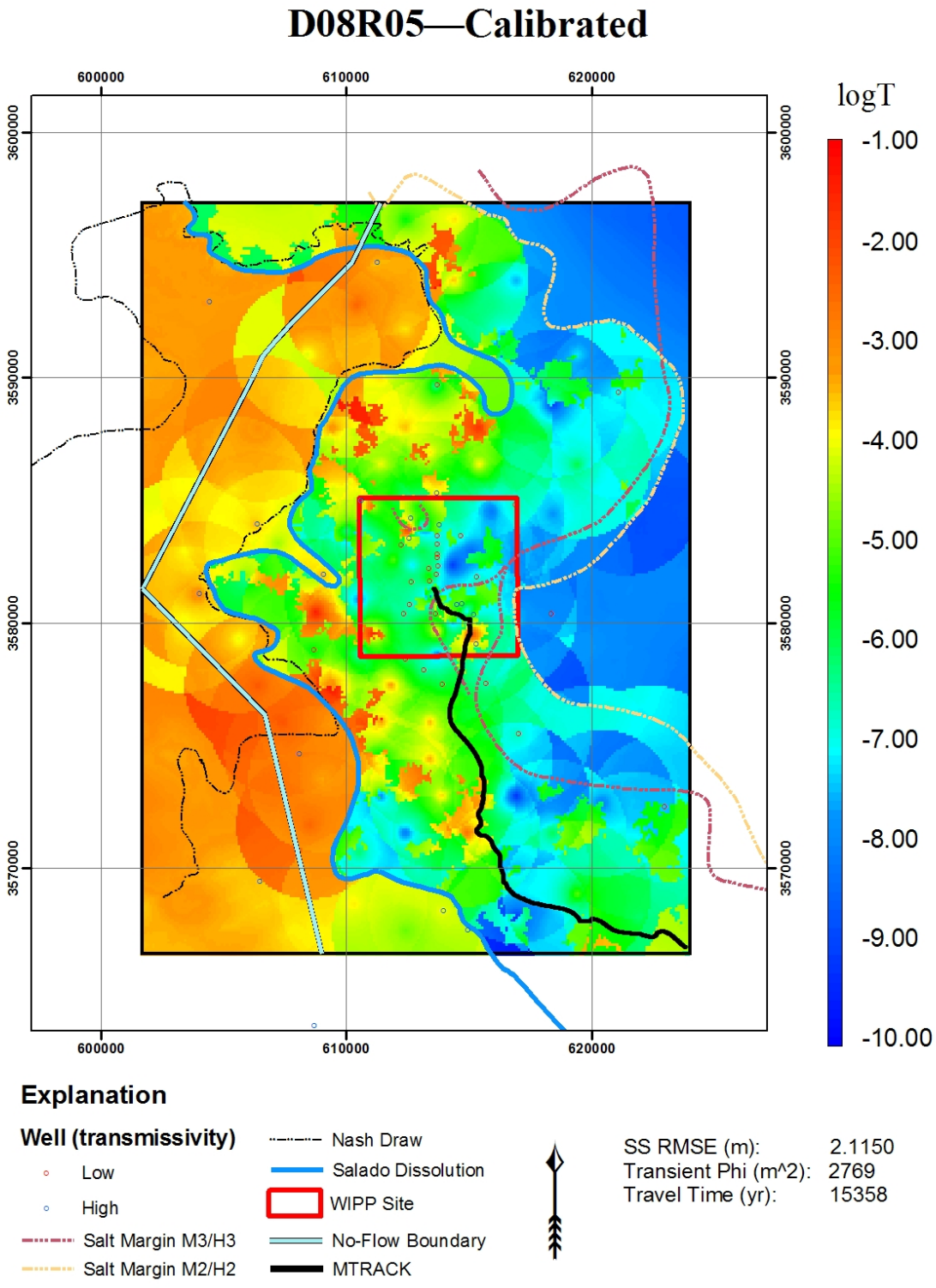
D08R05—Calibrated
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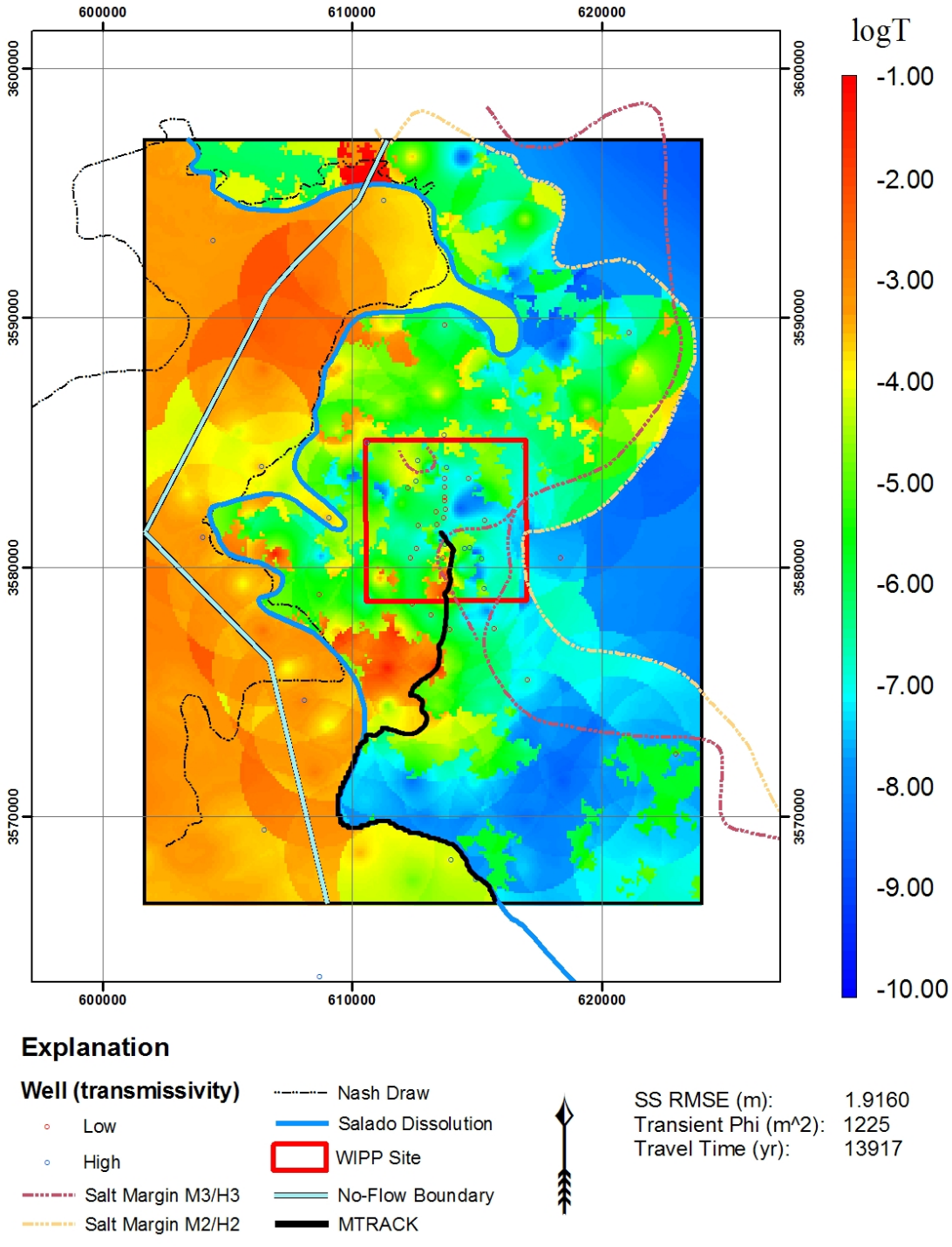
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.1150
Transient Phi (m^2): 2769
Travel Time (yr): 15358

1

D08R06—Calibrated



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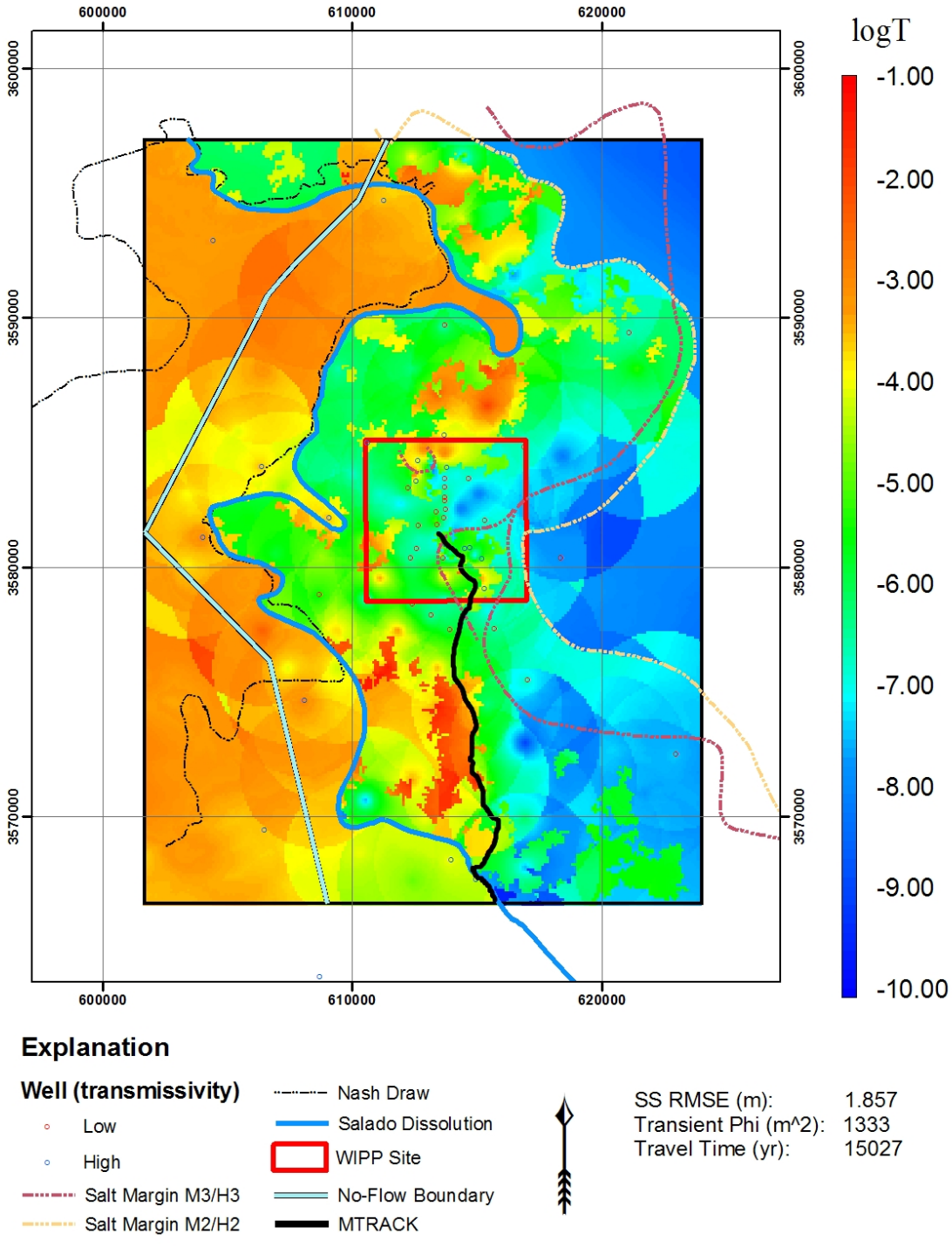
D08R07—Calibrated



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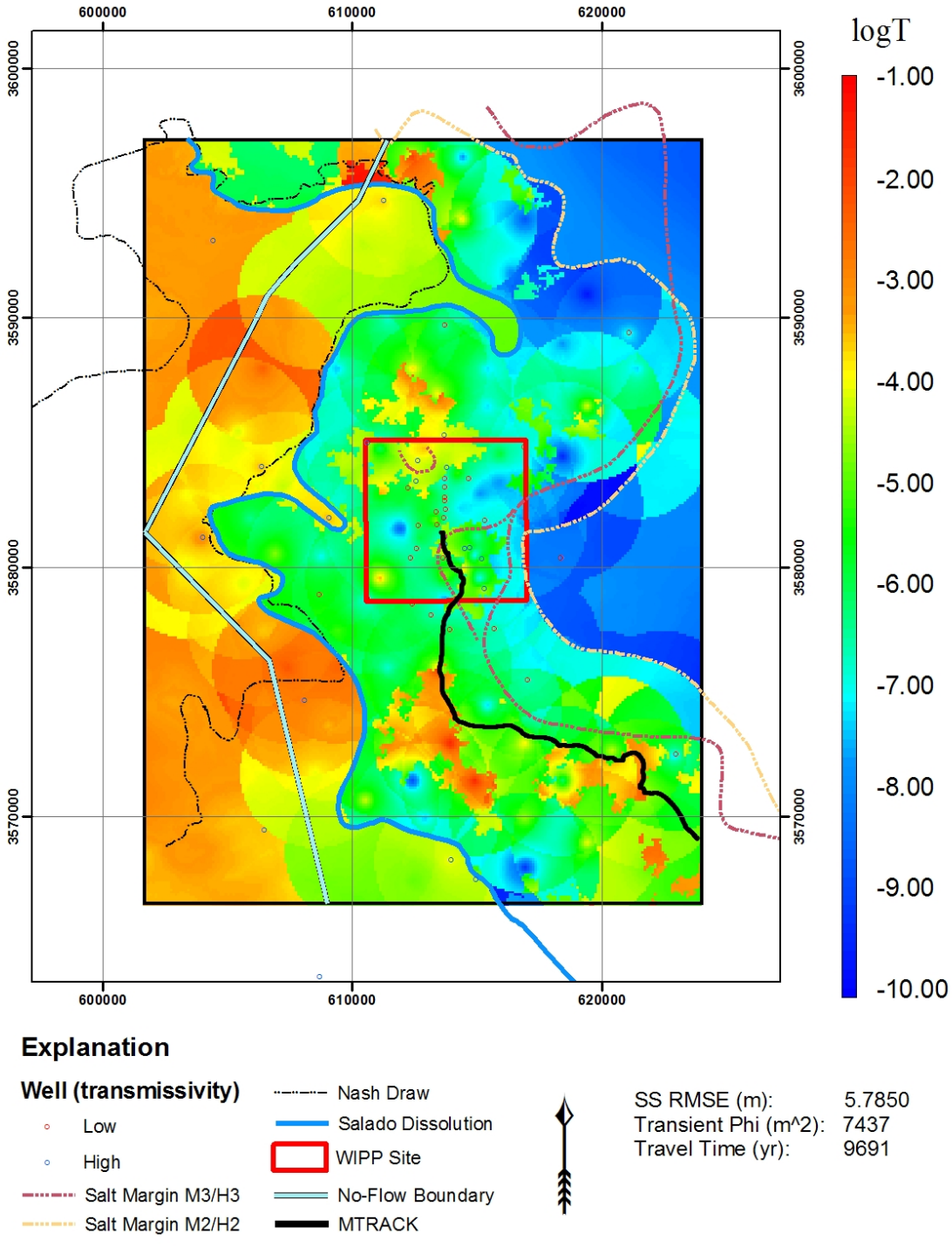
D08R09—Calibrated



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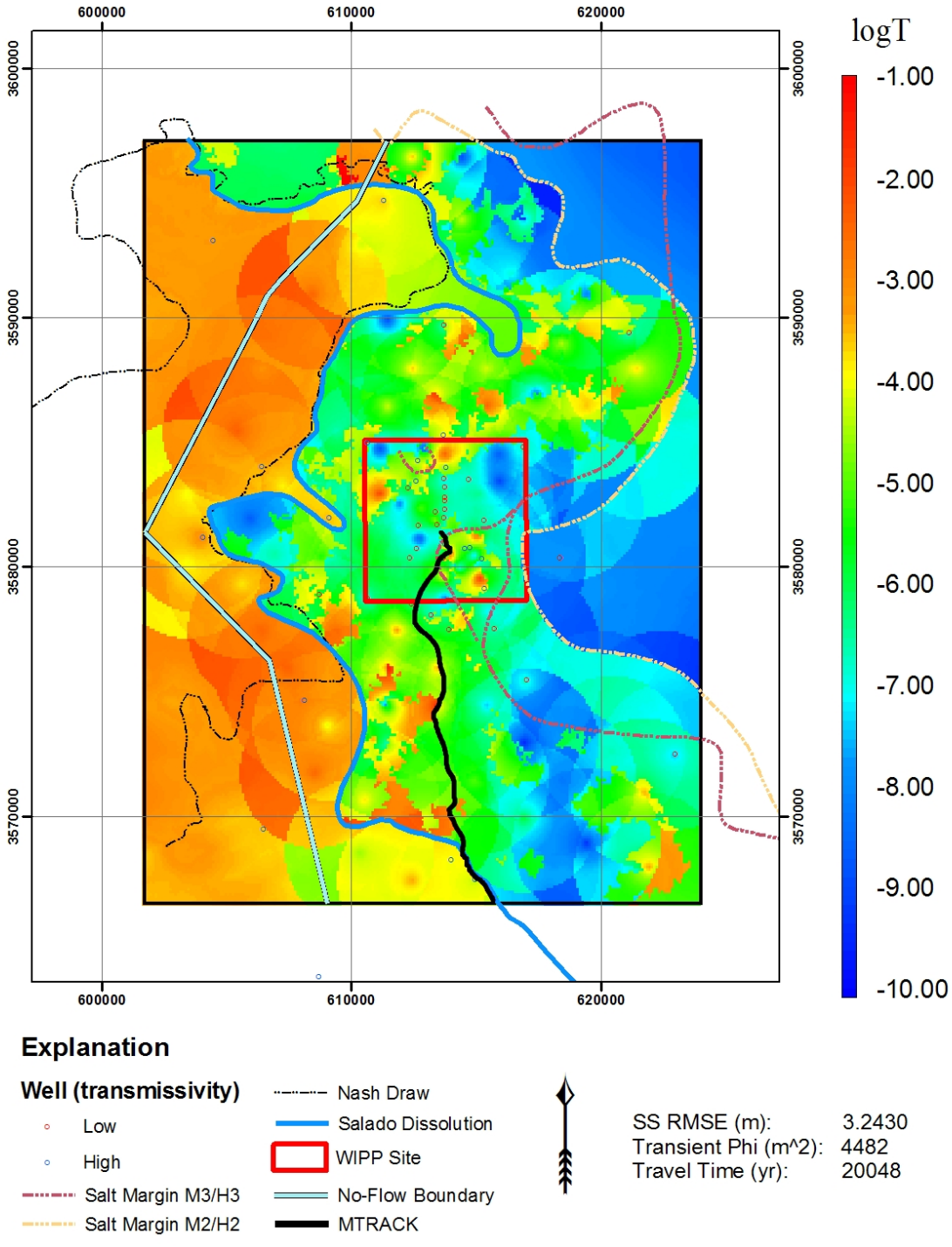
D09R02—Calibrated



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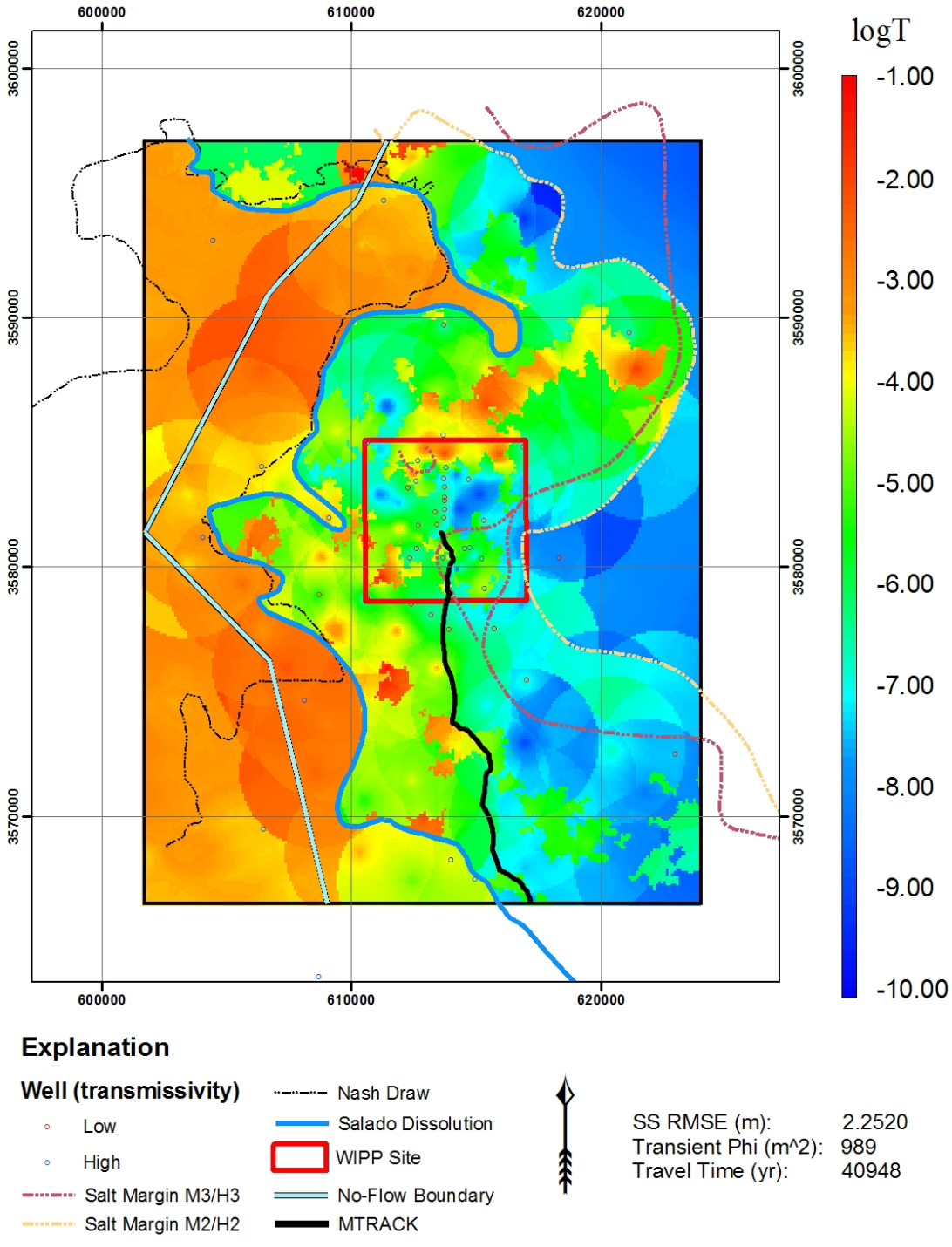
D09R03—Calibrated



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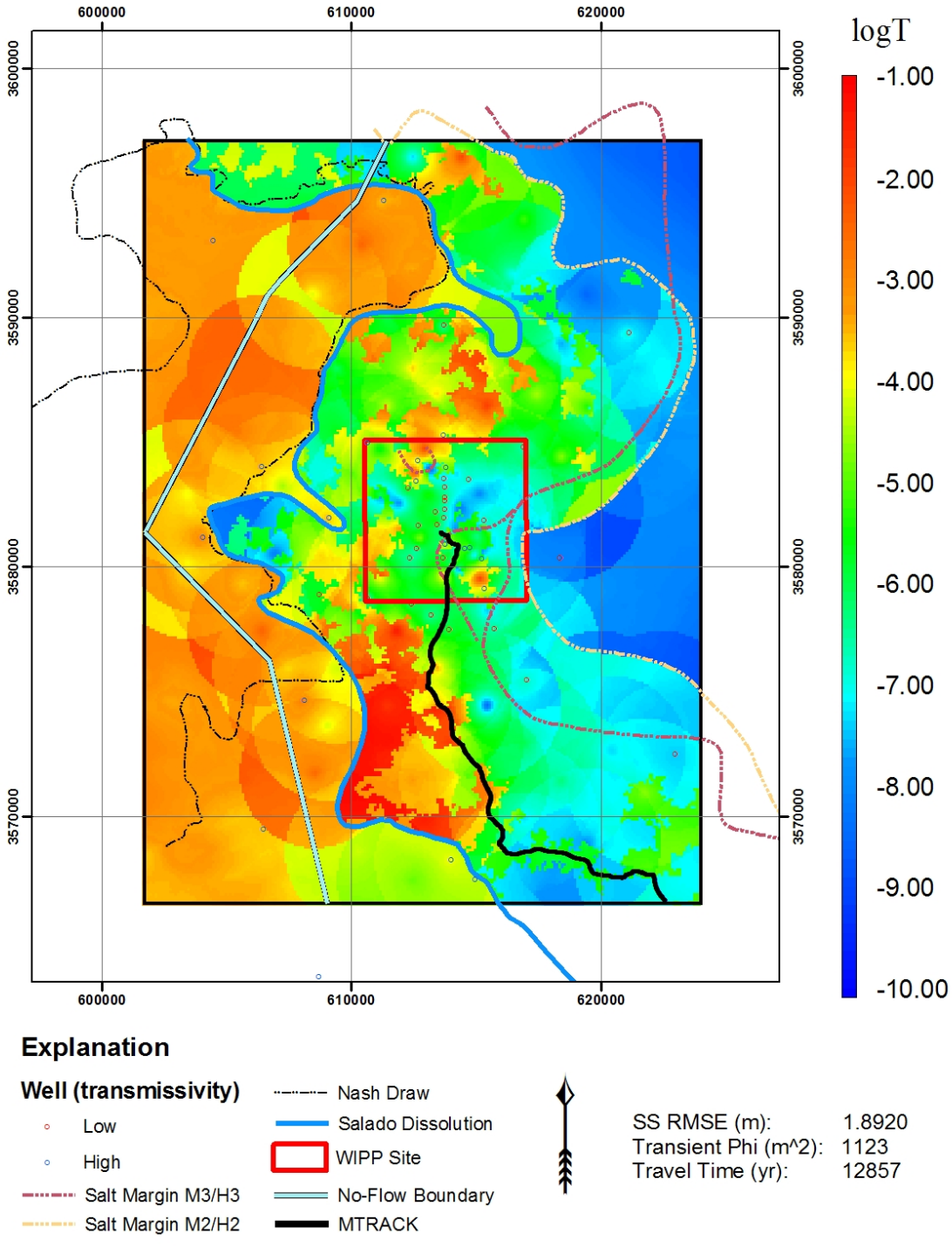
D09R04—Calibrated



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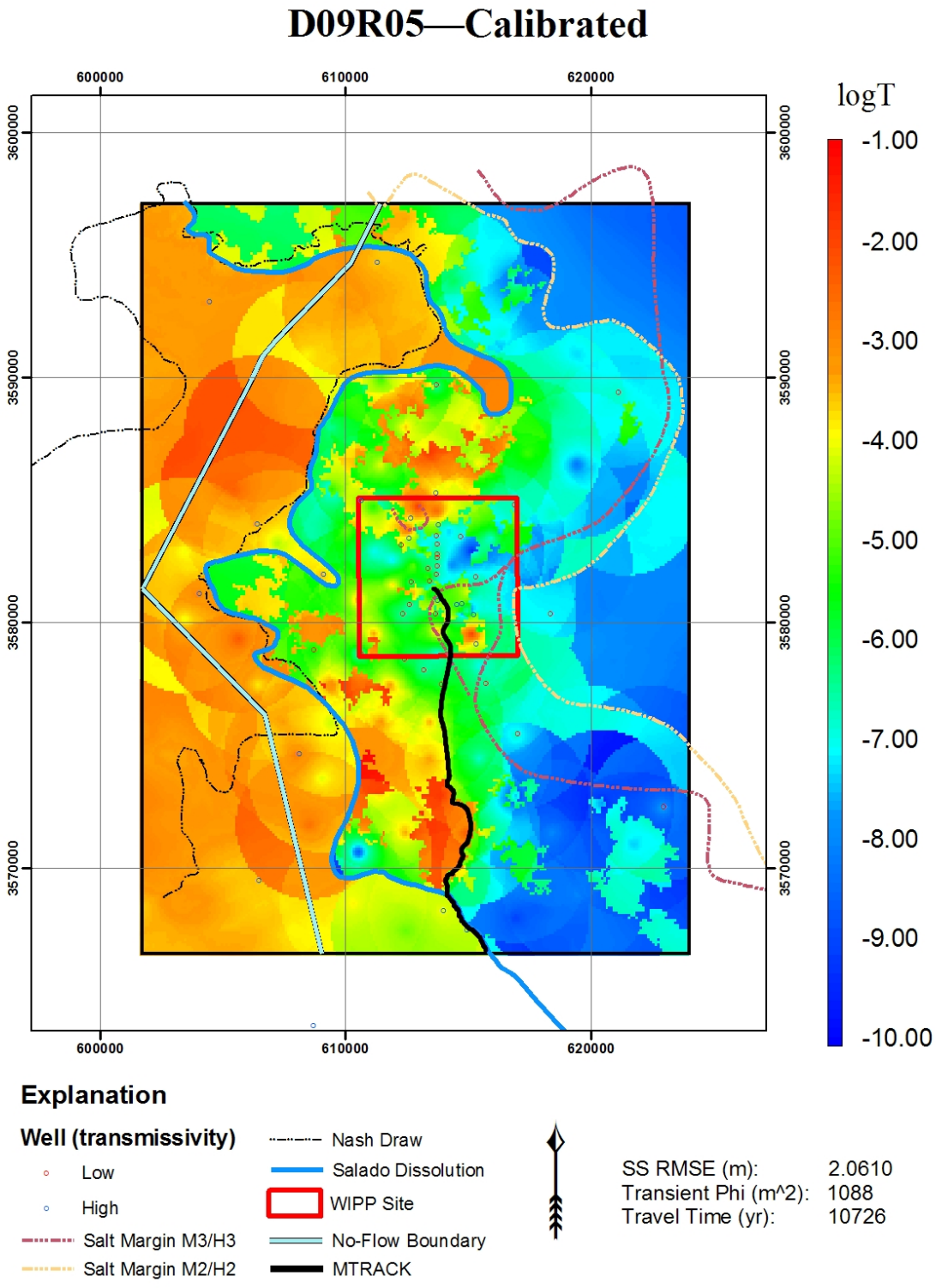
D09R05—Calibrated
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3600000
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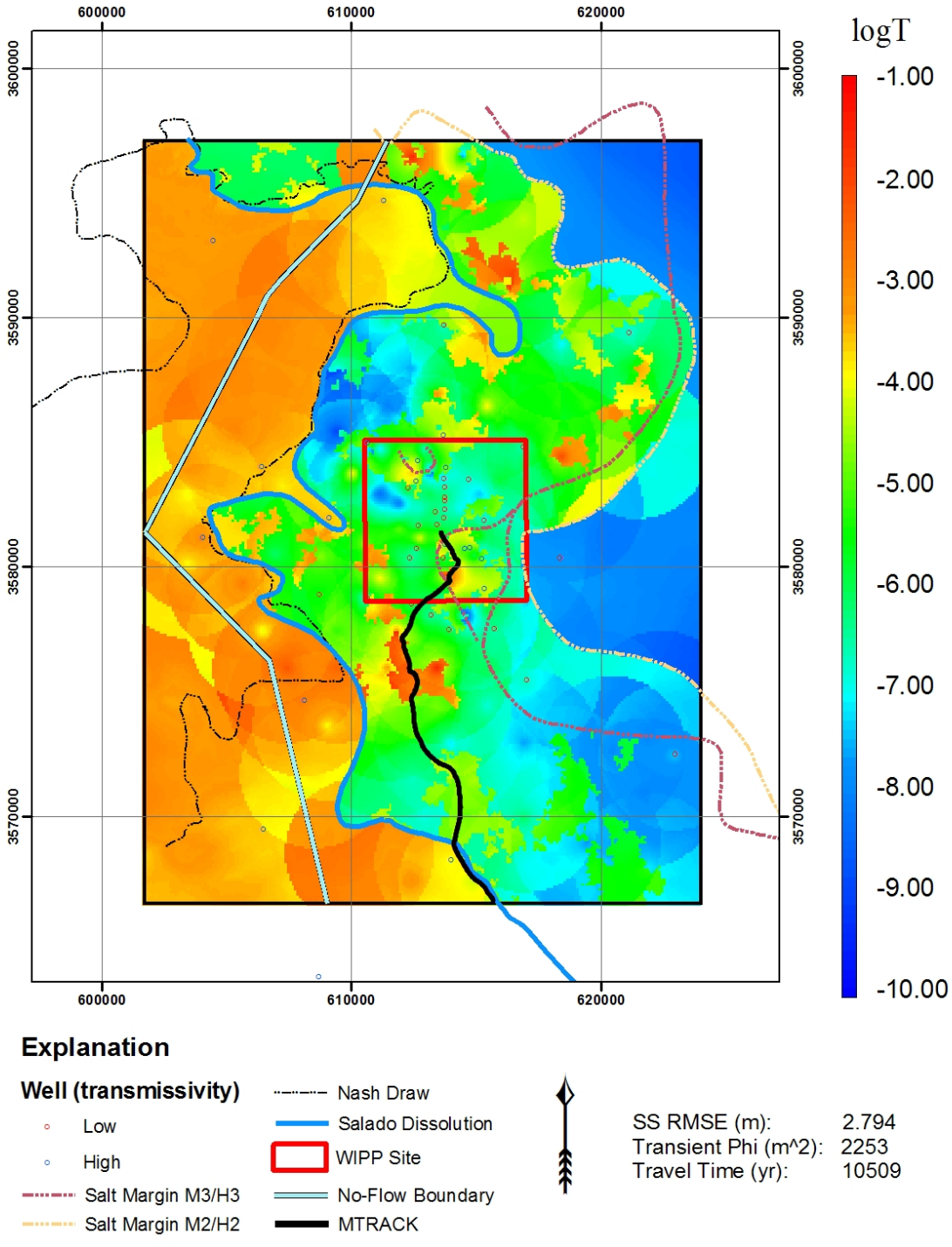
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.0610
Transient Phi (m^2): 1088
Travel Time (yr): 10726

1

D09R06—Calibrated



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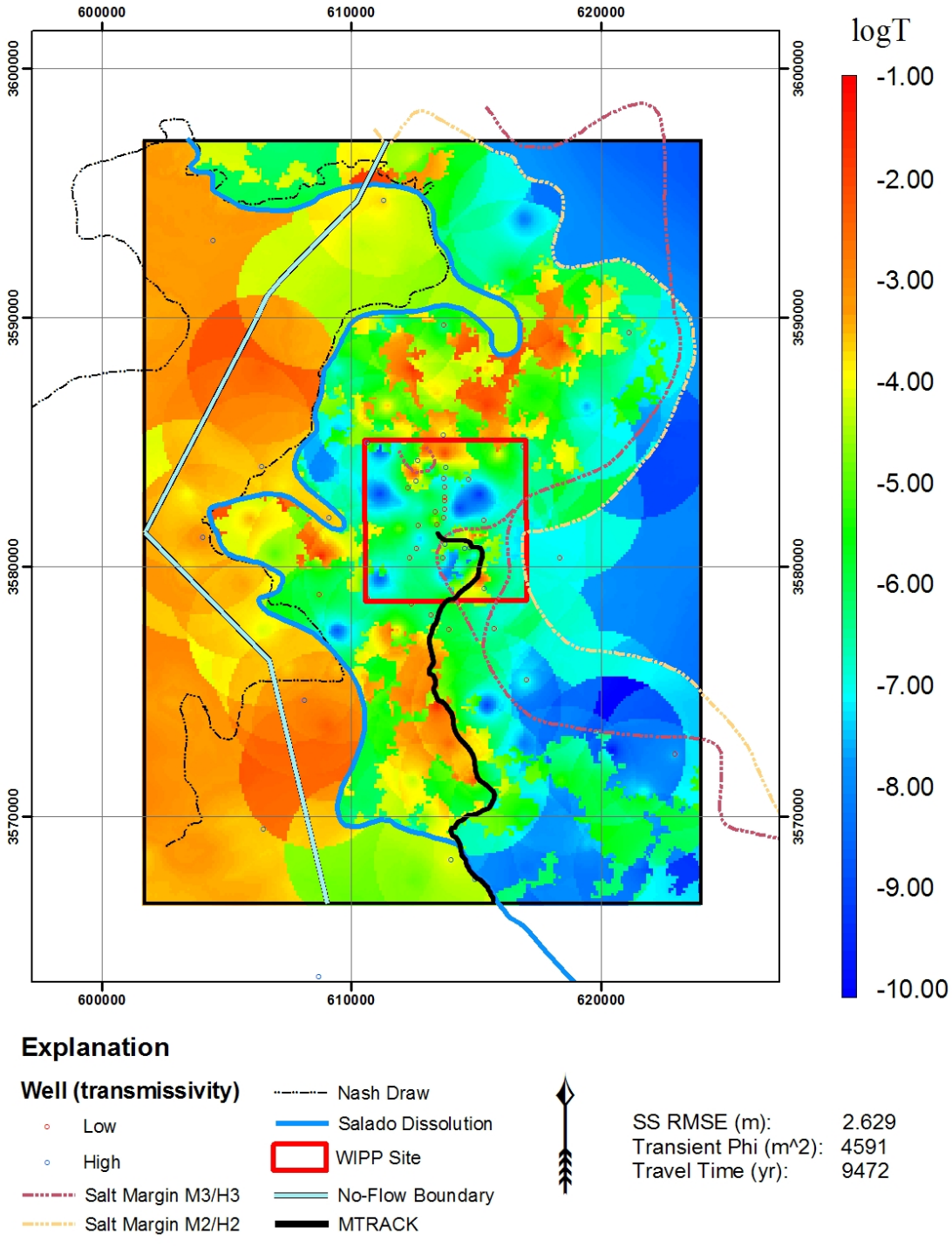
D09R07—Calibrated



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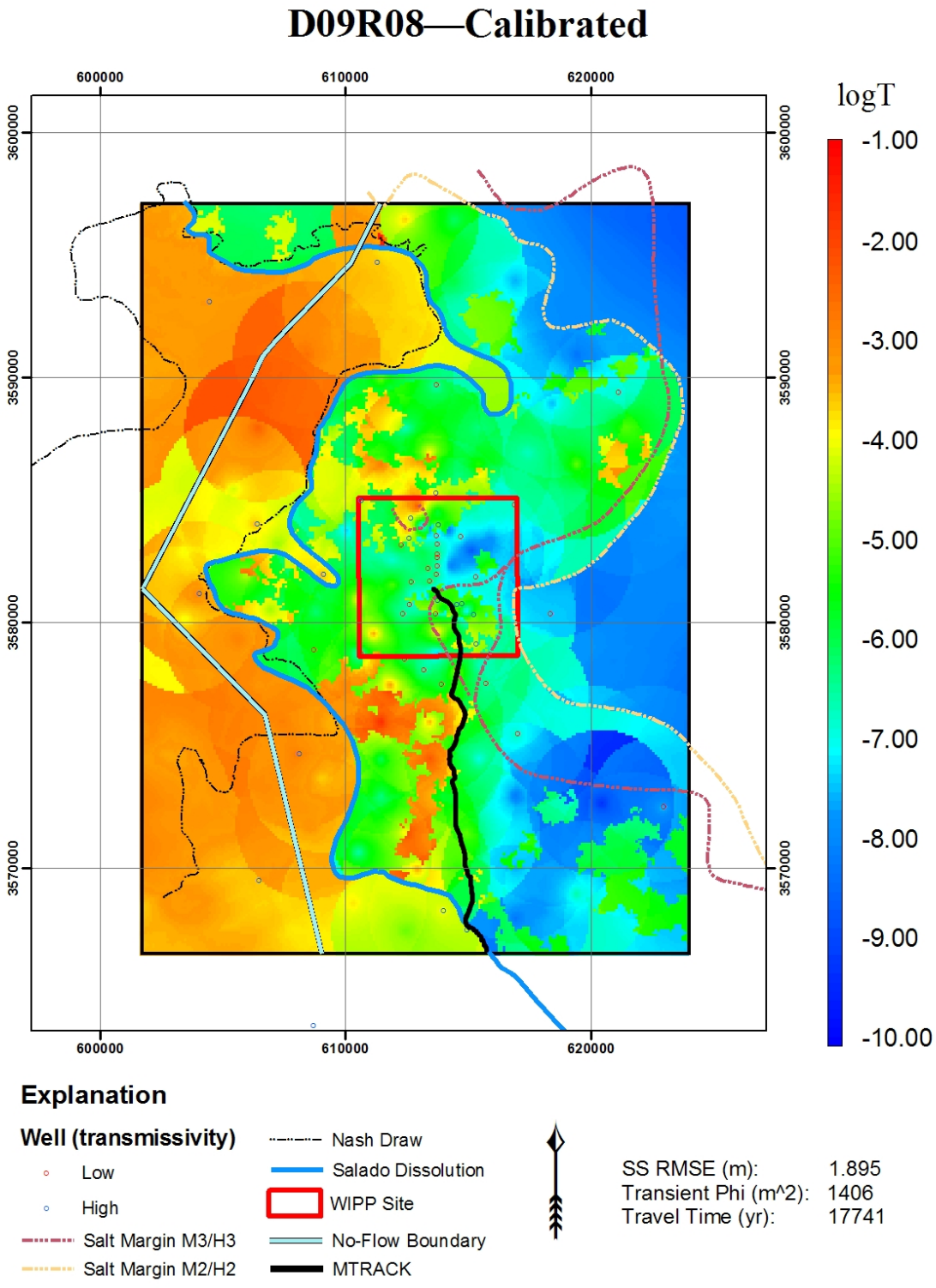
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logT
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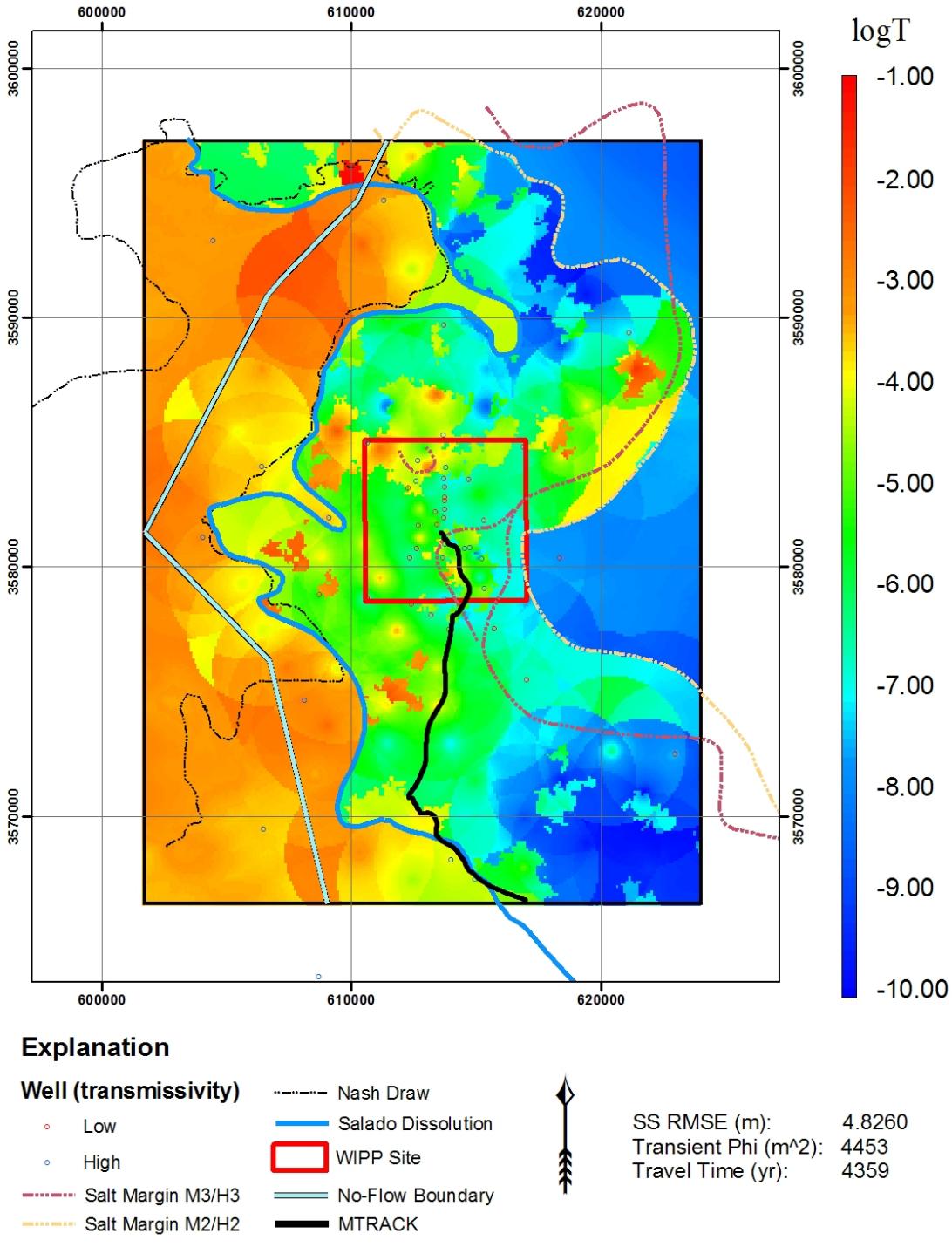
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.895
Transient Phi (m^2): 1406
Travel Time (yr): 17741

1

D09R09—Calibrated



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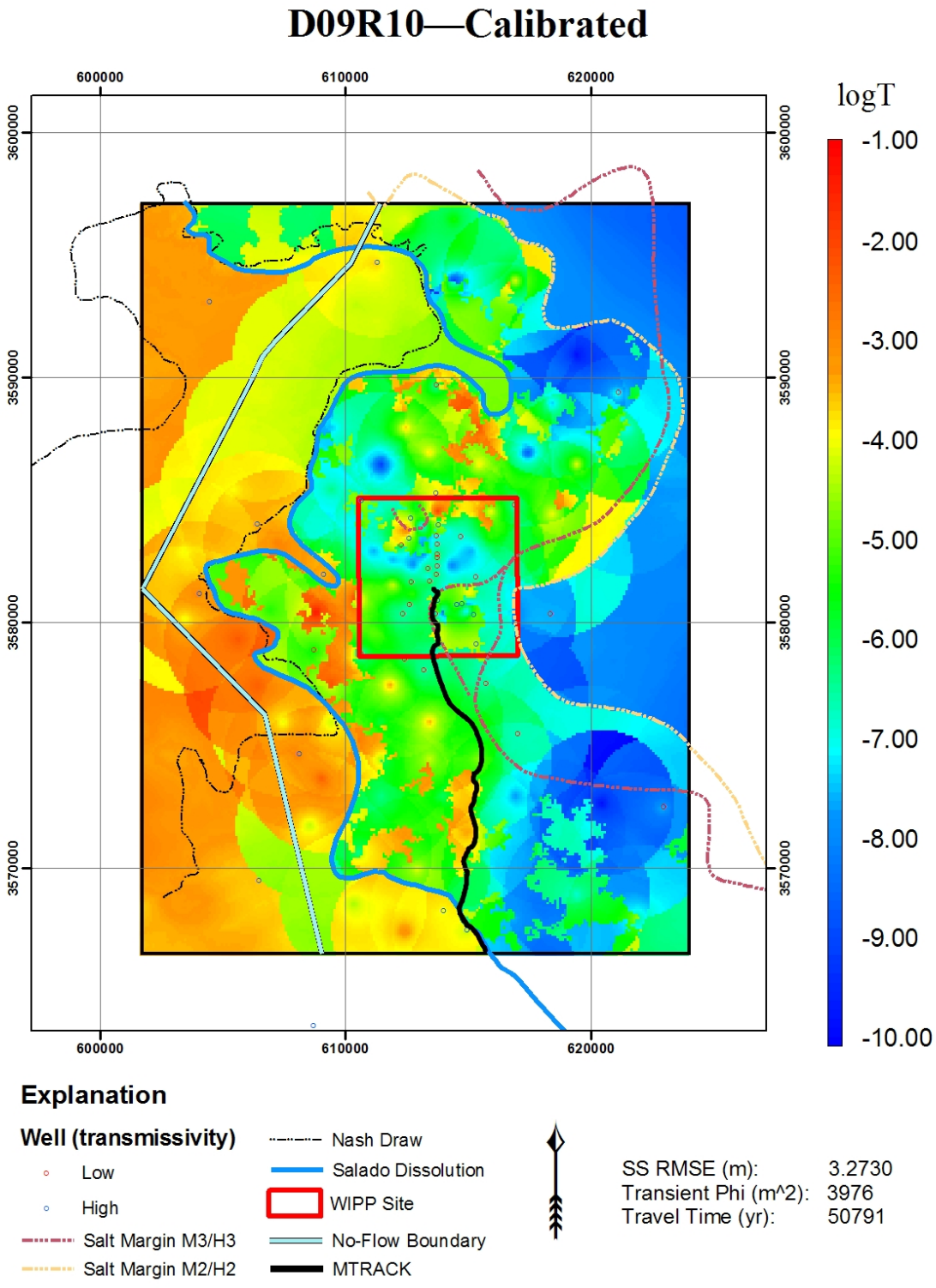
D09R10—Calibrated
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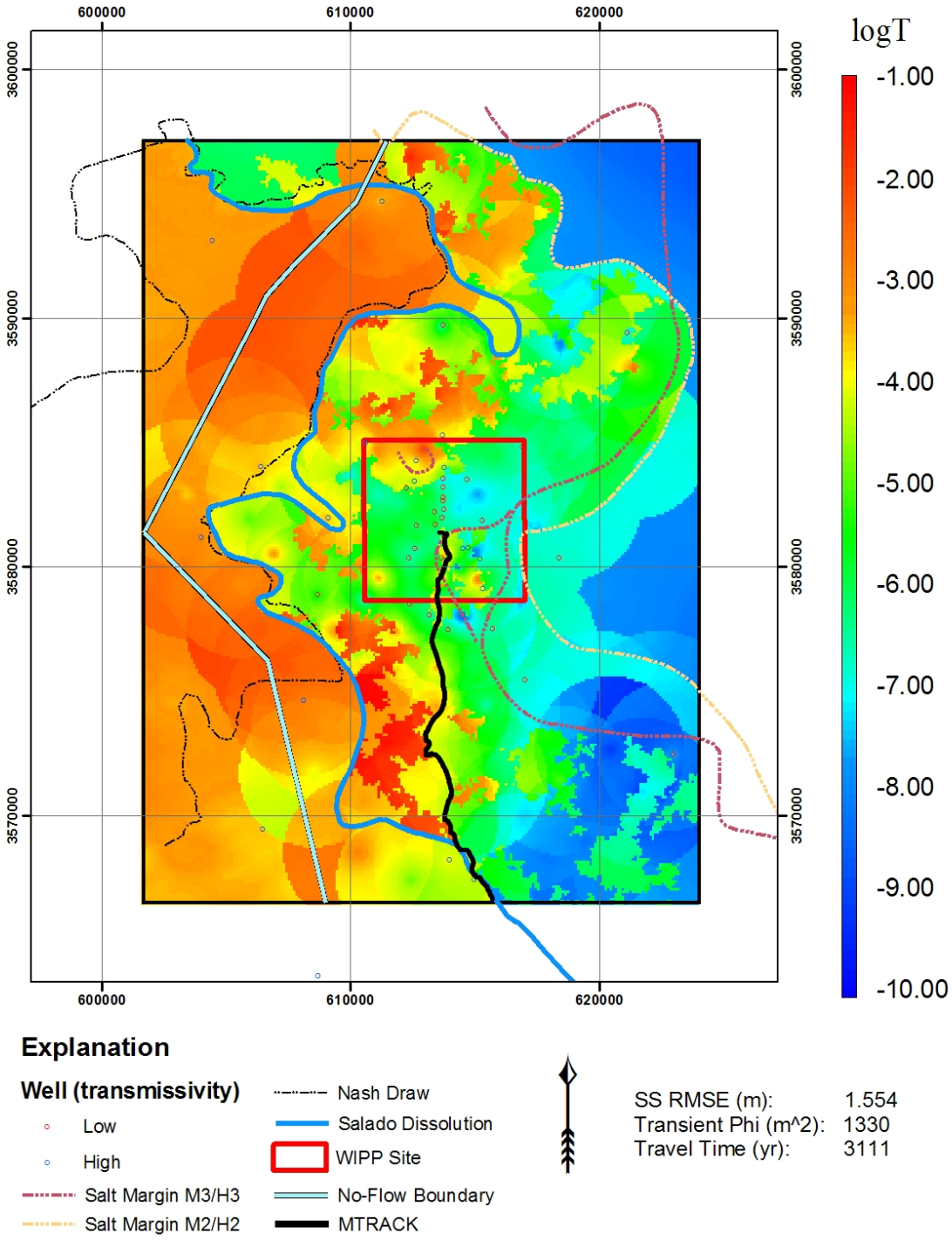
3600000
3590000
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.2730
Transient Phi (m^2): 3976
Travel Time (yr): 50791

1

D10R02—Calibrated



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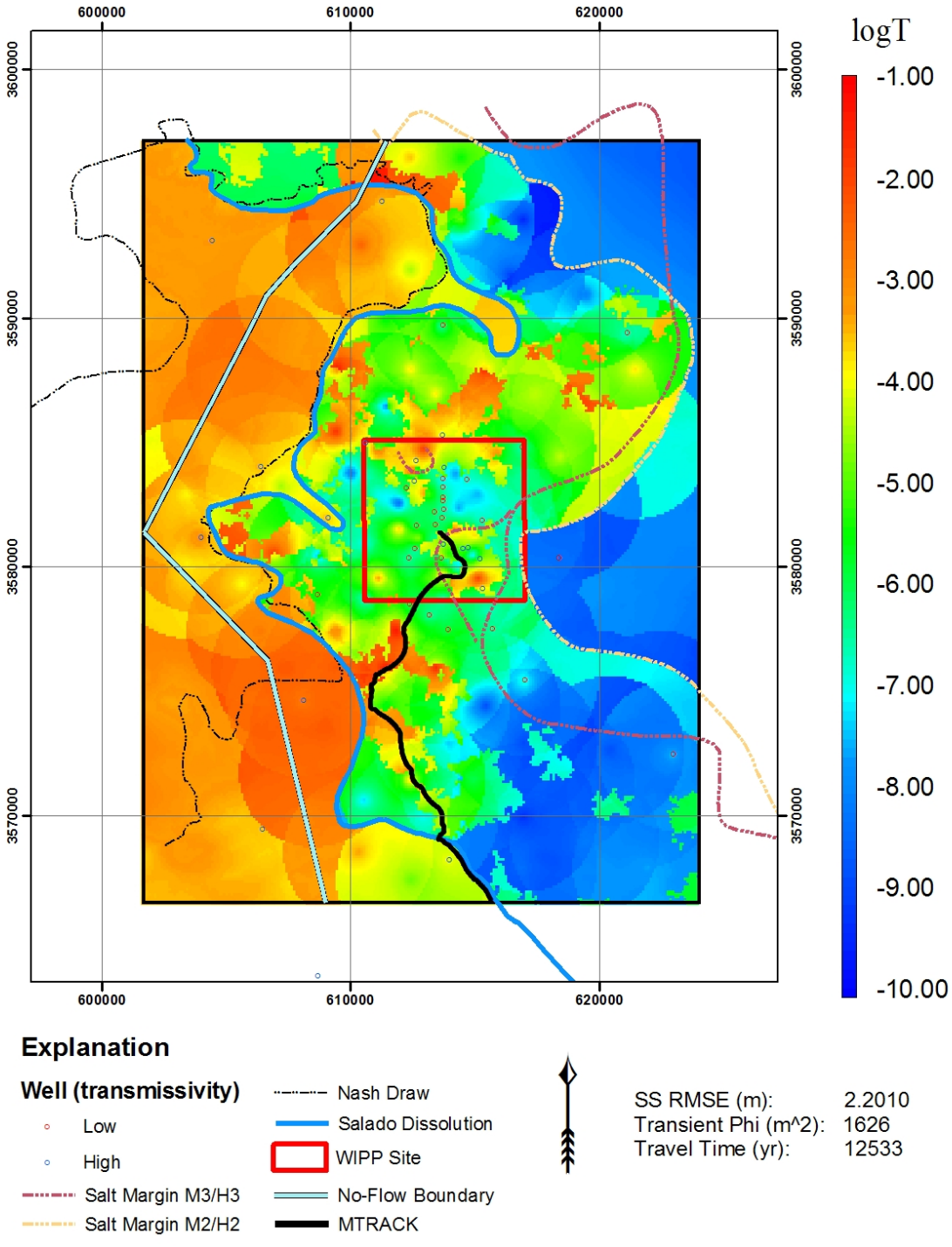
D10R03—Calibrated



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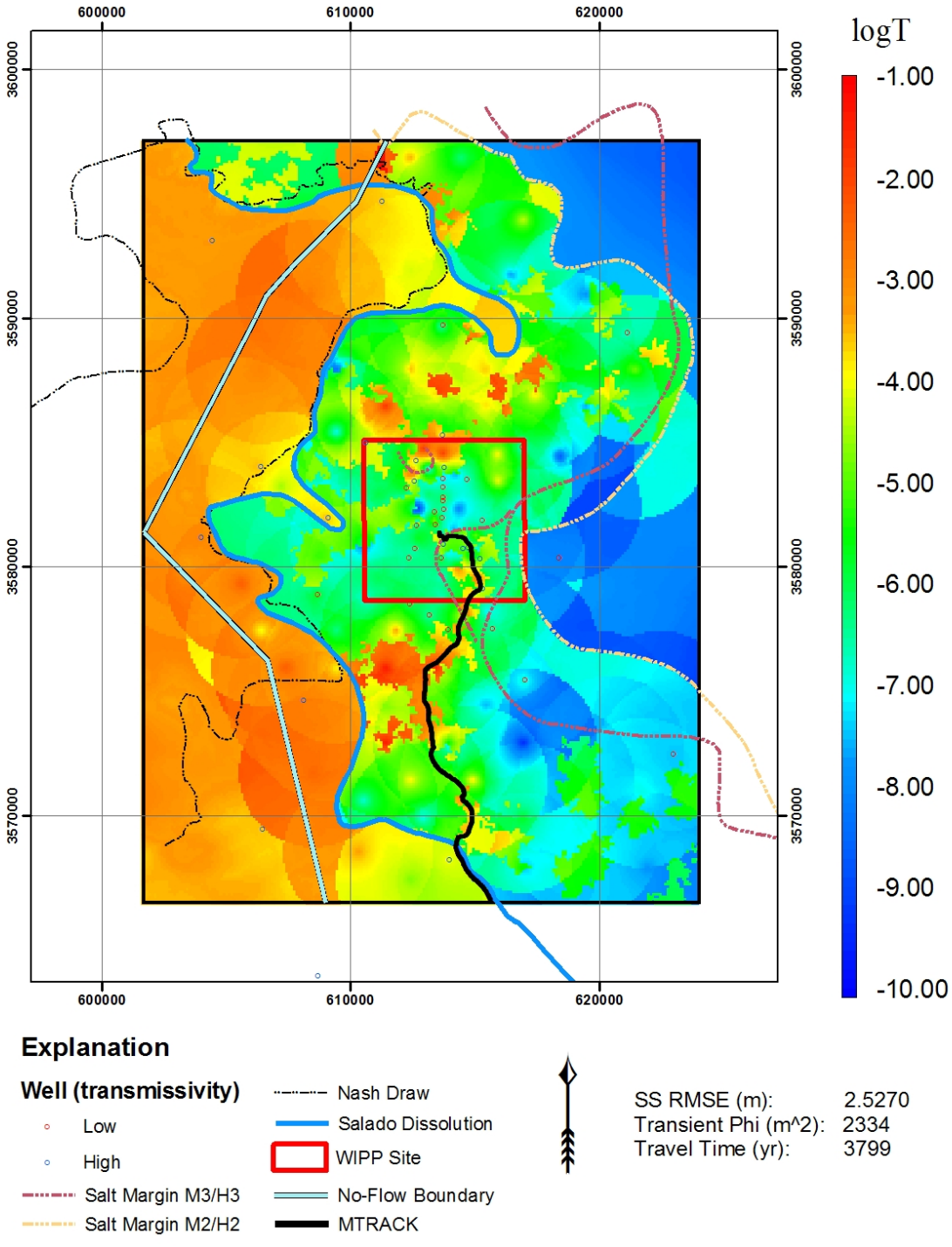
D10R04—Calibrated



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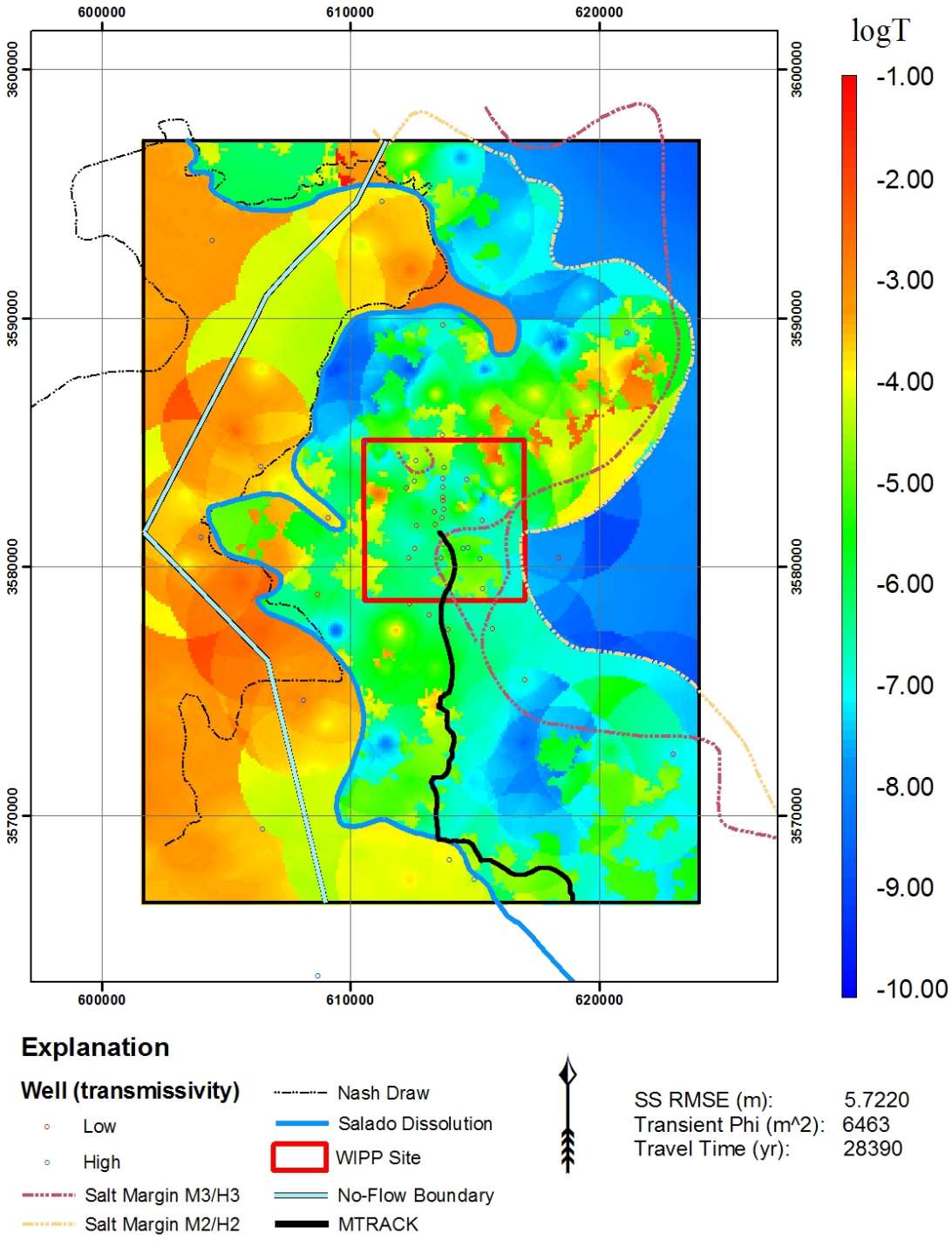
D10R05—Calibrated



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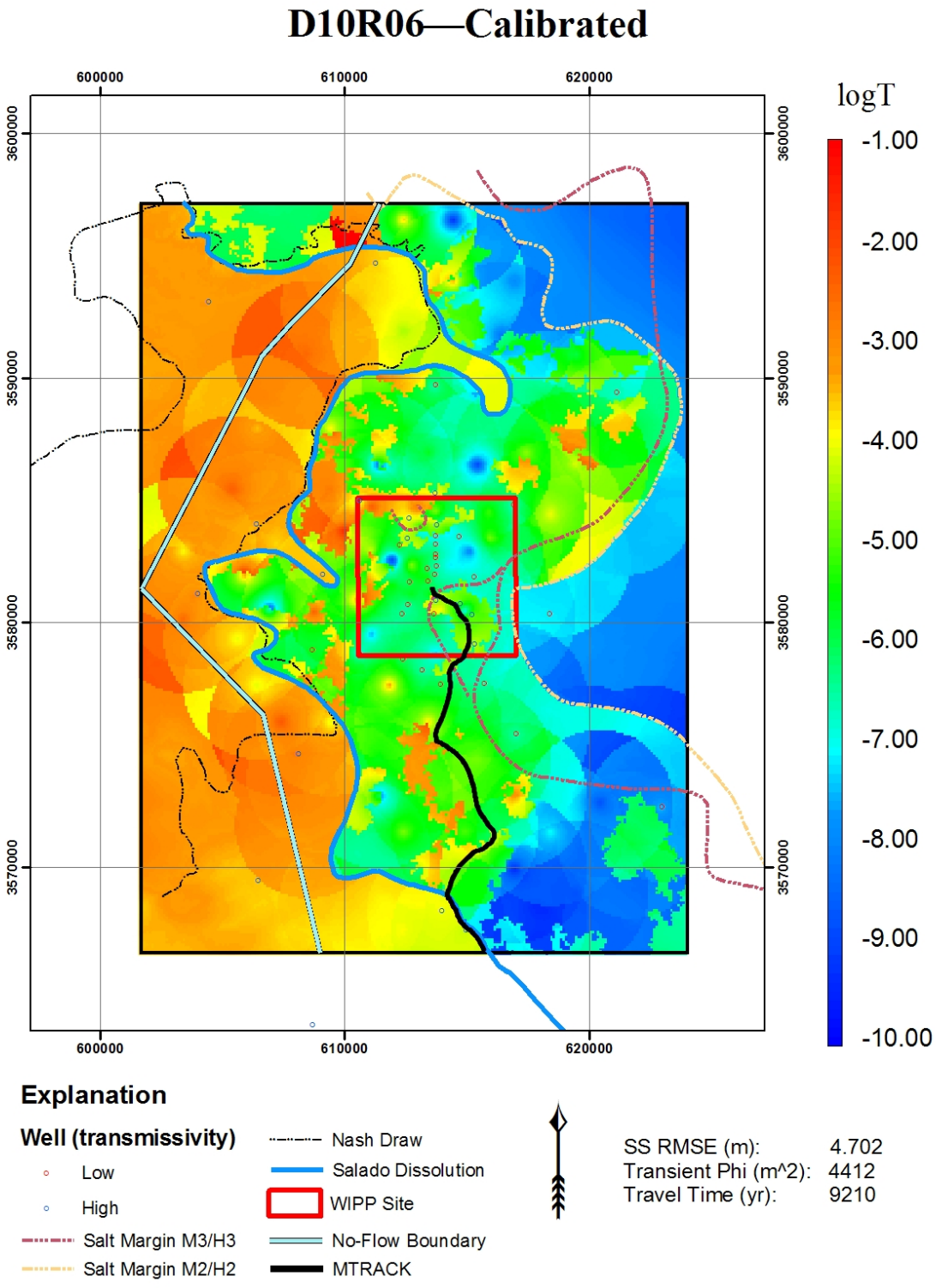
D10R06—Calibrated
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3580000
3570000
logT
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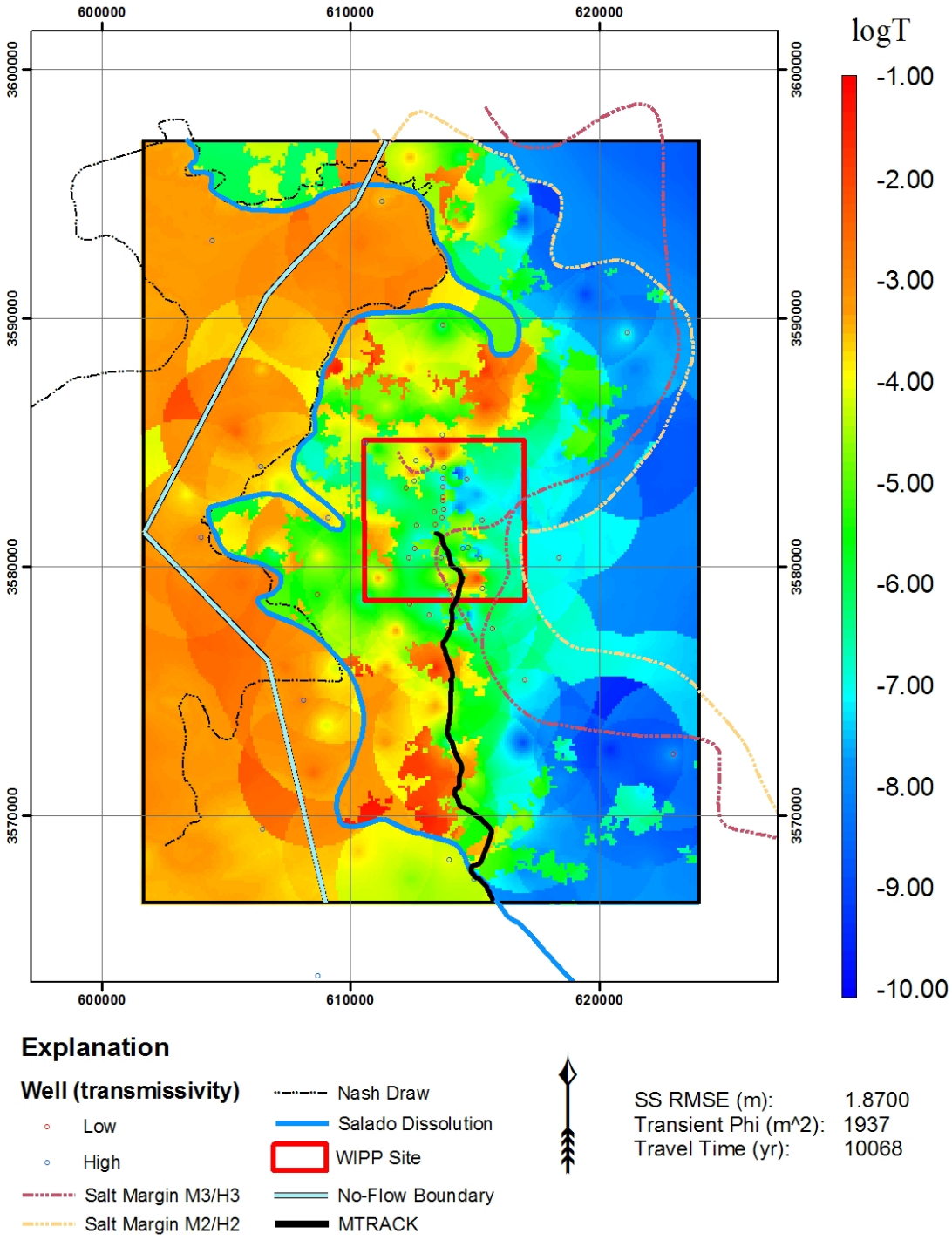
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 4.702
Transient Phi (m^2): 4412
Travel Time (yr): 9210

1

D10R07—Calibrated



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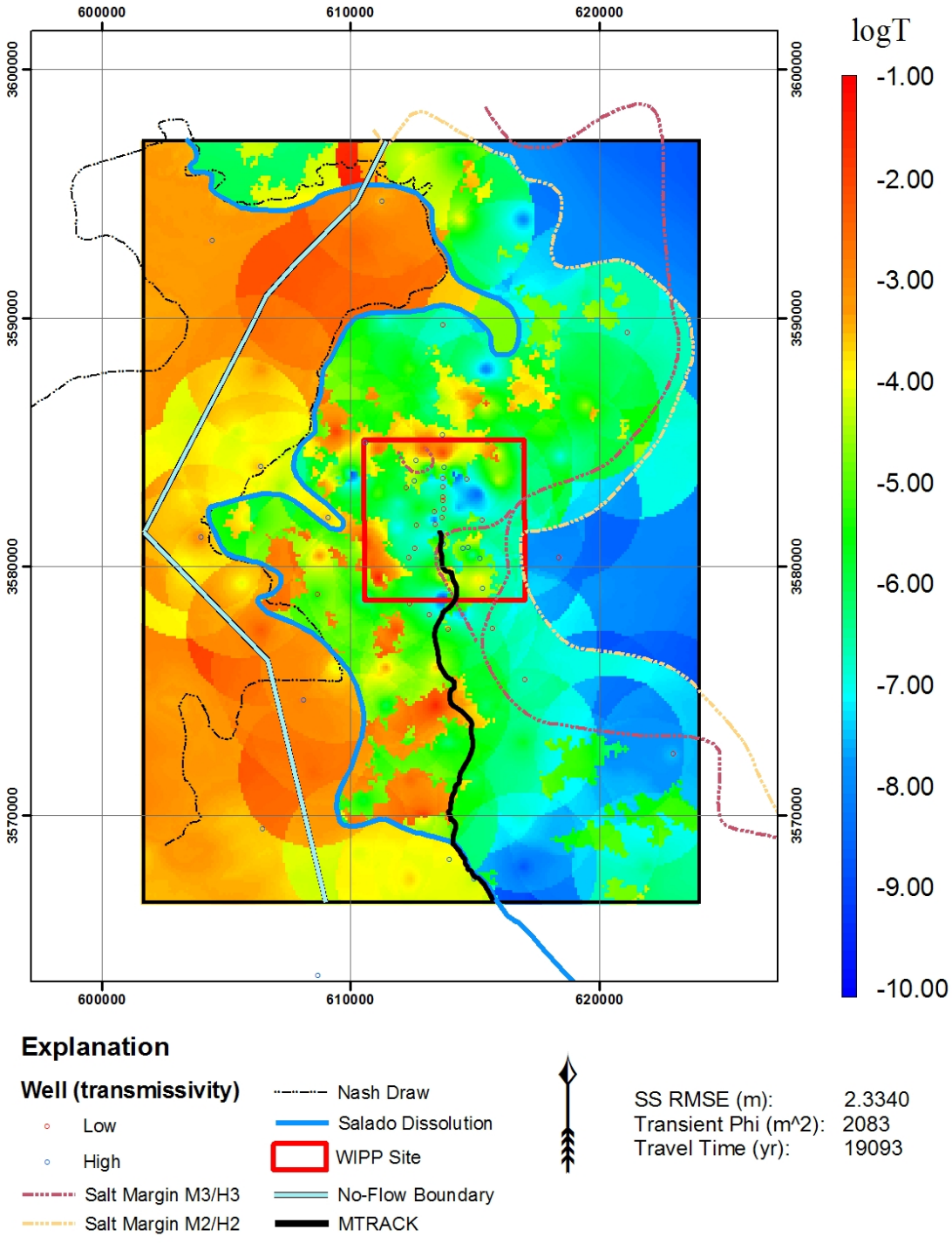
D10R08—Calibrated



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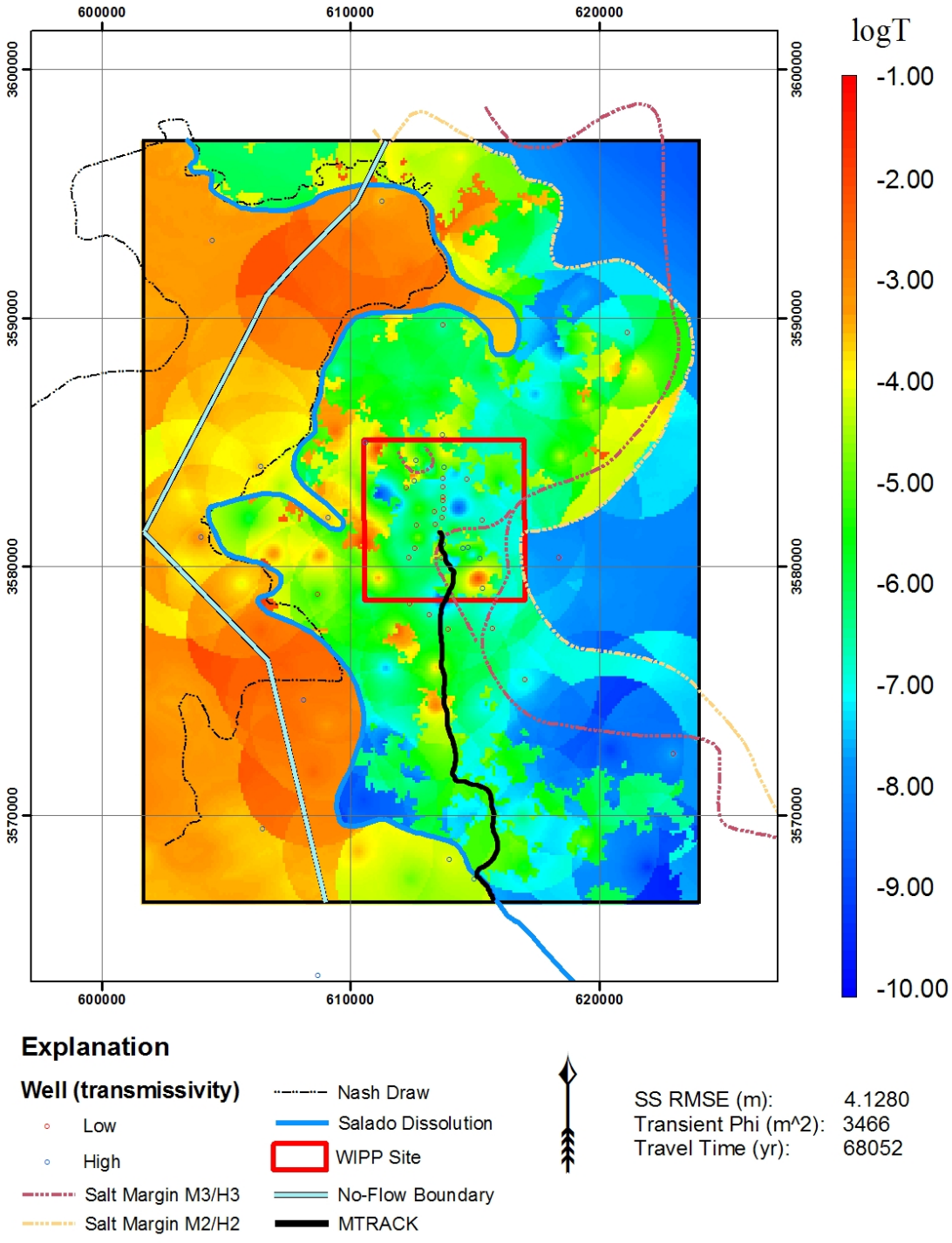
D10R09—Calibrated



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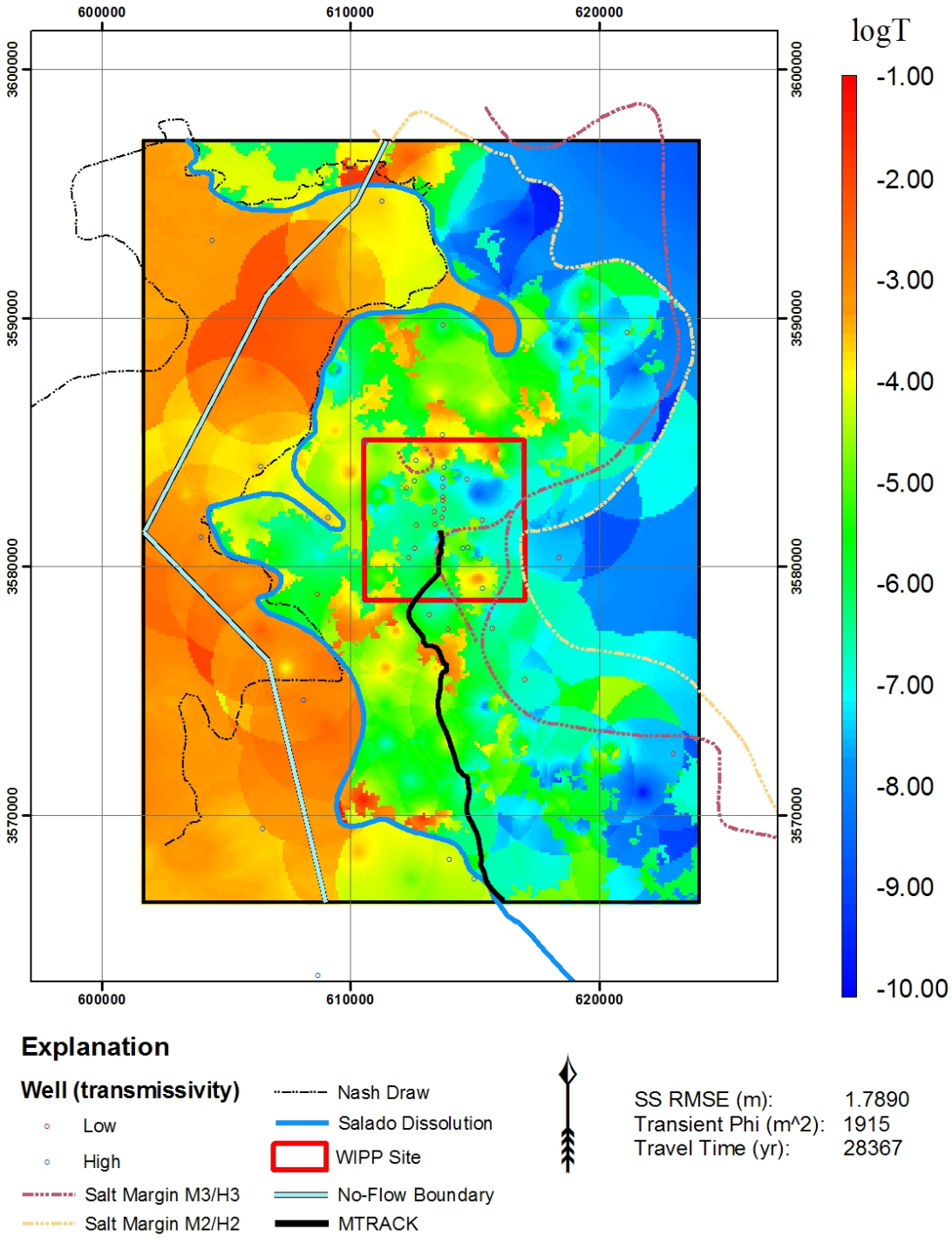
D10R10—Calibrated



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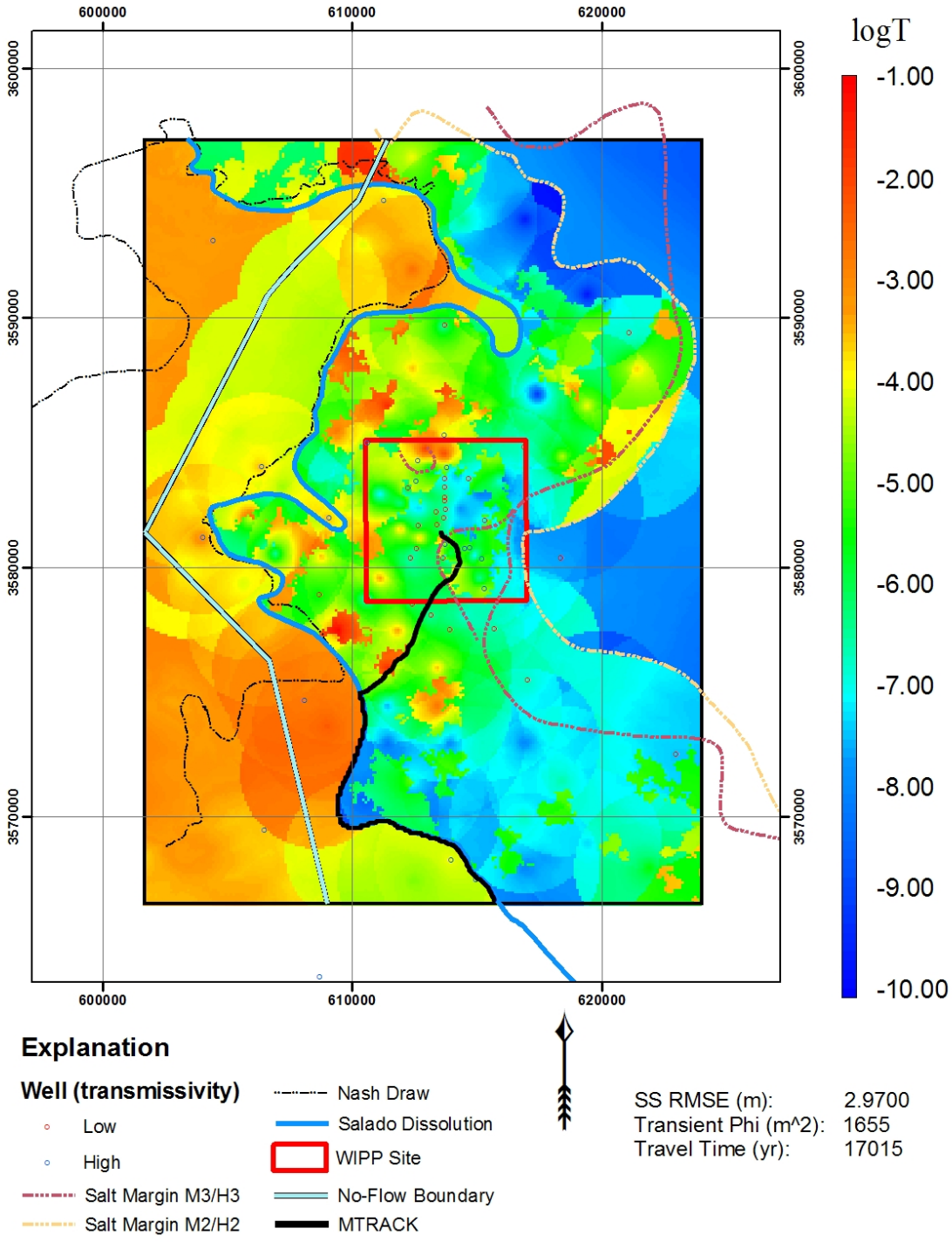
D11R01—Calibrated



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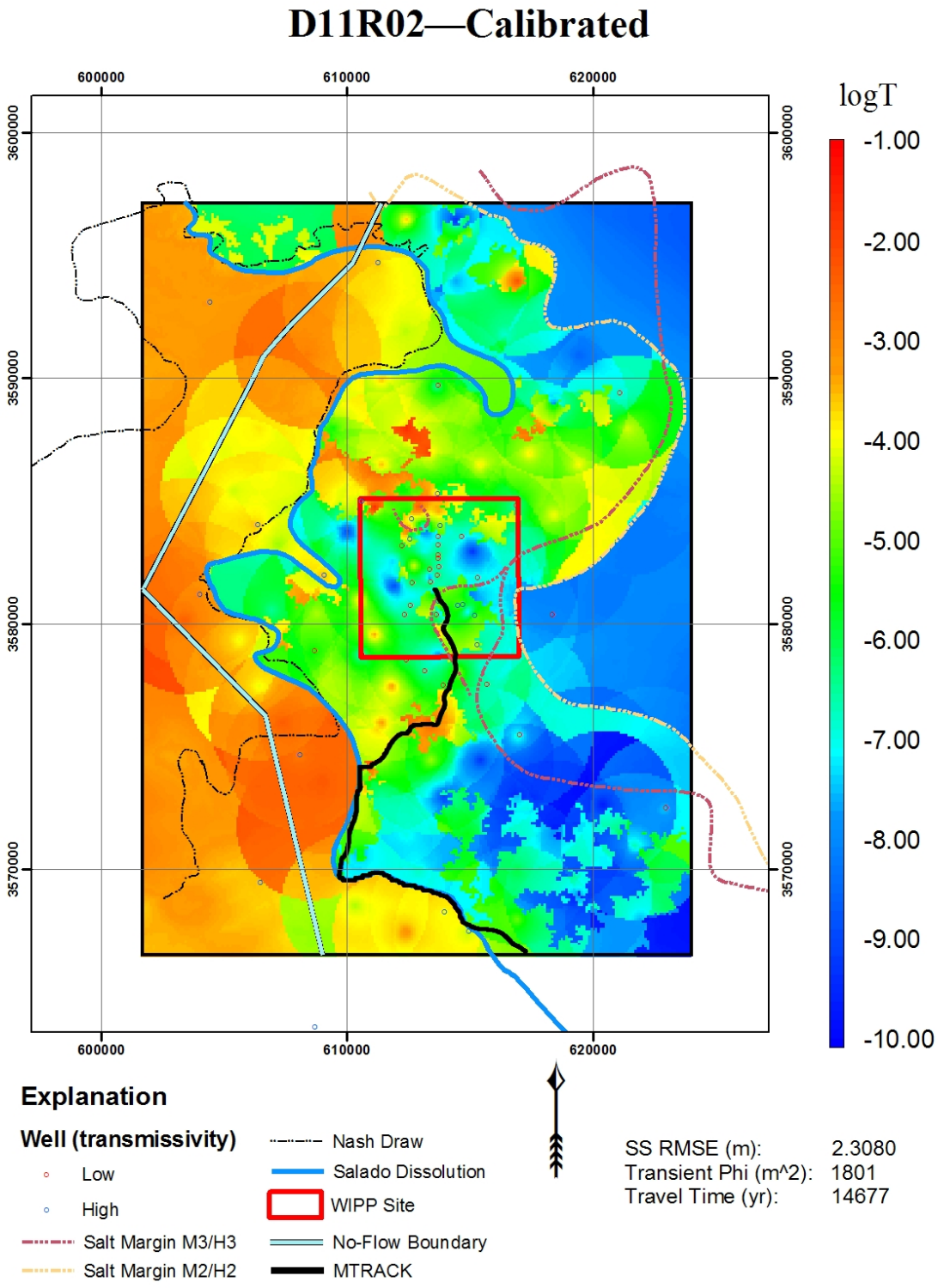
D11R02—Calibrated
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3600000
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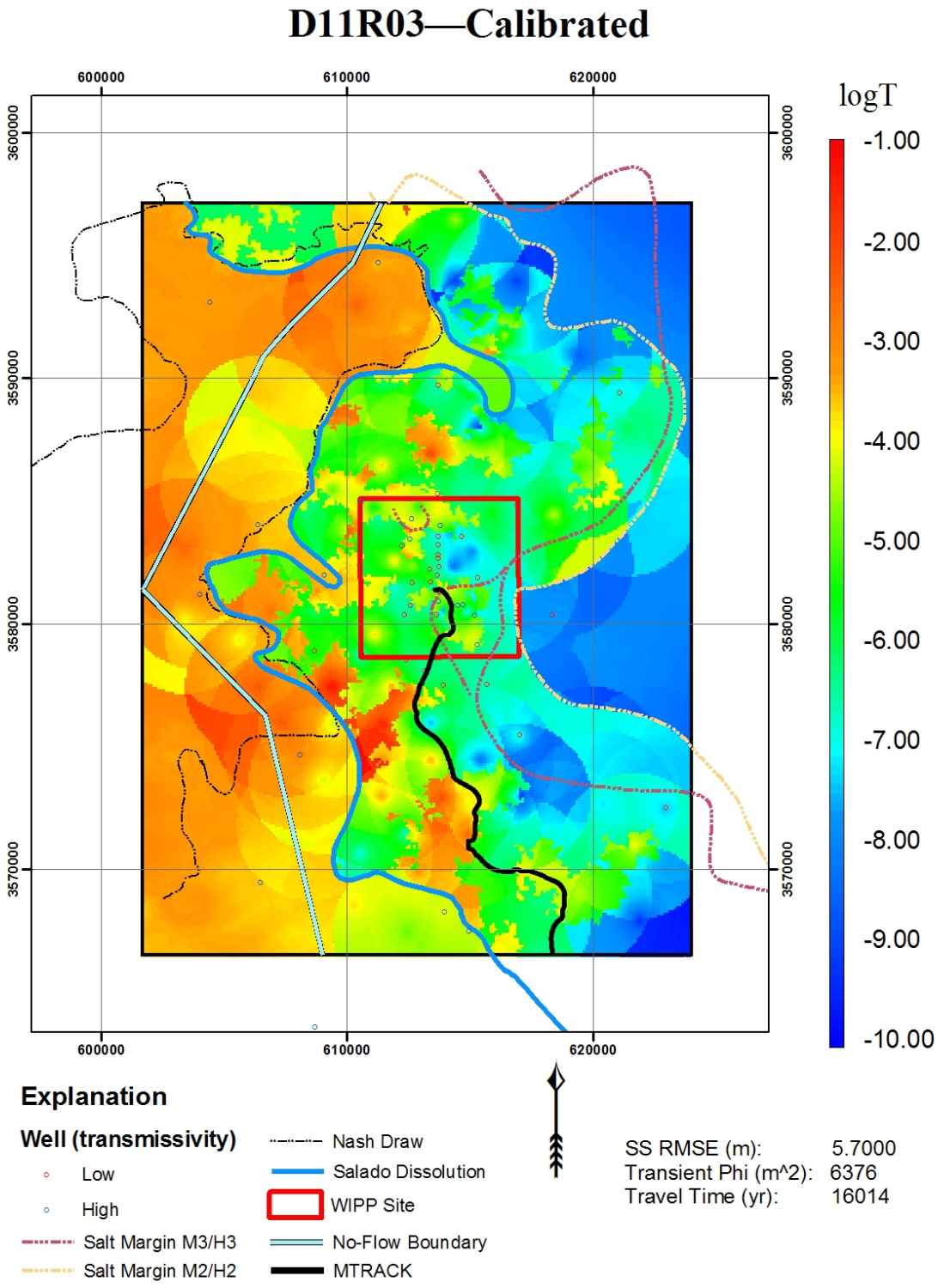
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.3080
Transient Phi (m^2): 1801
Travel Time (yr): 14677

1


D11R03—Calibrated
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3570000
logT
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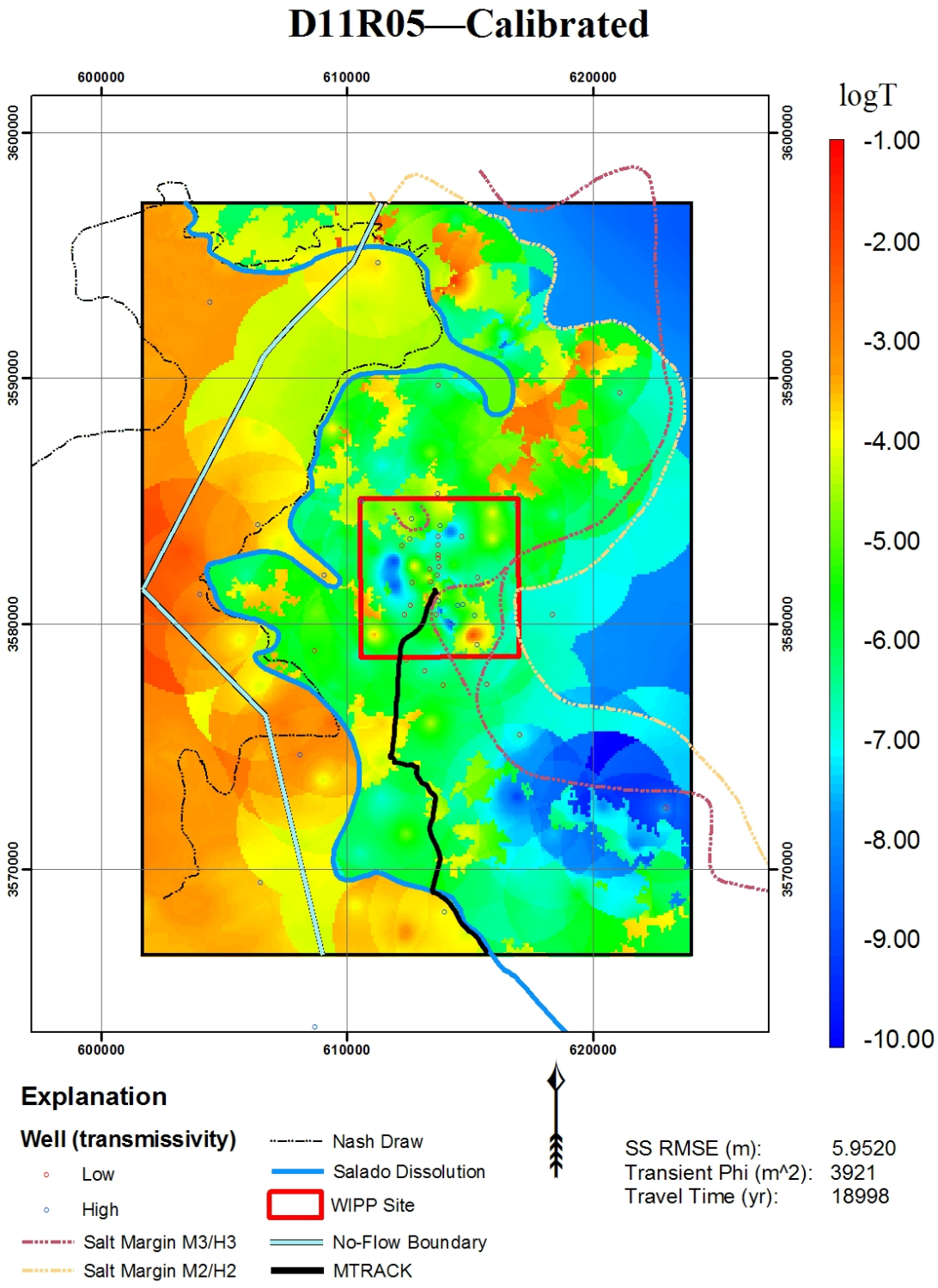
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.7000
Transient Phi (m^2): 6376
Travel Time (yr): 16014

1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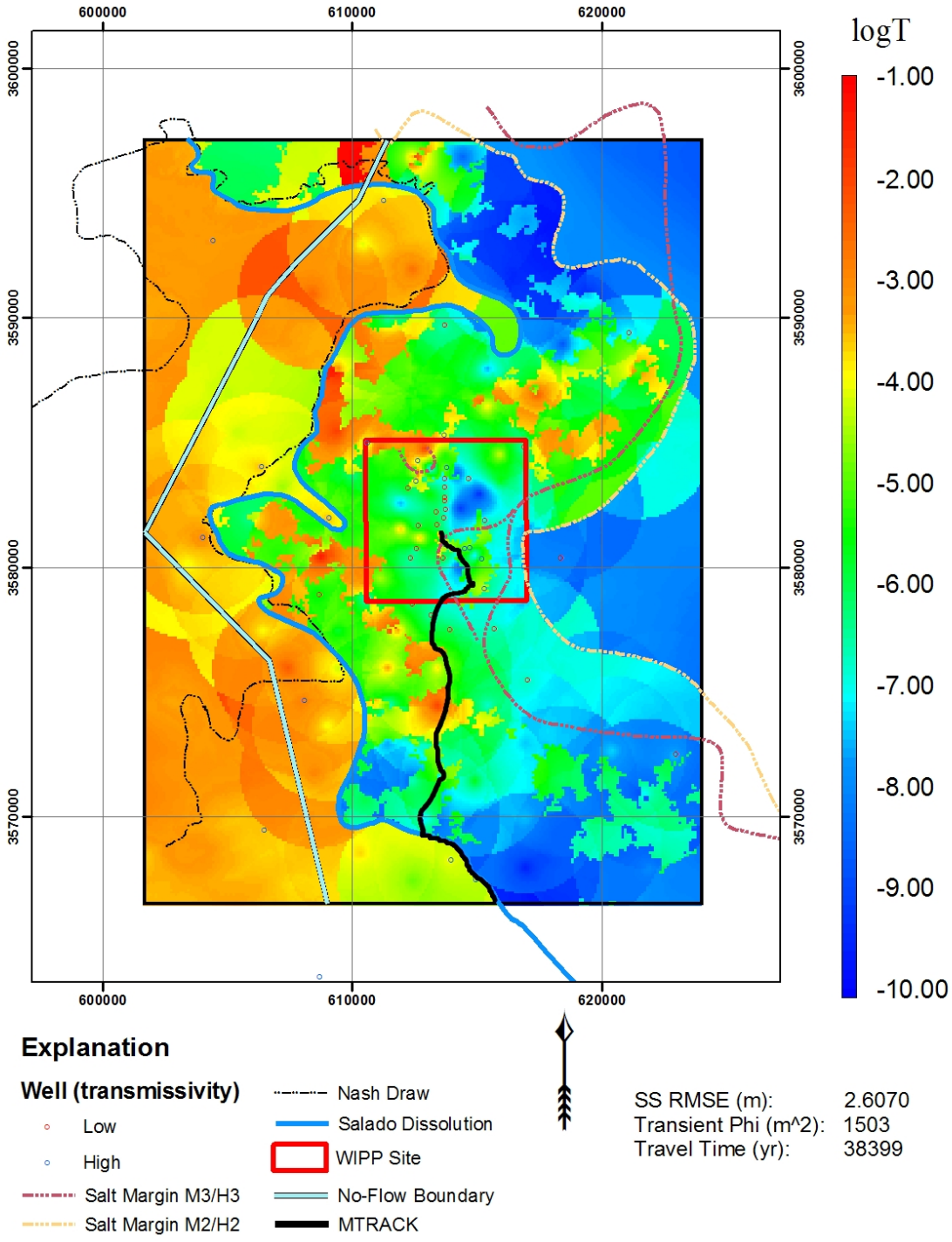
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.9520
Transient Phi (m^2): 3921
Travel Time (yr): 18998

1

D11R06—Calibrated



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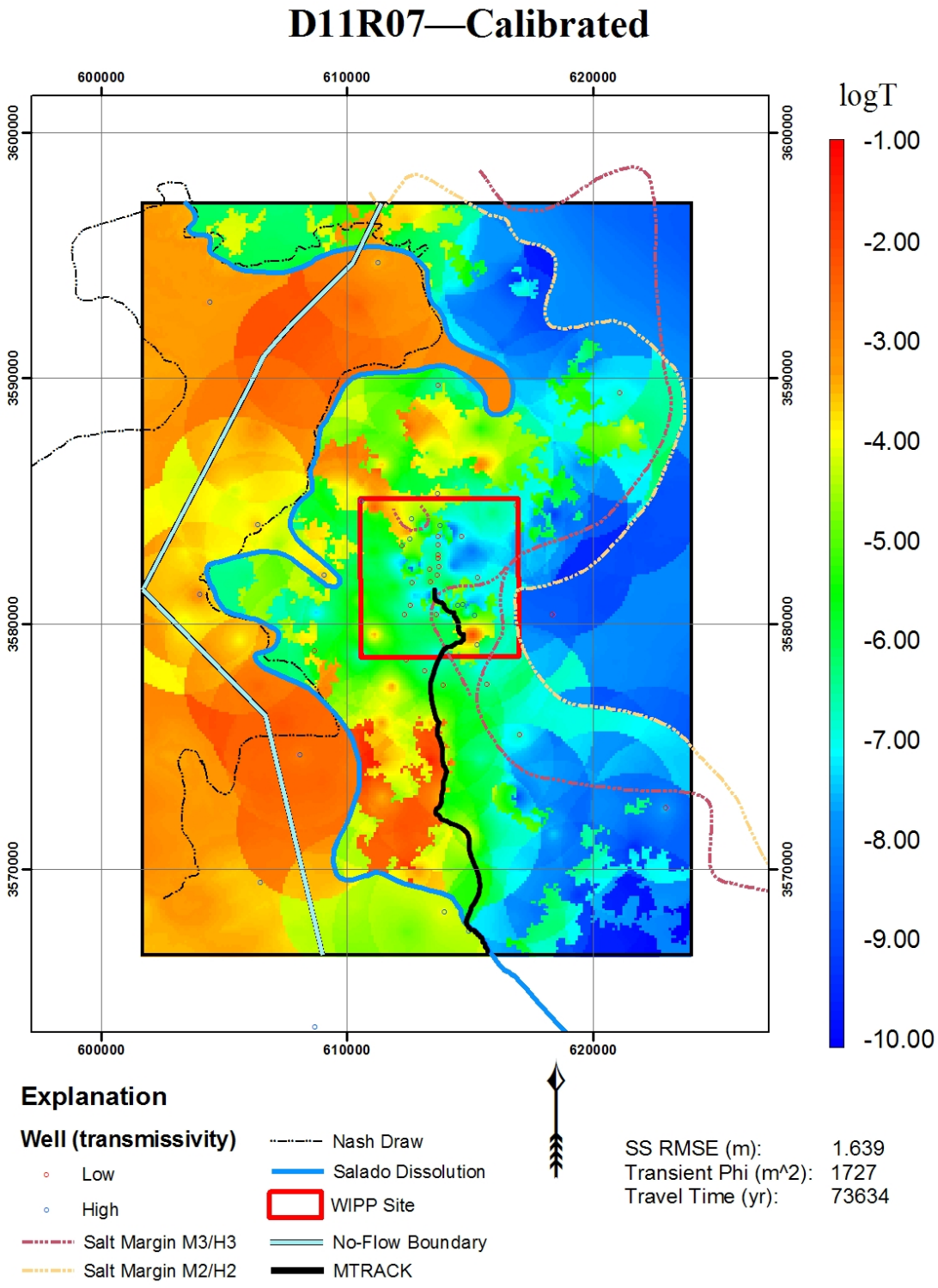
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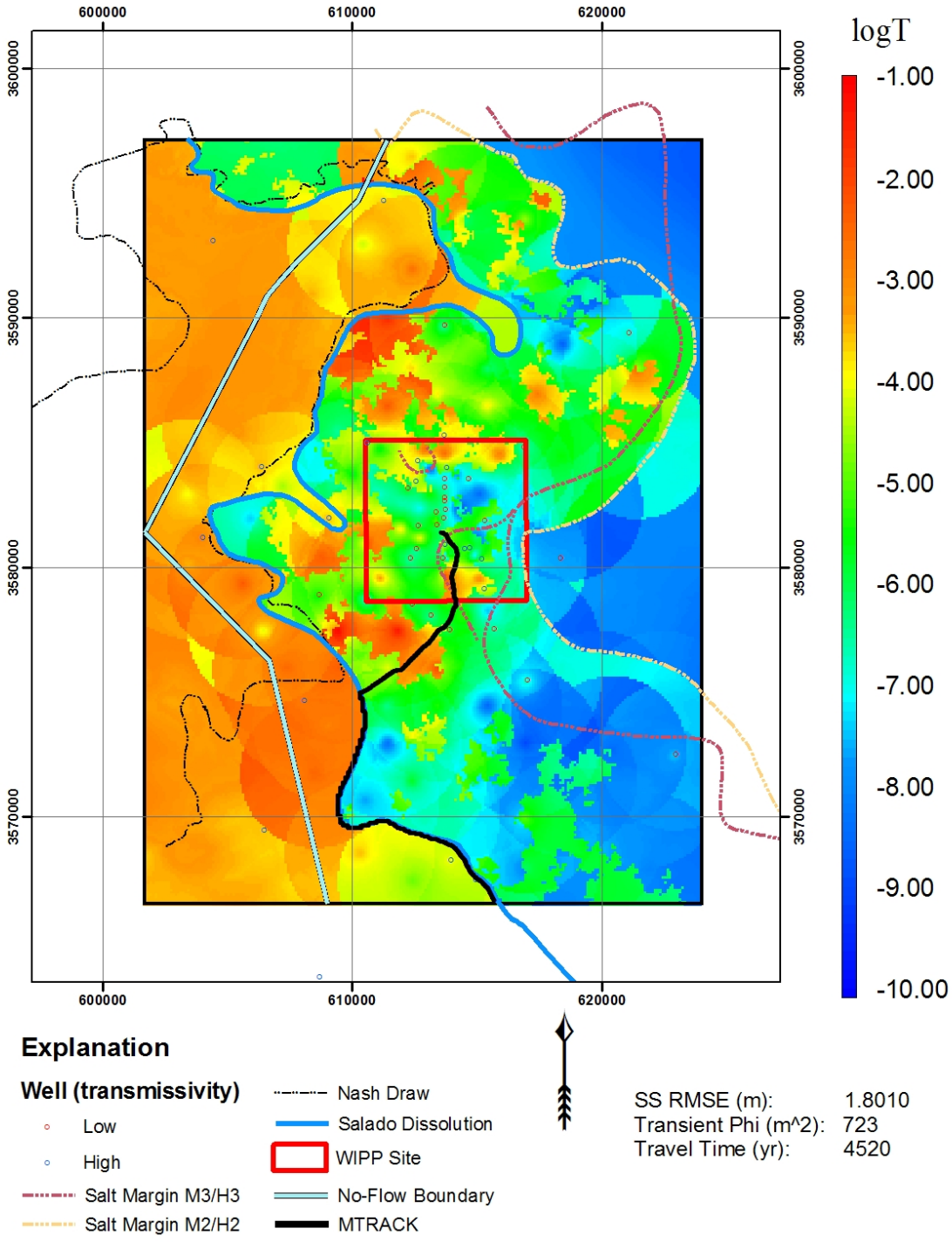
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.639
Transient Phi (m^2): 1727
Travel Time (yr): 73634

1

D11R08—Calibrated



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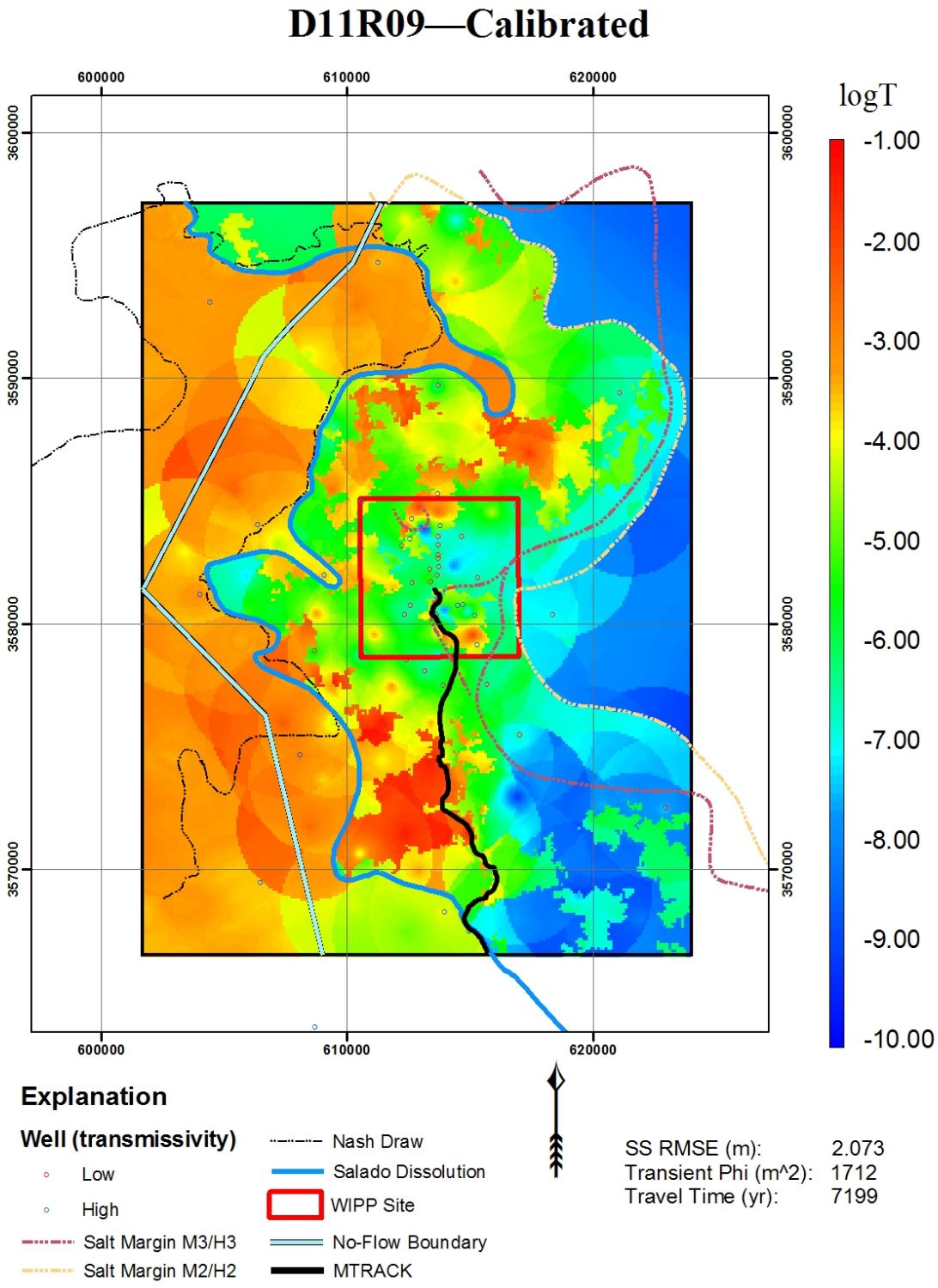
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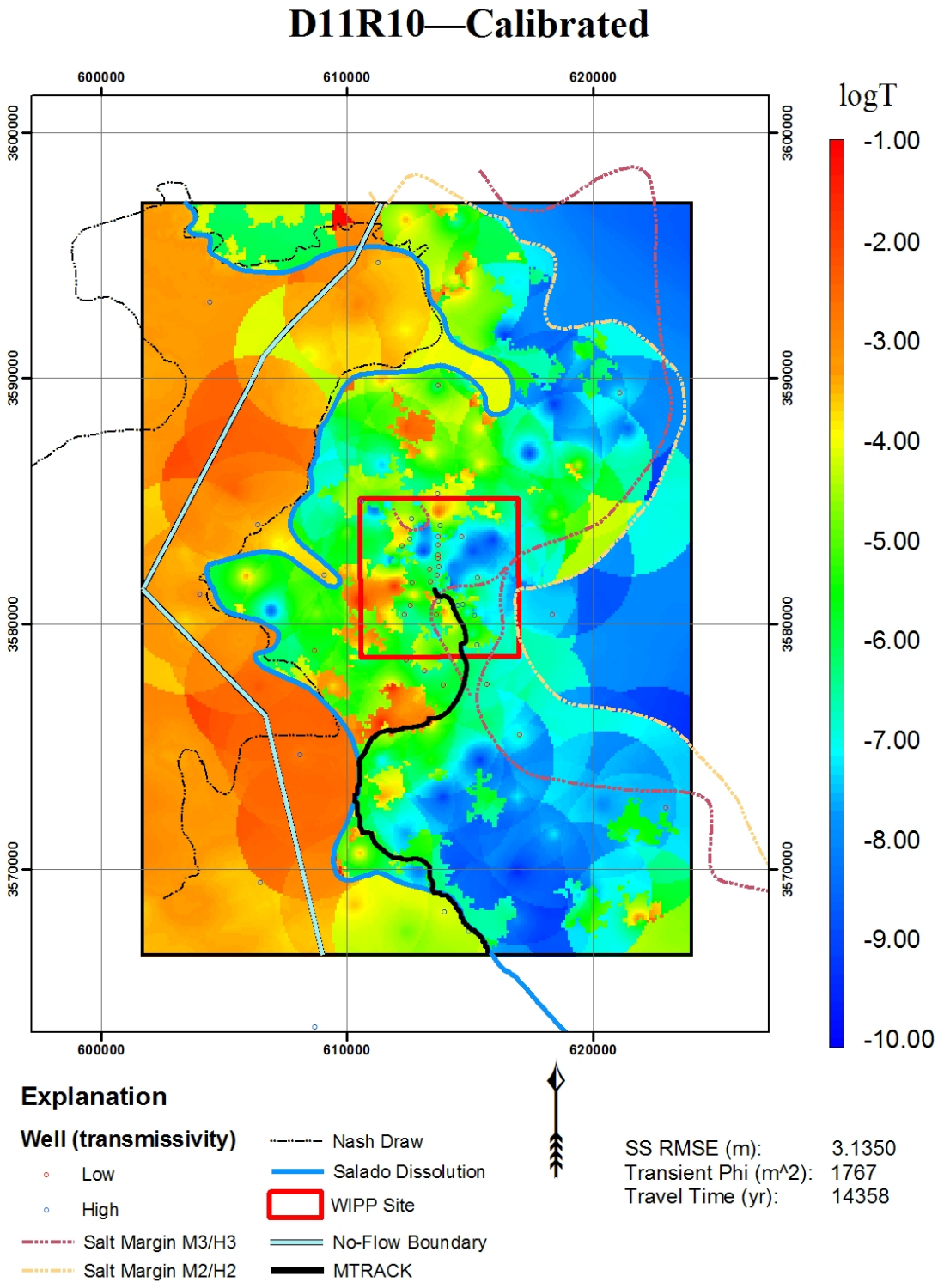
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.073
Transient Phi (m^2): 1712
Travel Time (yr): 7199

1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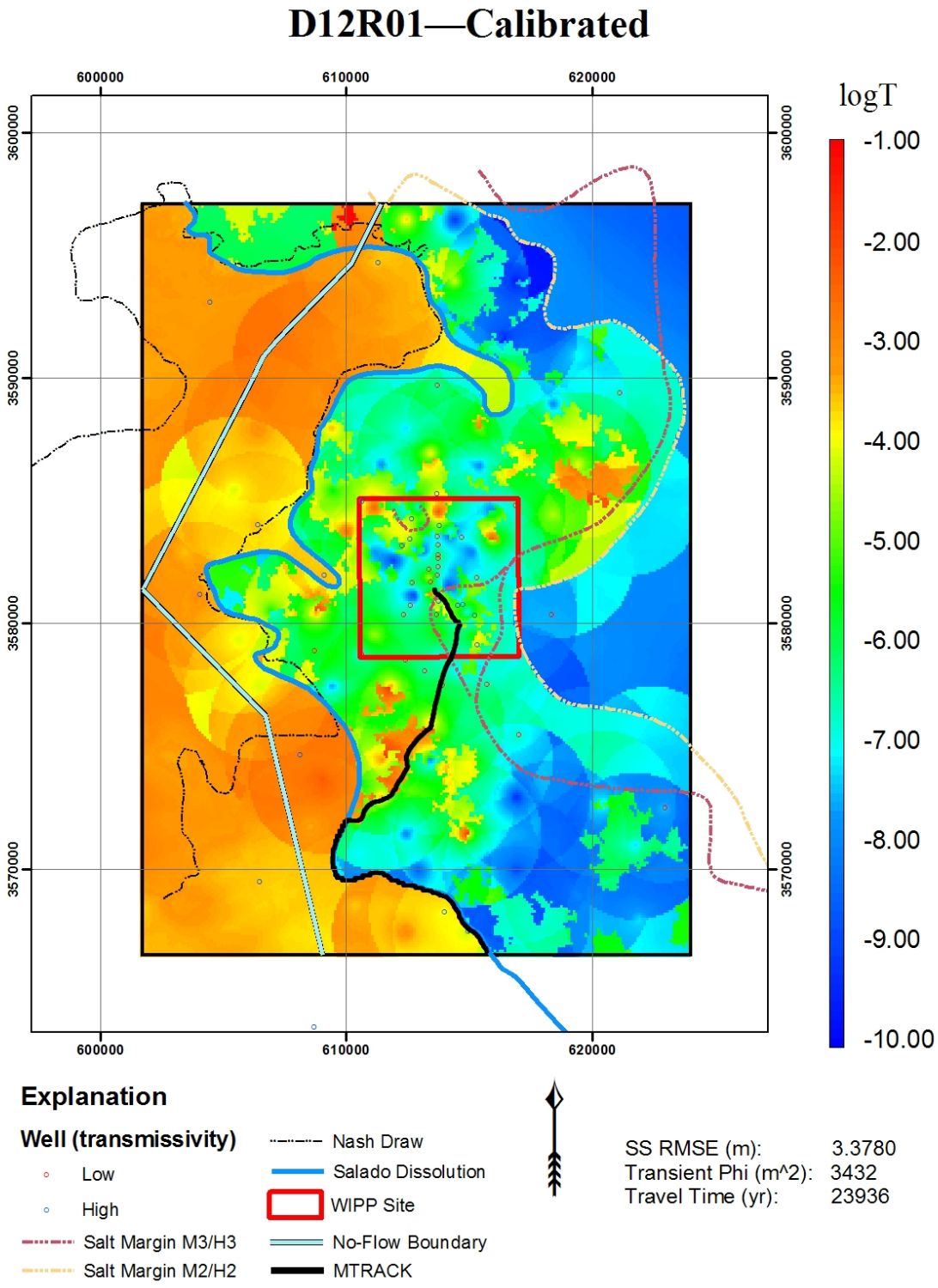
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.1350
Transient Phi (m^2): 1767
Travel Time (yr): 14358

1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Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 3.3780
Transient Phi (m^2): 3432
Travel Time (yr): 23936

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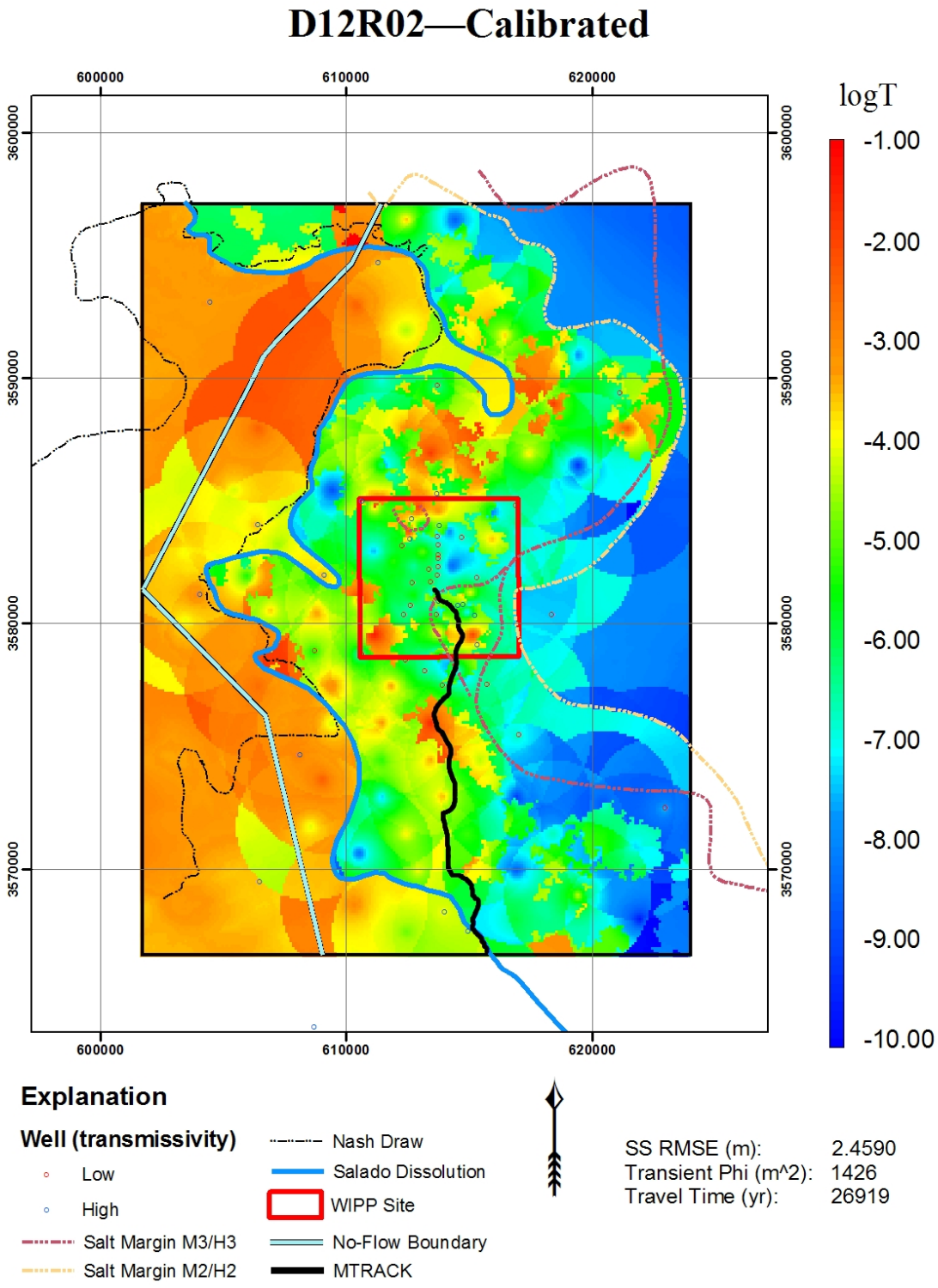
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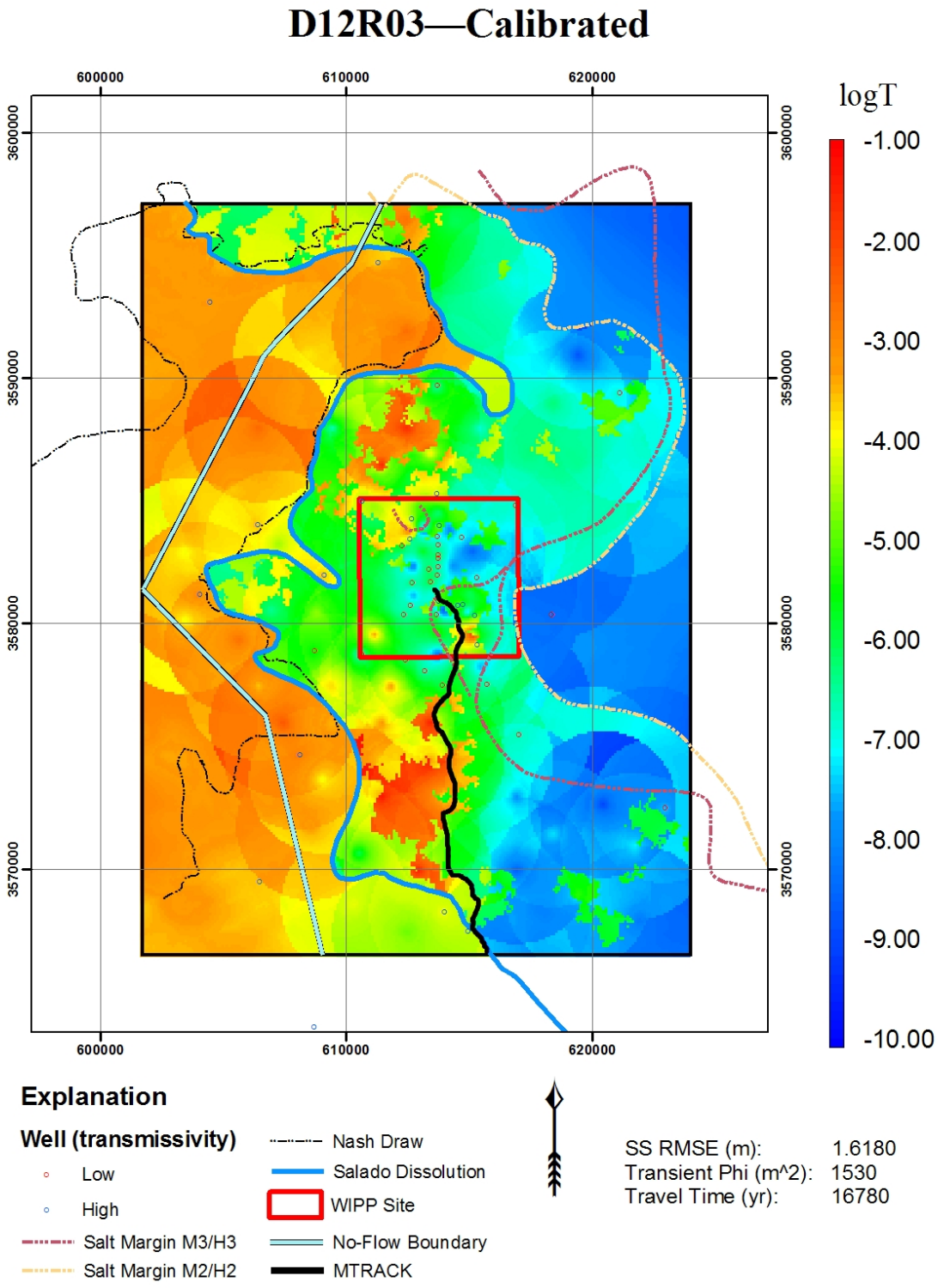
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.4590
Transient Phi (m^2): 1426
Travel Time (yr): 26919

1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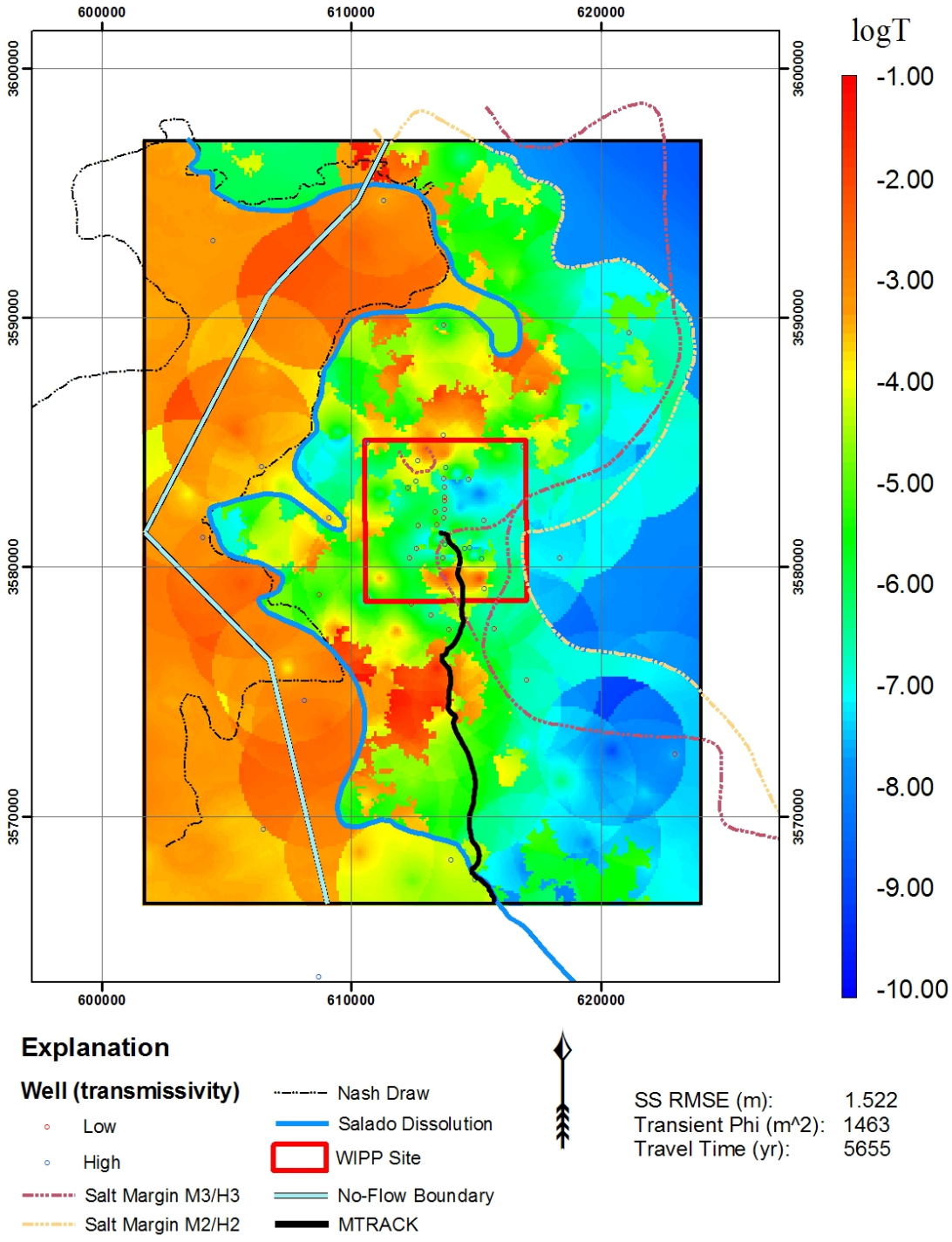
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.6180
Transient Phi (m^2): 1530
Travel Time (yr): 16780

1

D12R05—Calibrated



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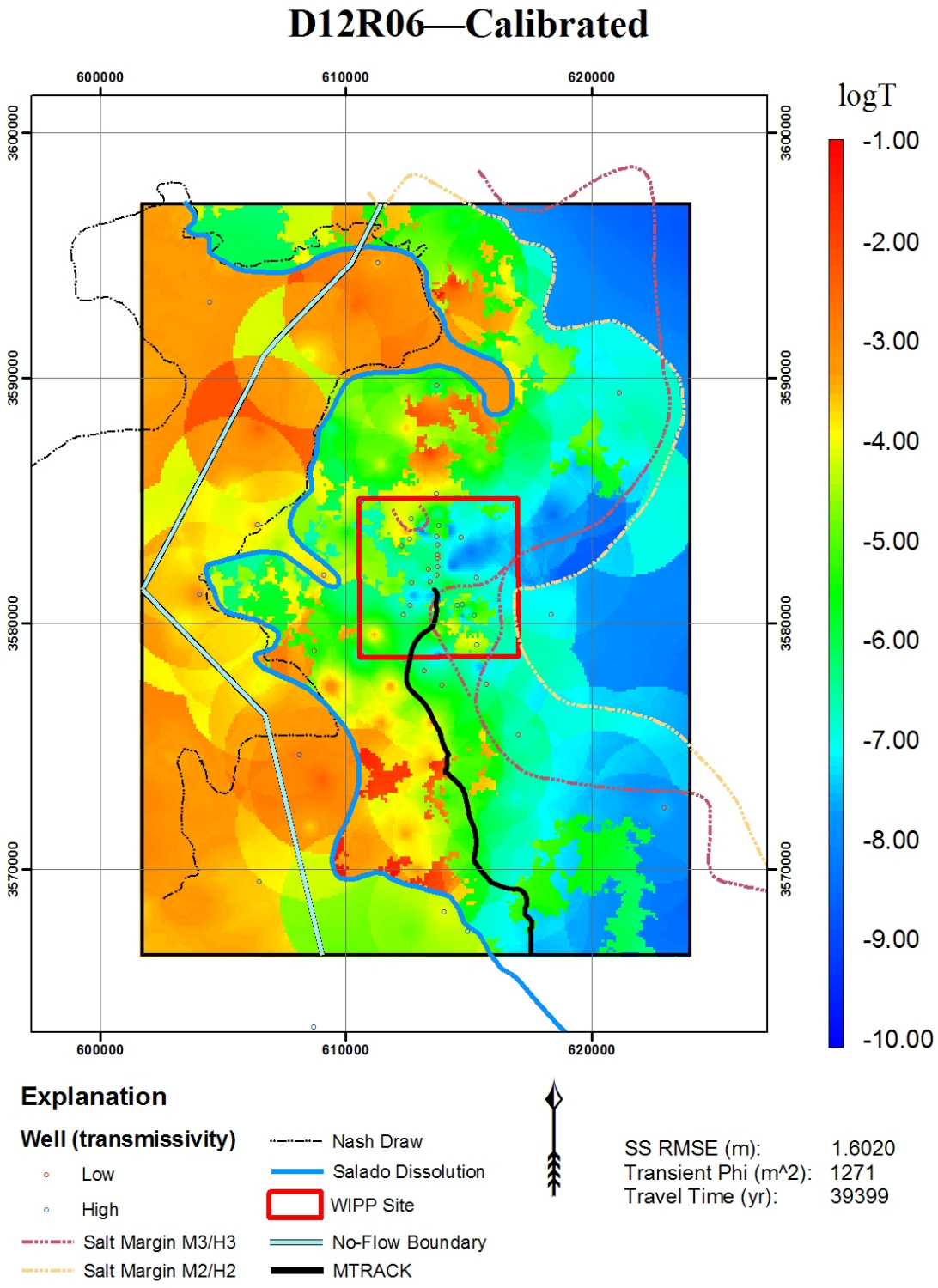
D12R06—Calibrated
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logT
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-2.00
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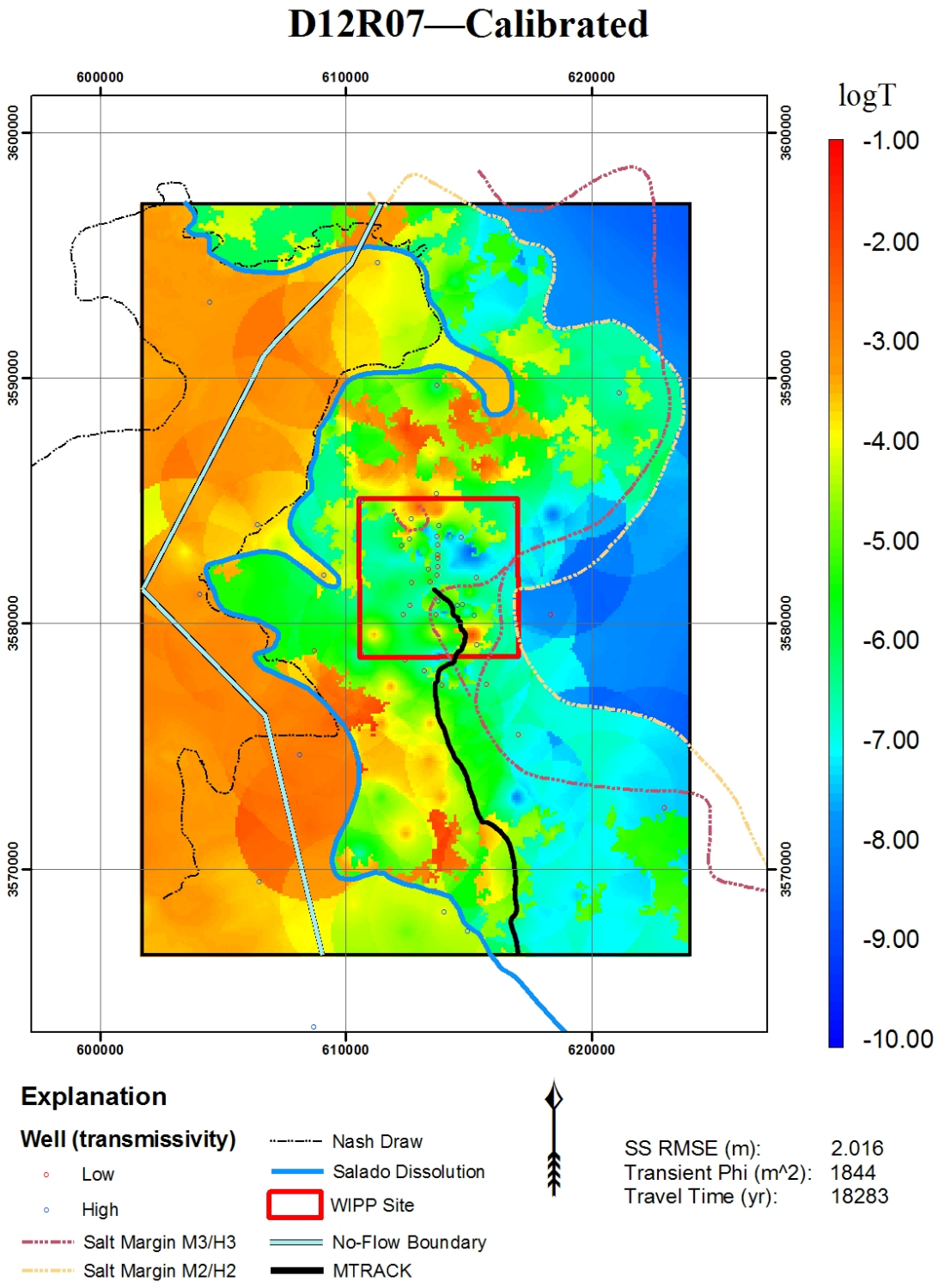
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.6020
Transient Phi (m^2): 1271
Travel Time (yr): 39399

1


D12R07—Calibrated
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logT
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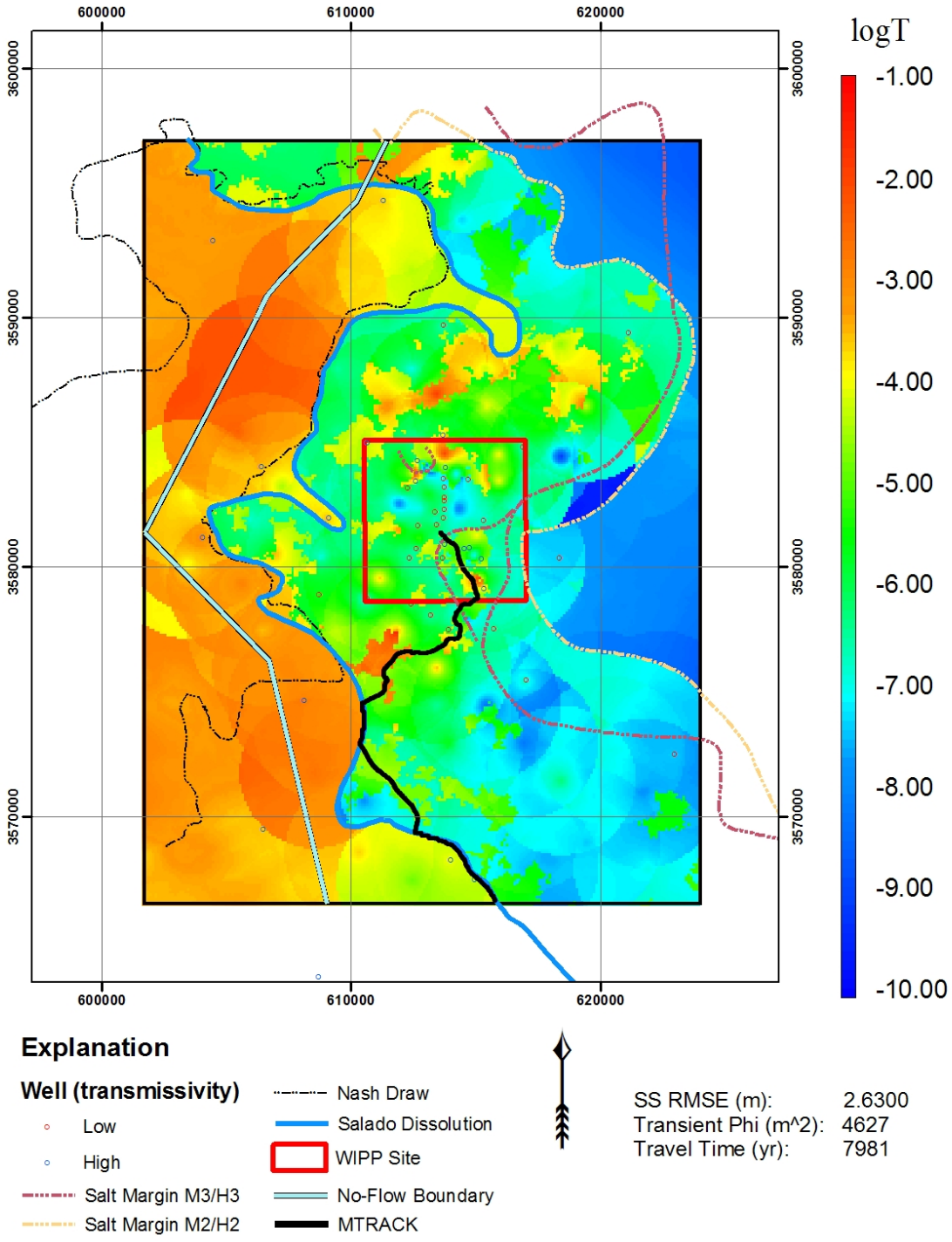
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.016
Transient Phi (m^2): 1844
Travel Time (yr): 18283

1

D12R08—Calibrated



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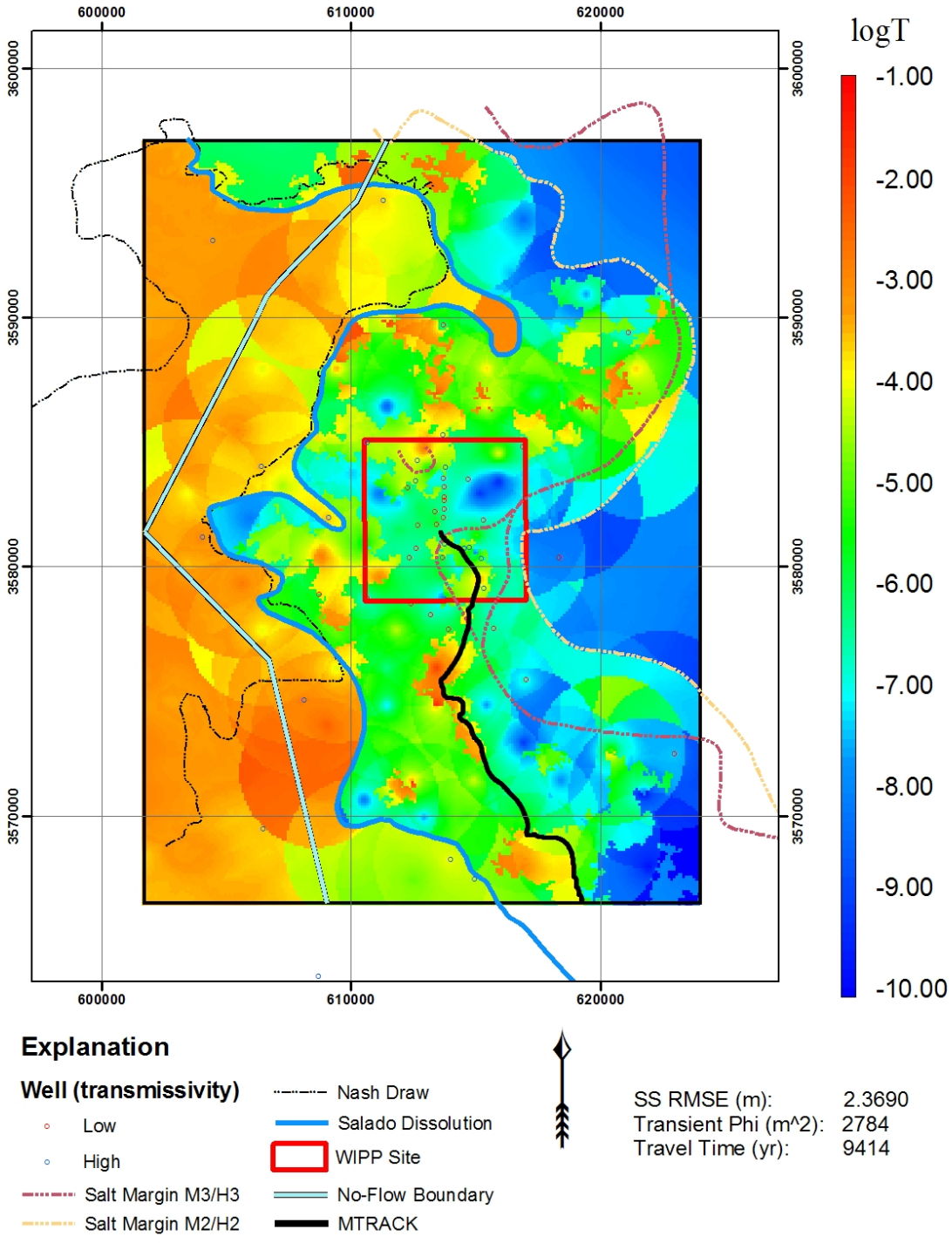
D12R09—Calibrated



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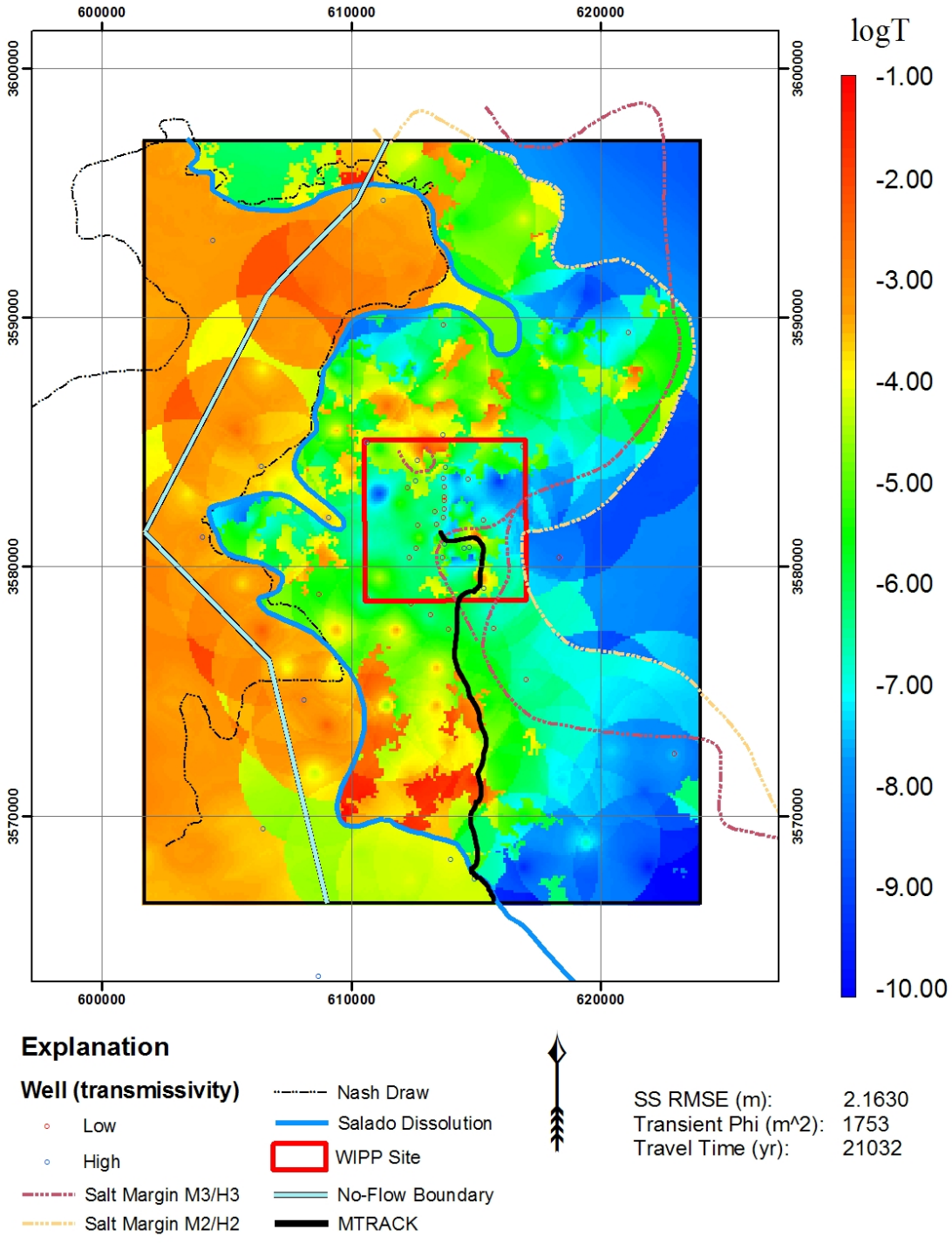
D13R01—Calibrated



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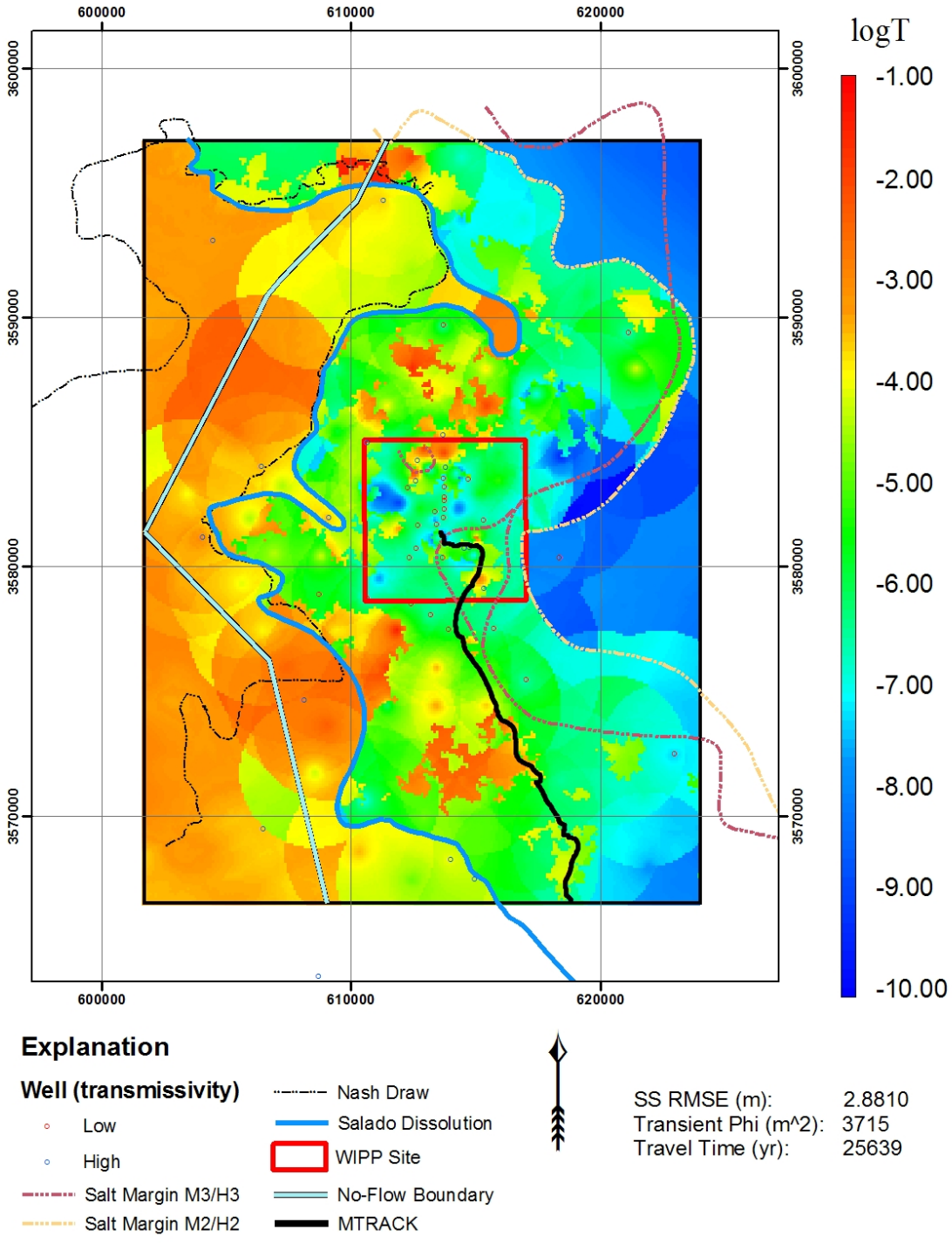
D13R02—Calibrated



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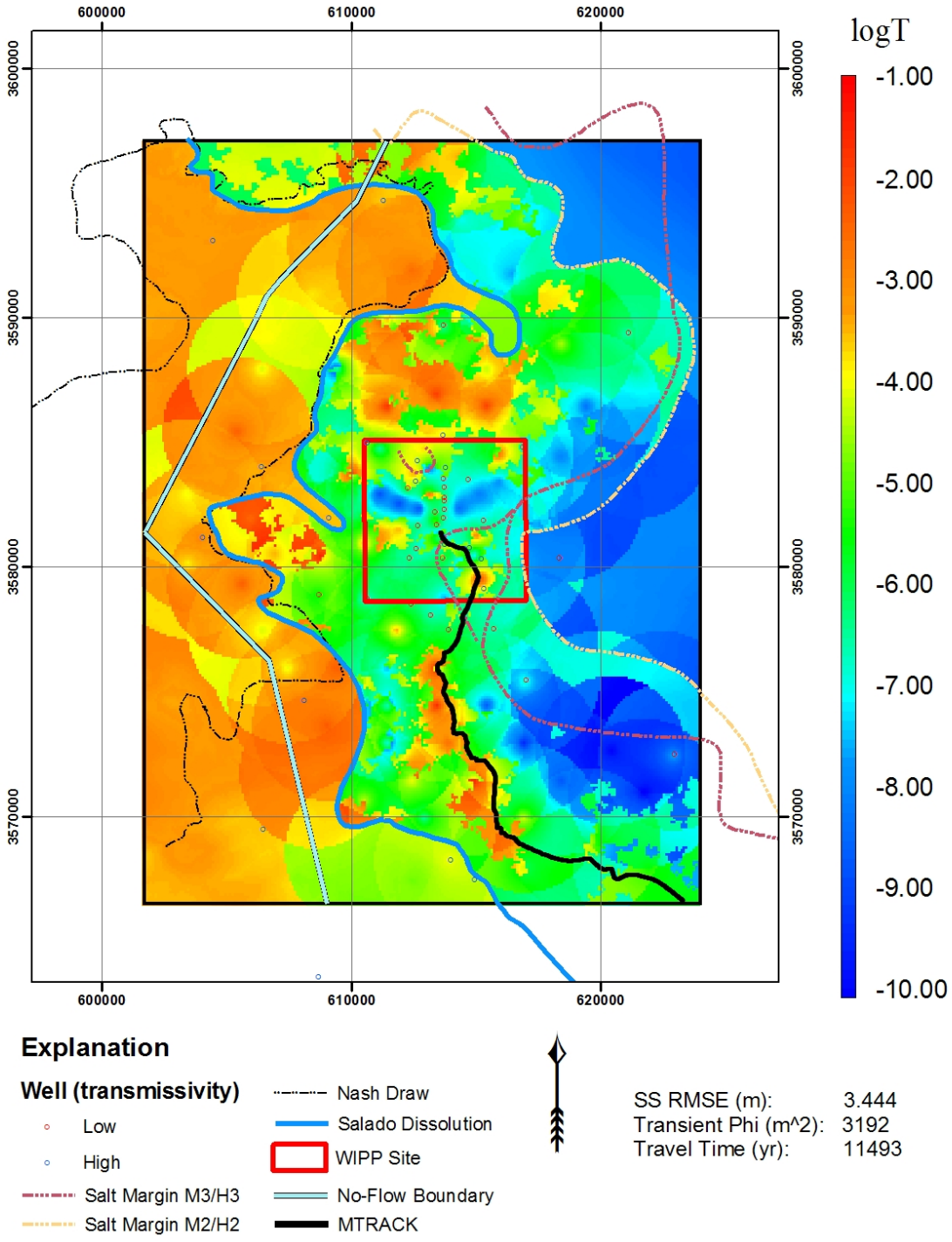

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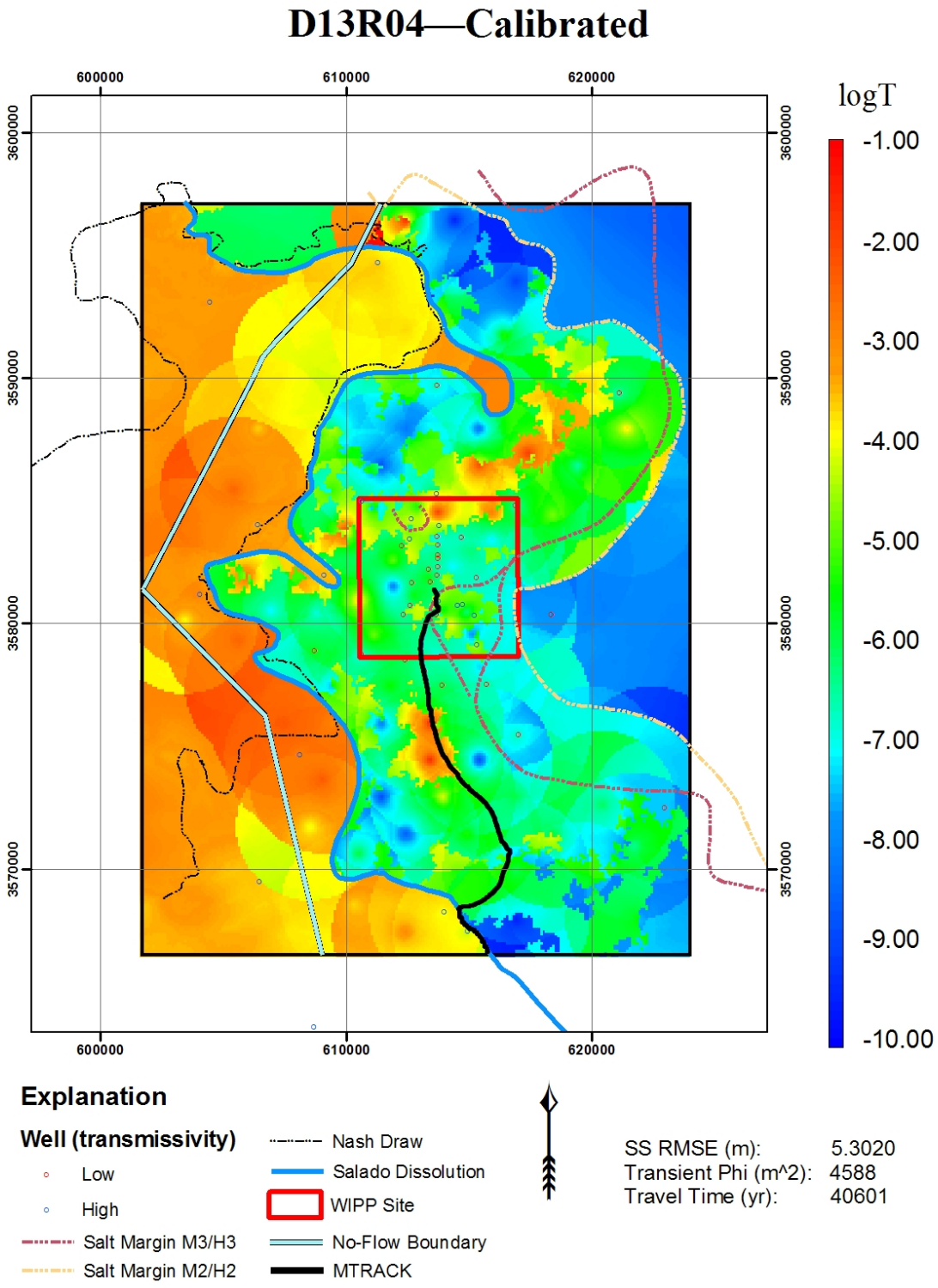
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-4.00
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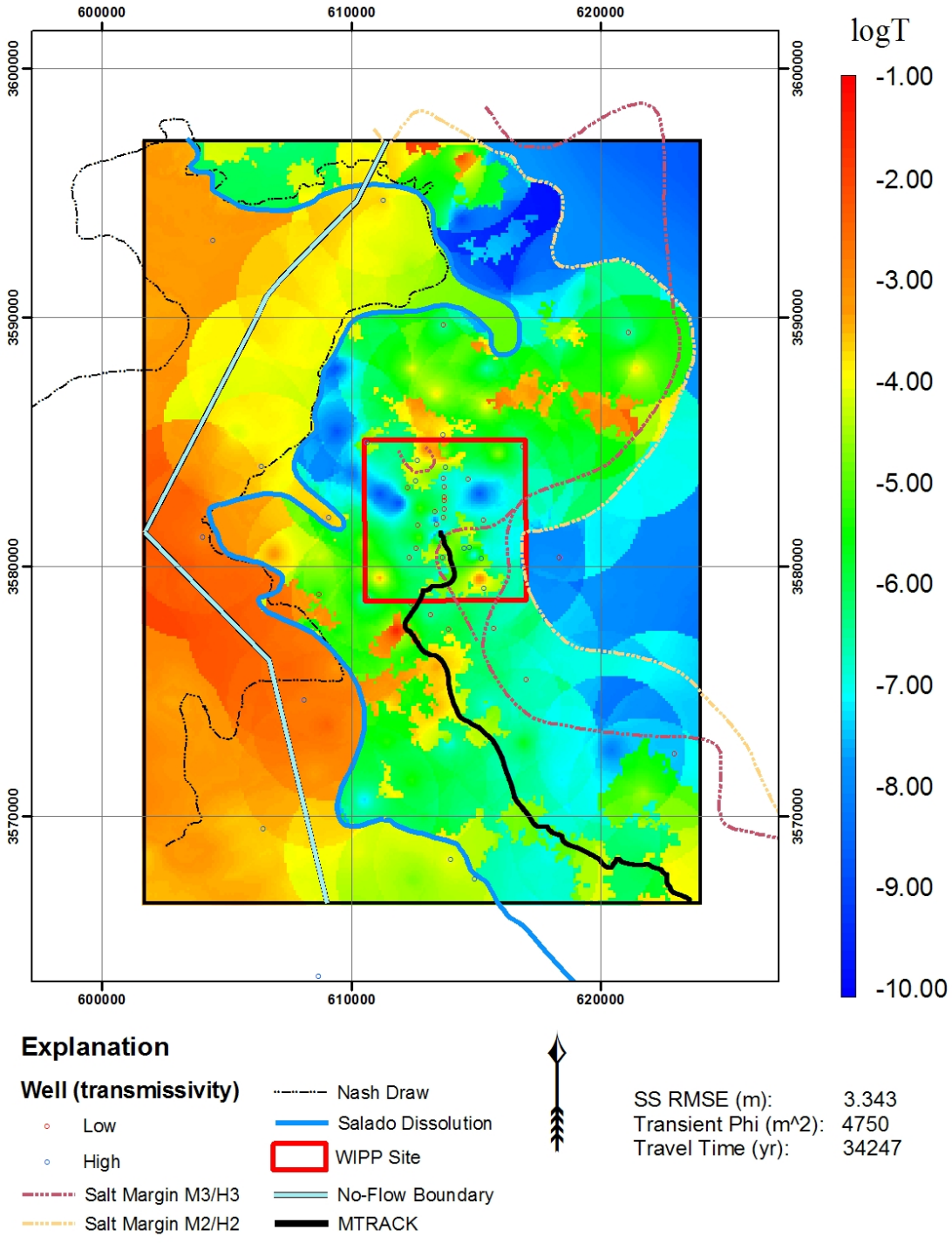
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 5.3020
Transient Phi (m^2): 4588
Travel Time (yr): 40601

1

D13R05—Calibrated



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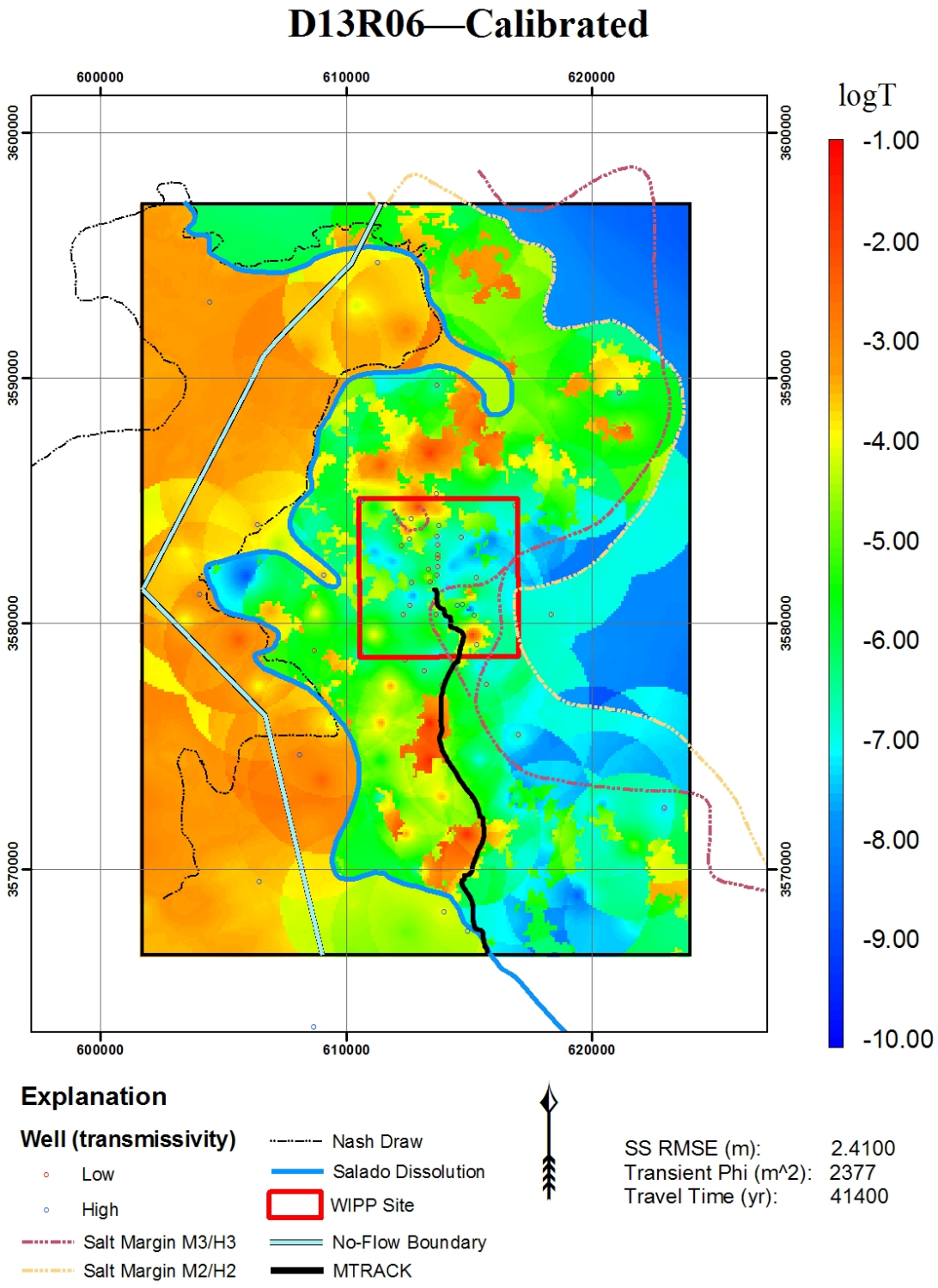
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logT
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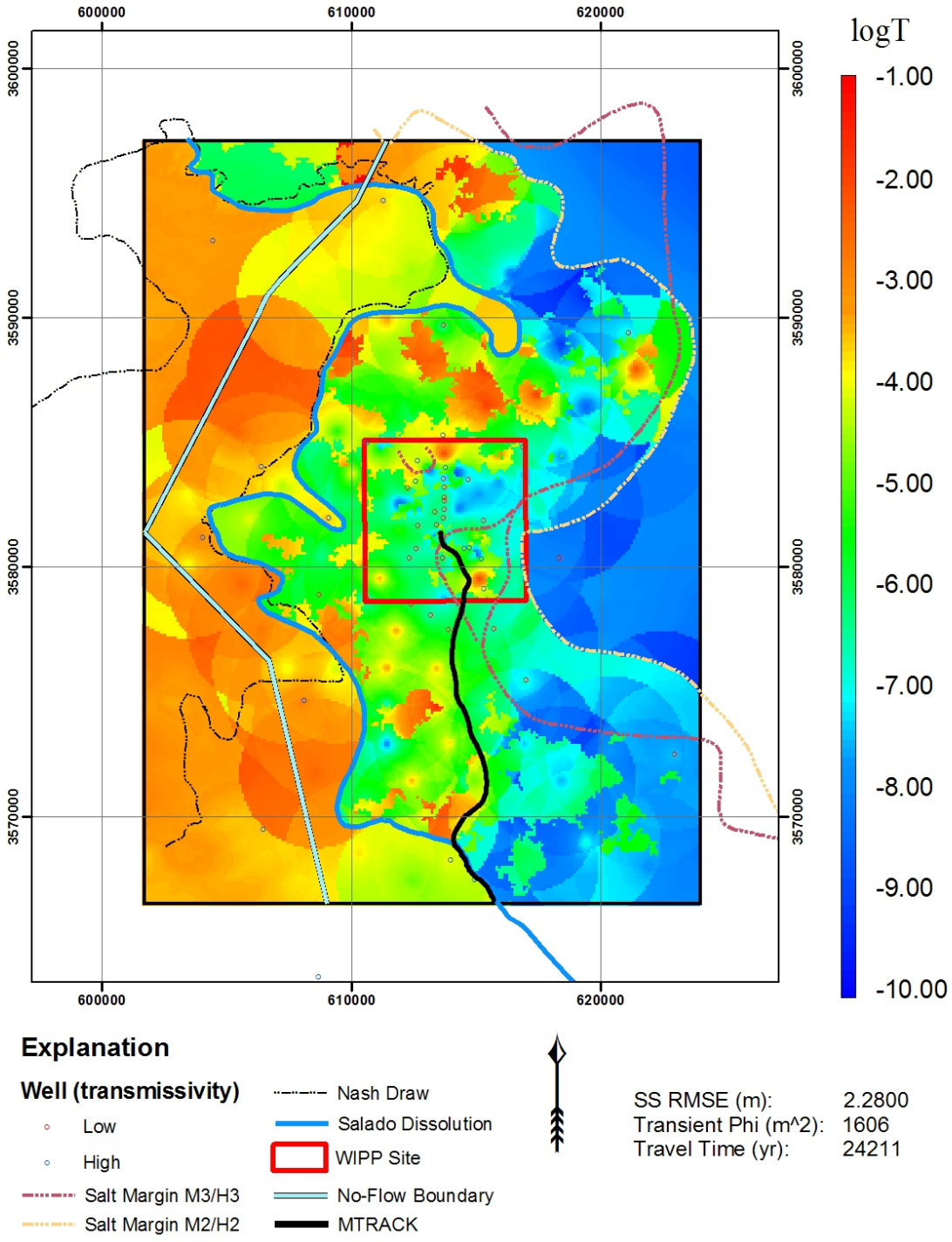
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 2.4100
Transient Phi (m^2): 2377
Travel Time (yr): 41400

1

D13R07—Calibrated



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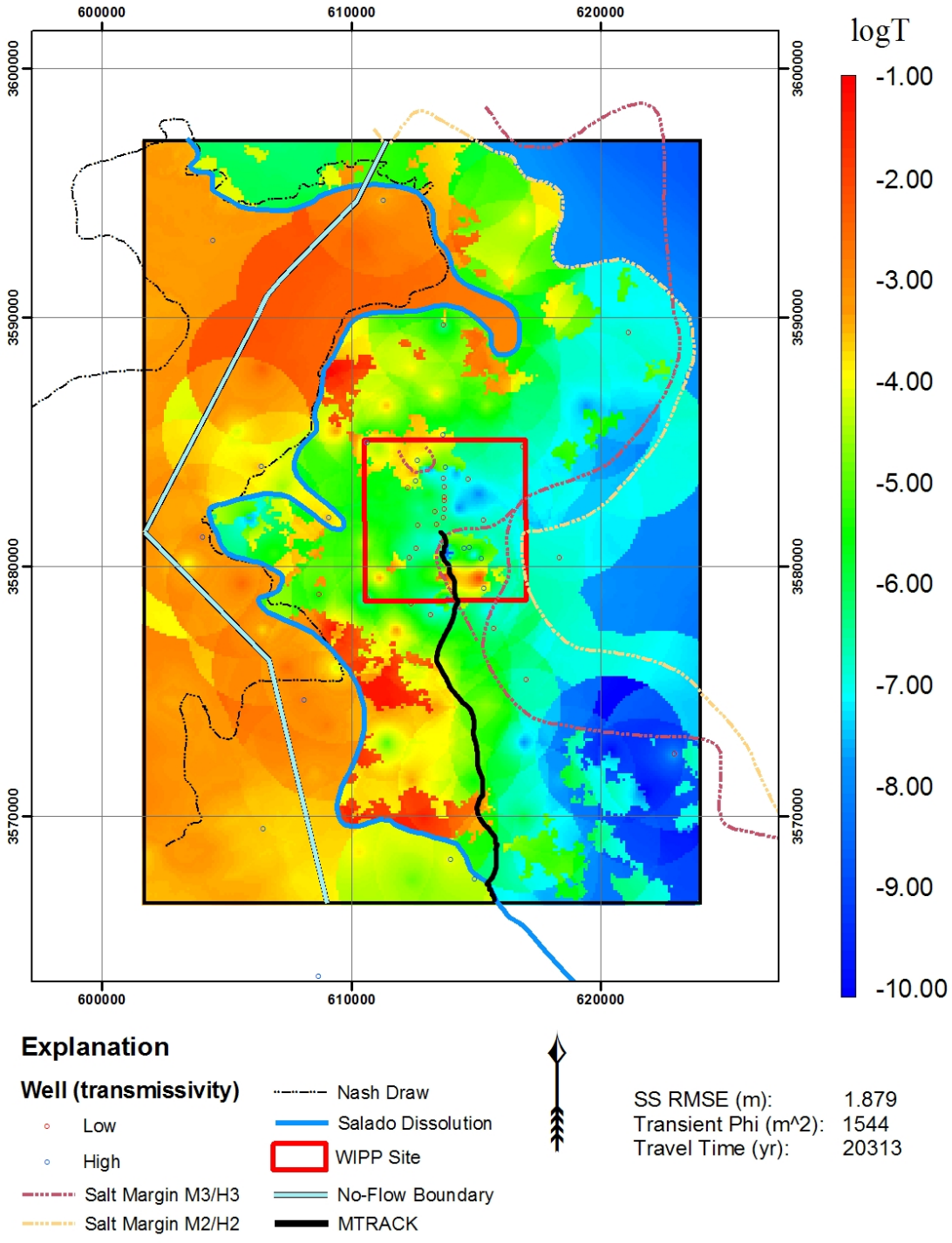
D13R08—Calibrated



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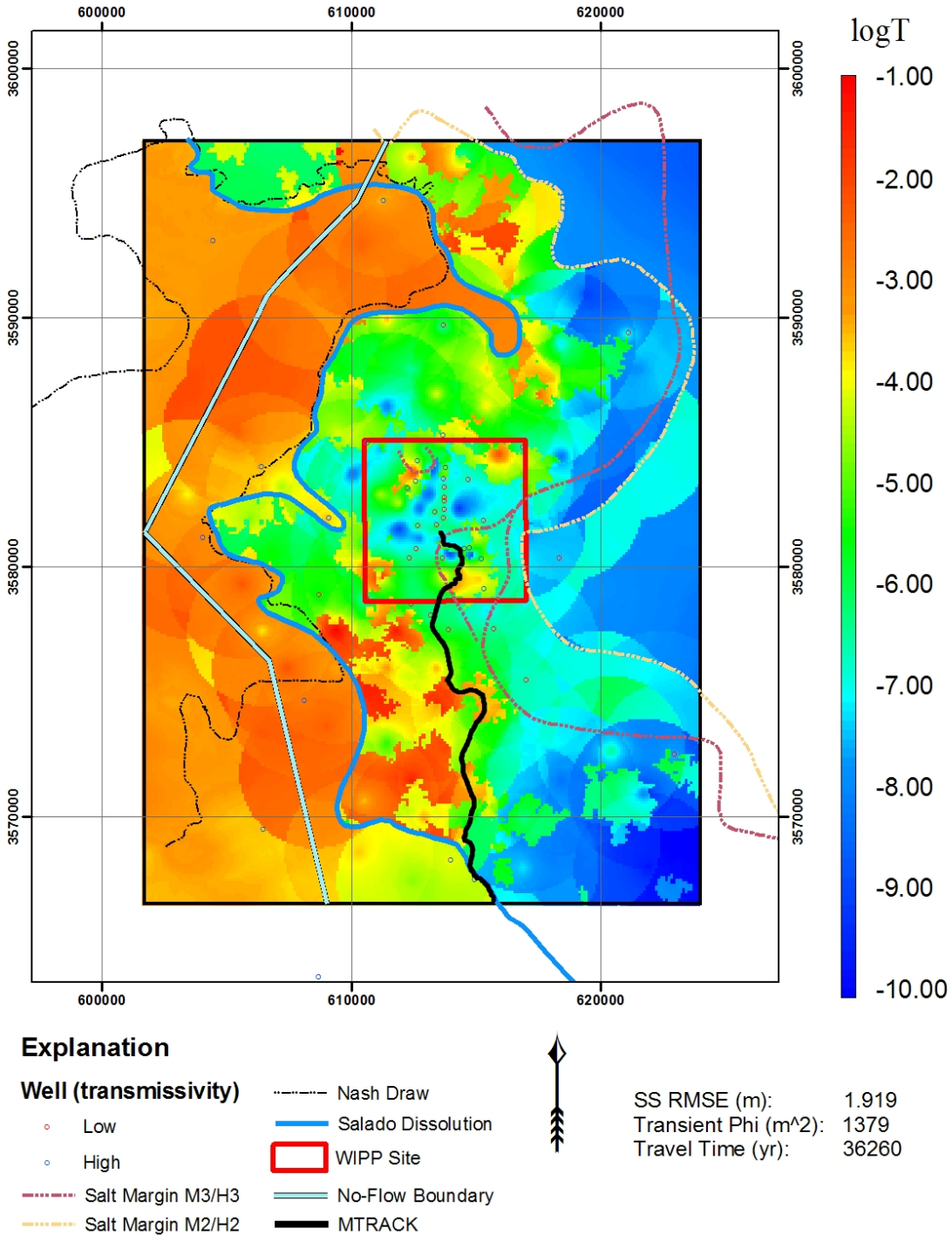
D13R09—Calibrated



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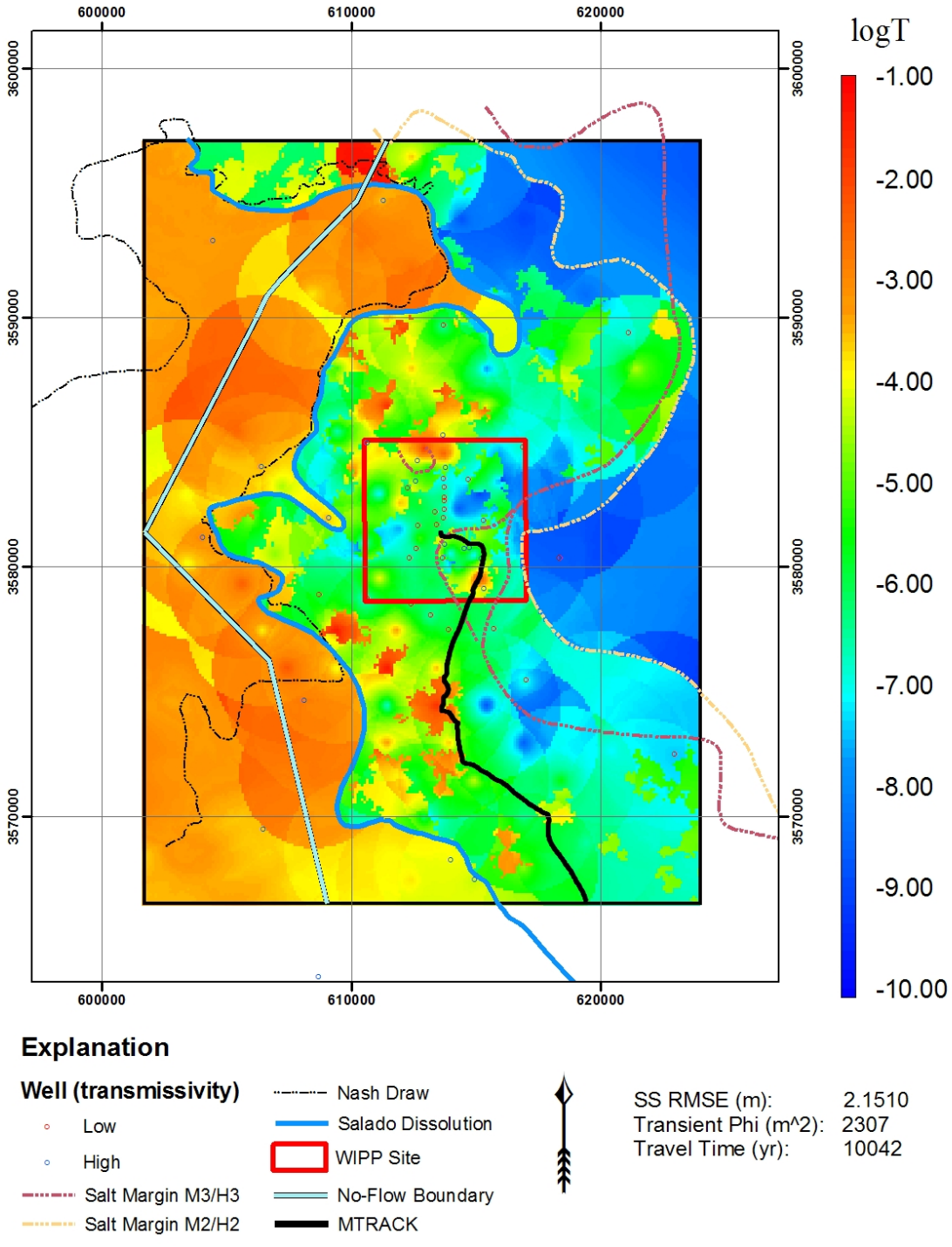

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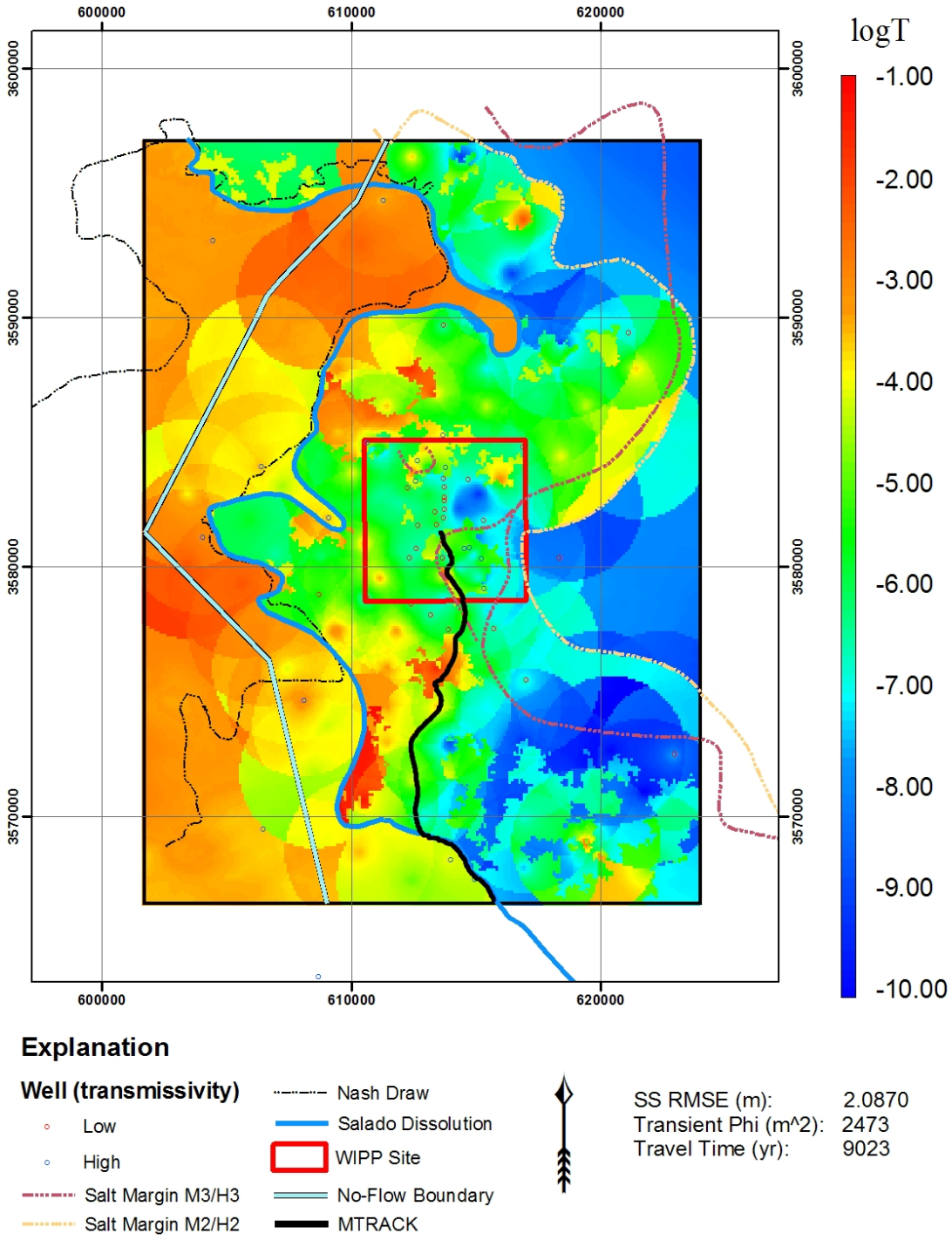

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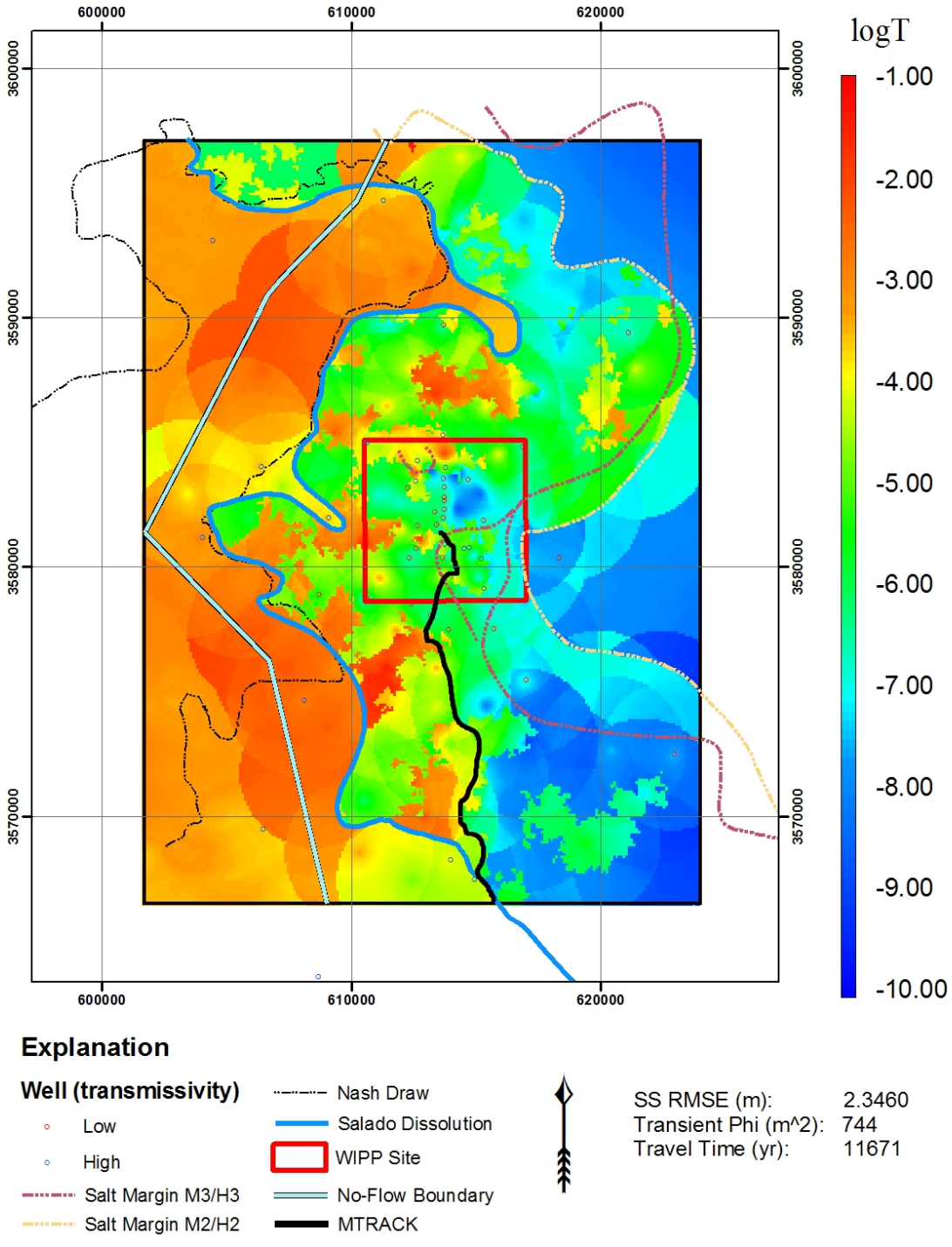

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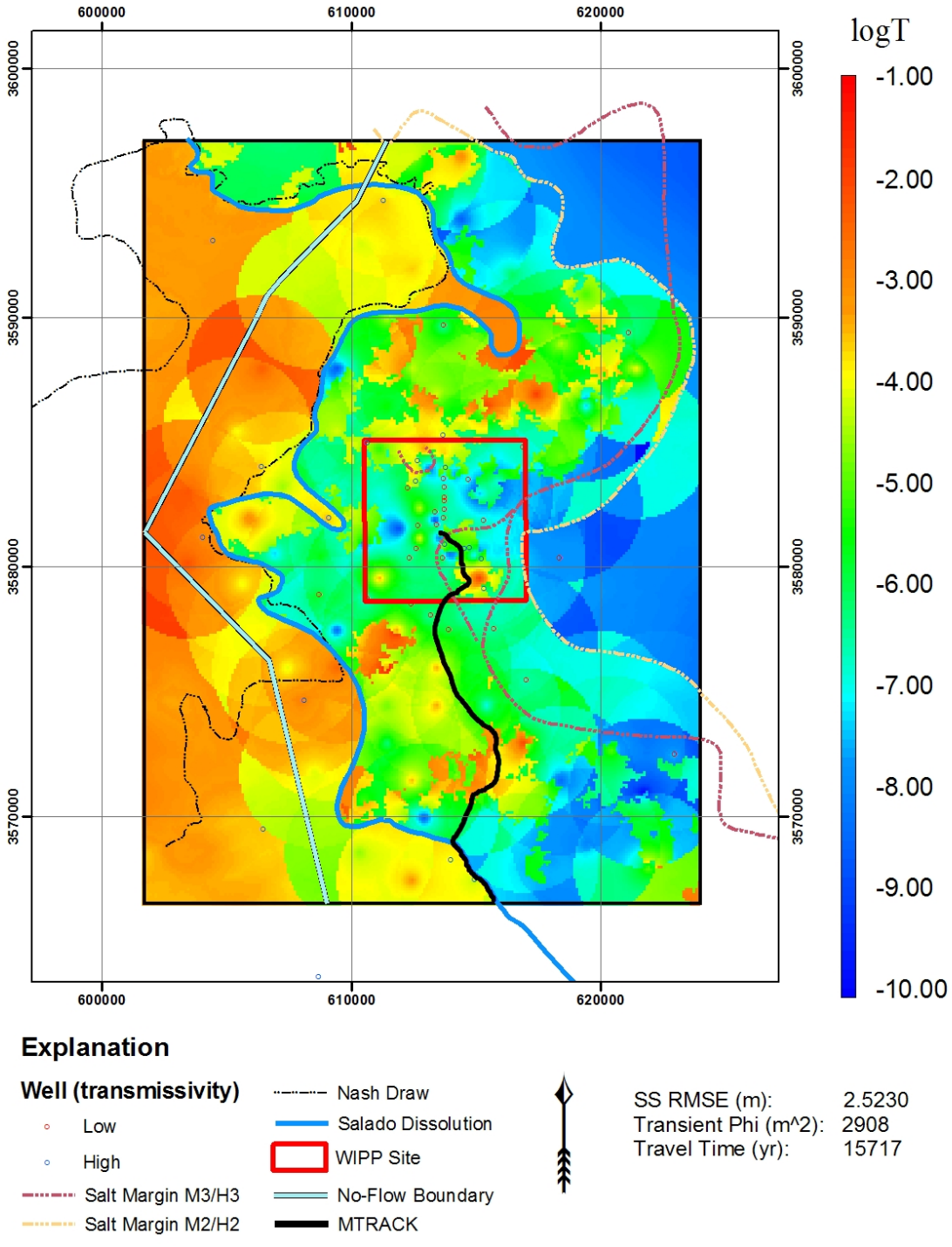

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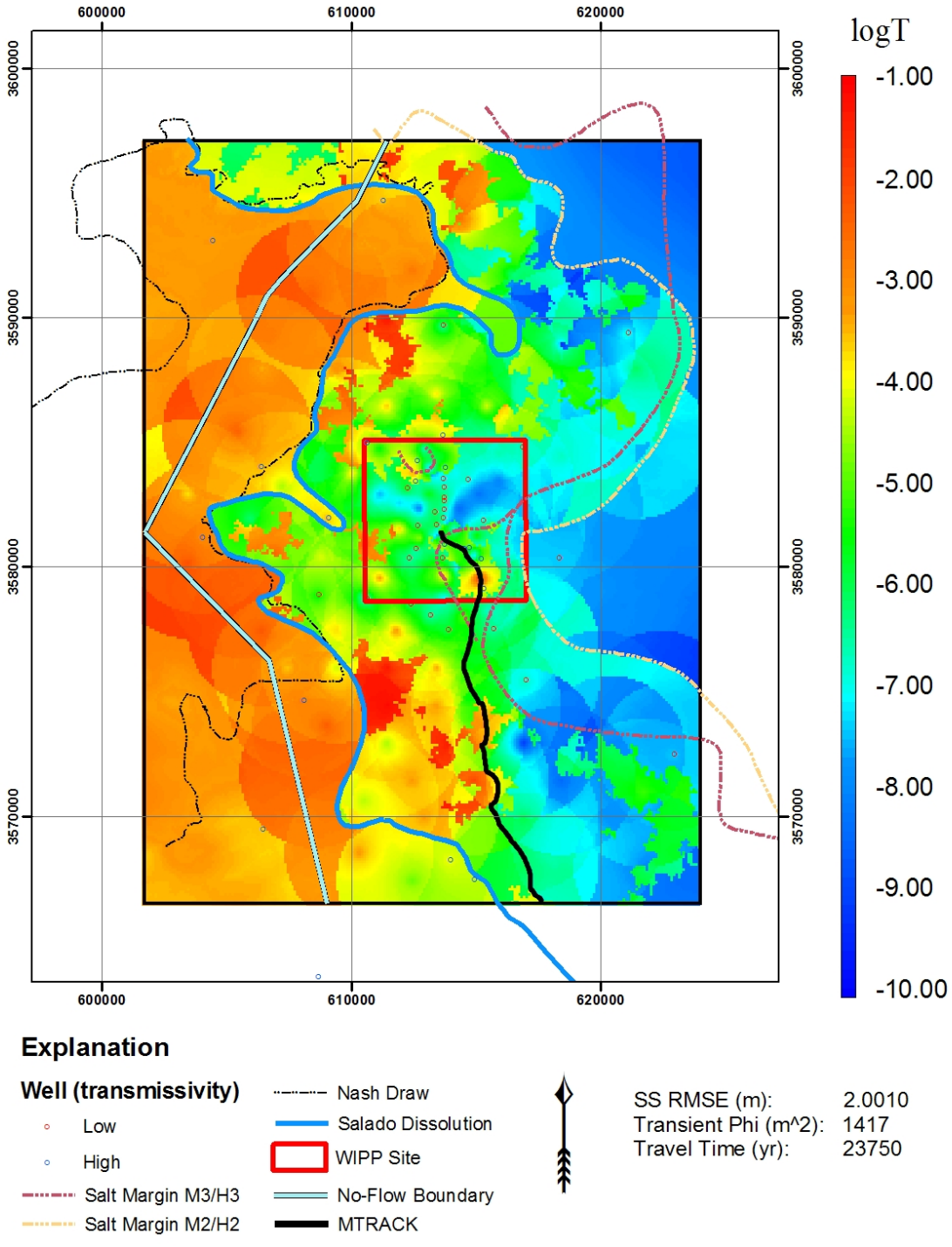

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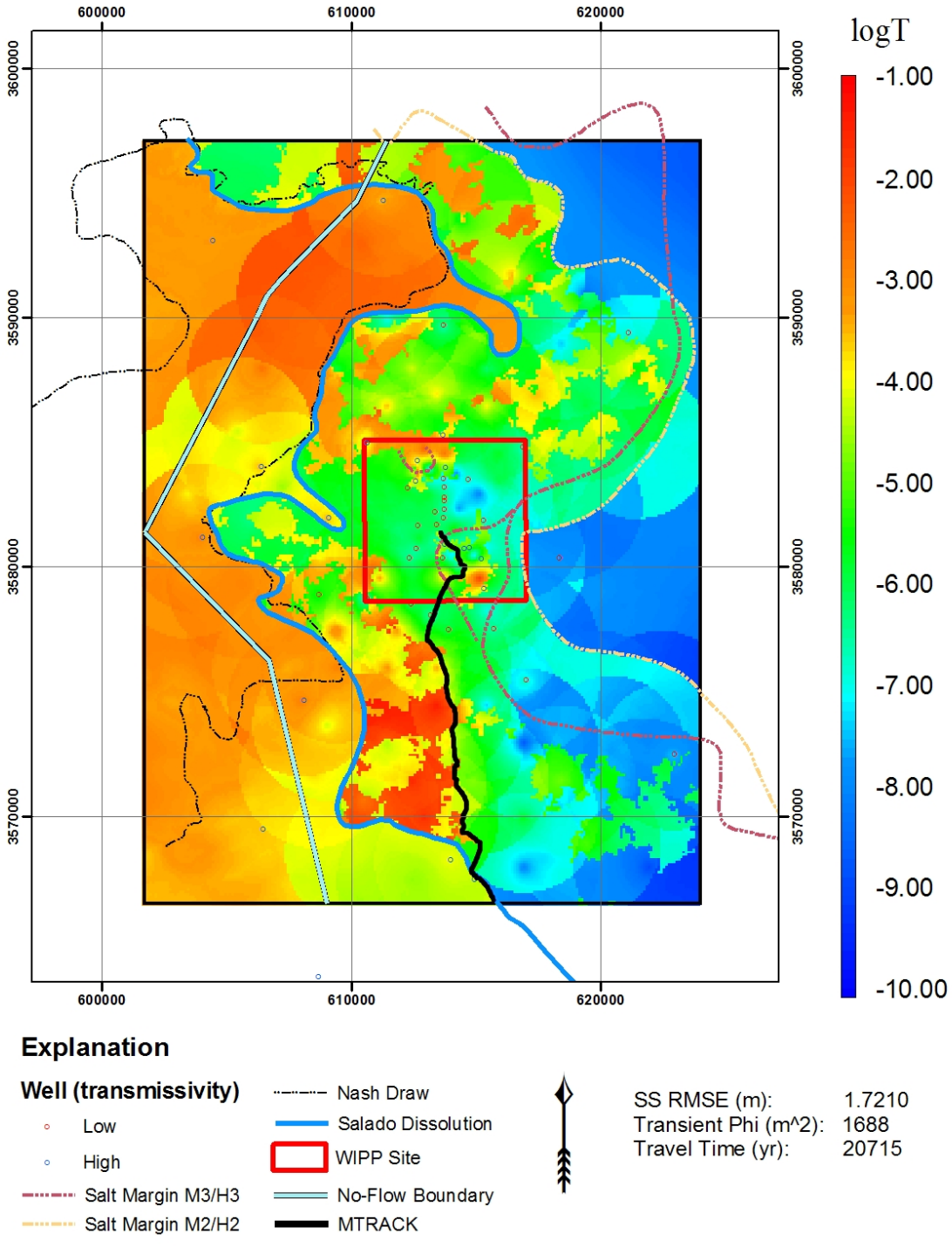

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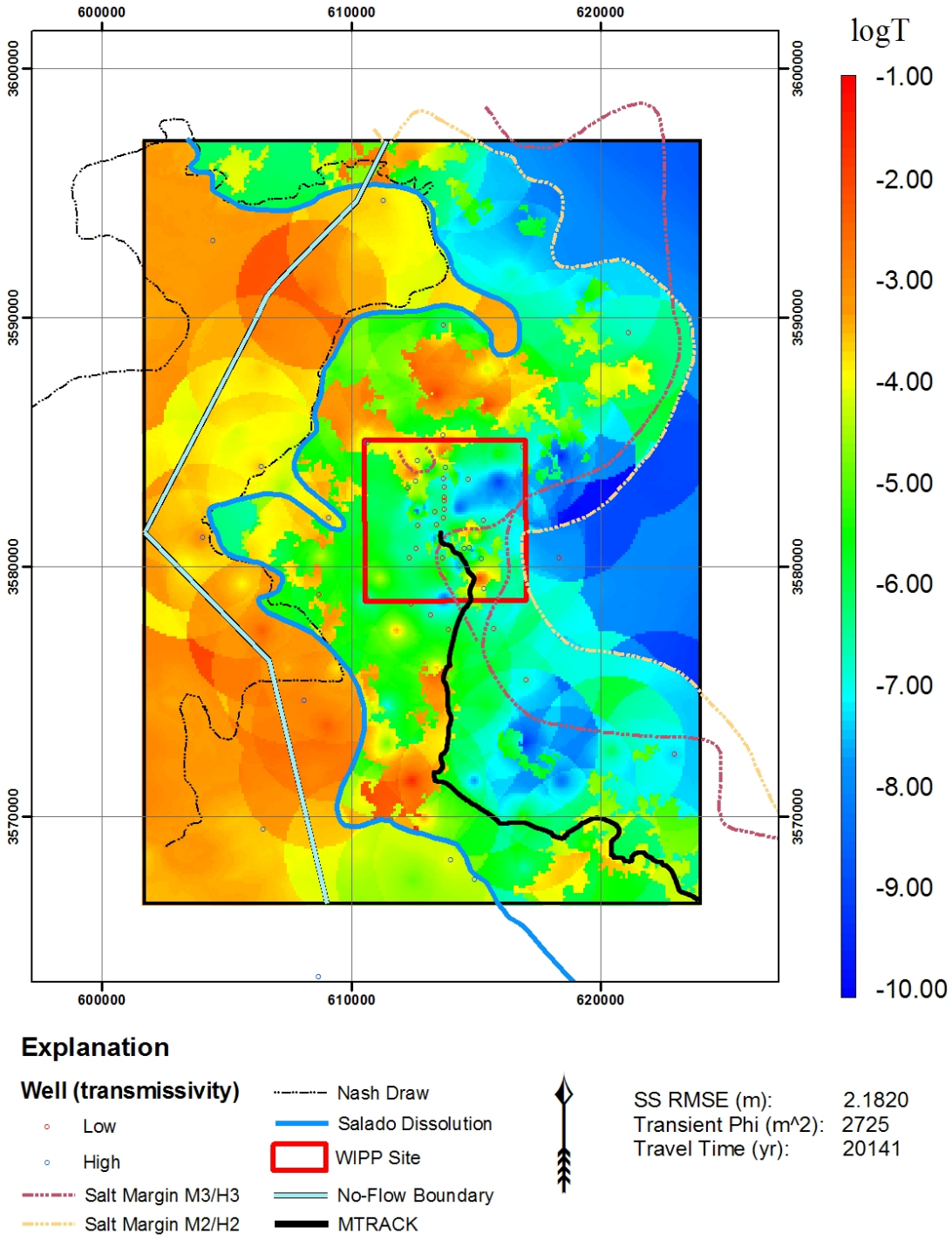

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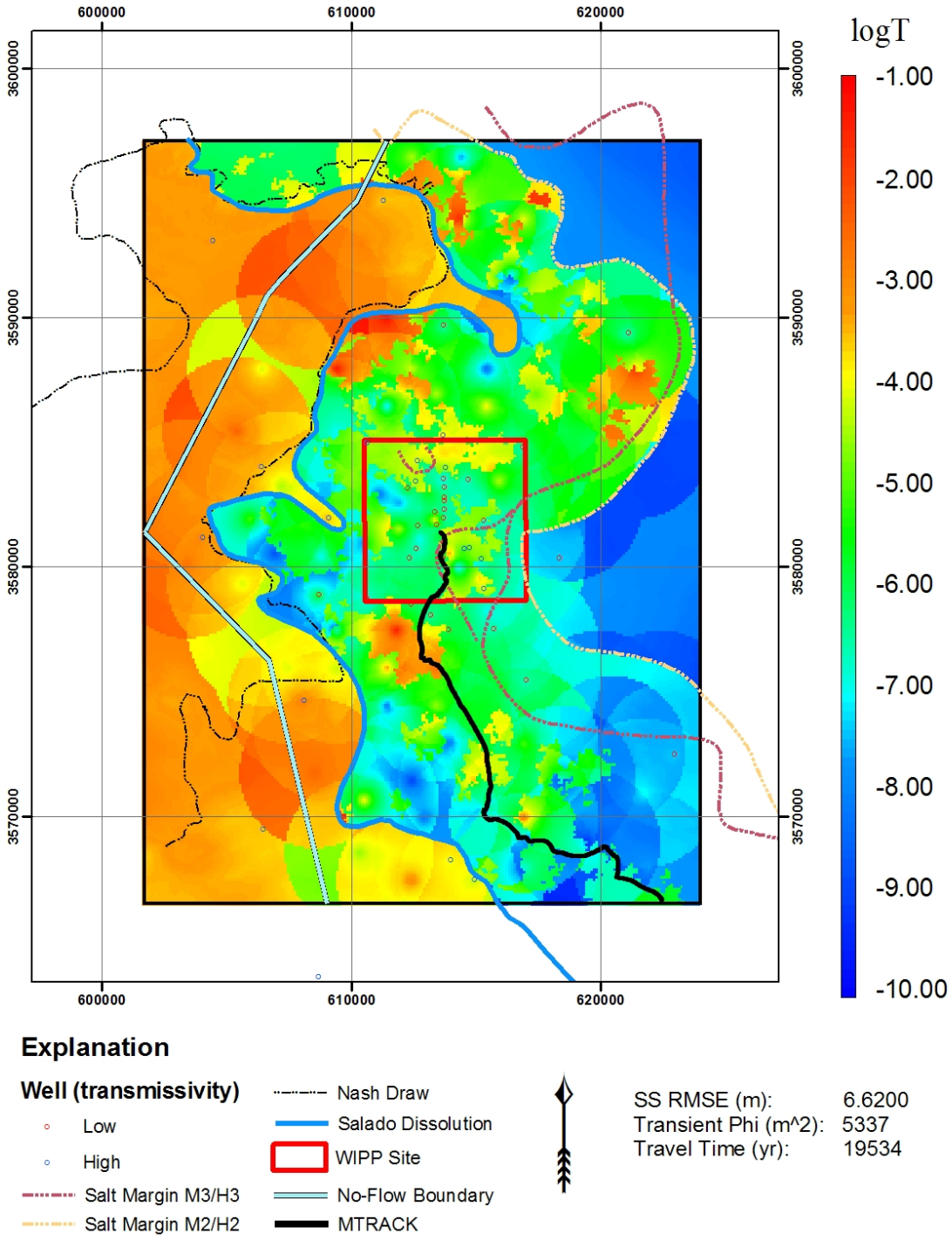
D21R08—Calibrated



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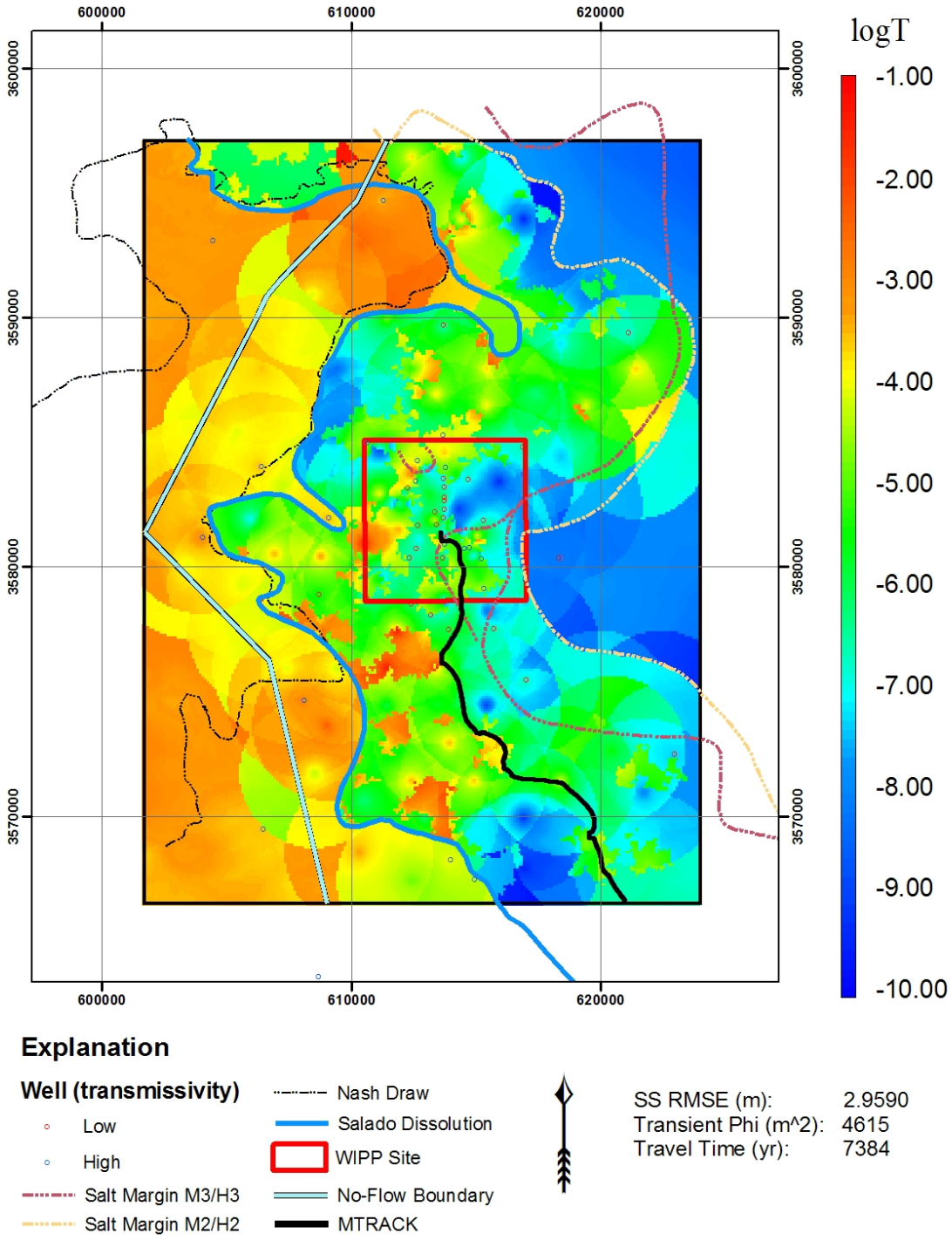
D21R10—Calibrated



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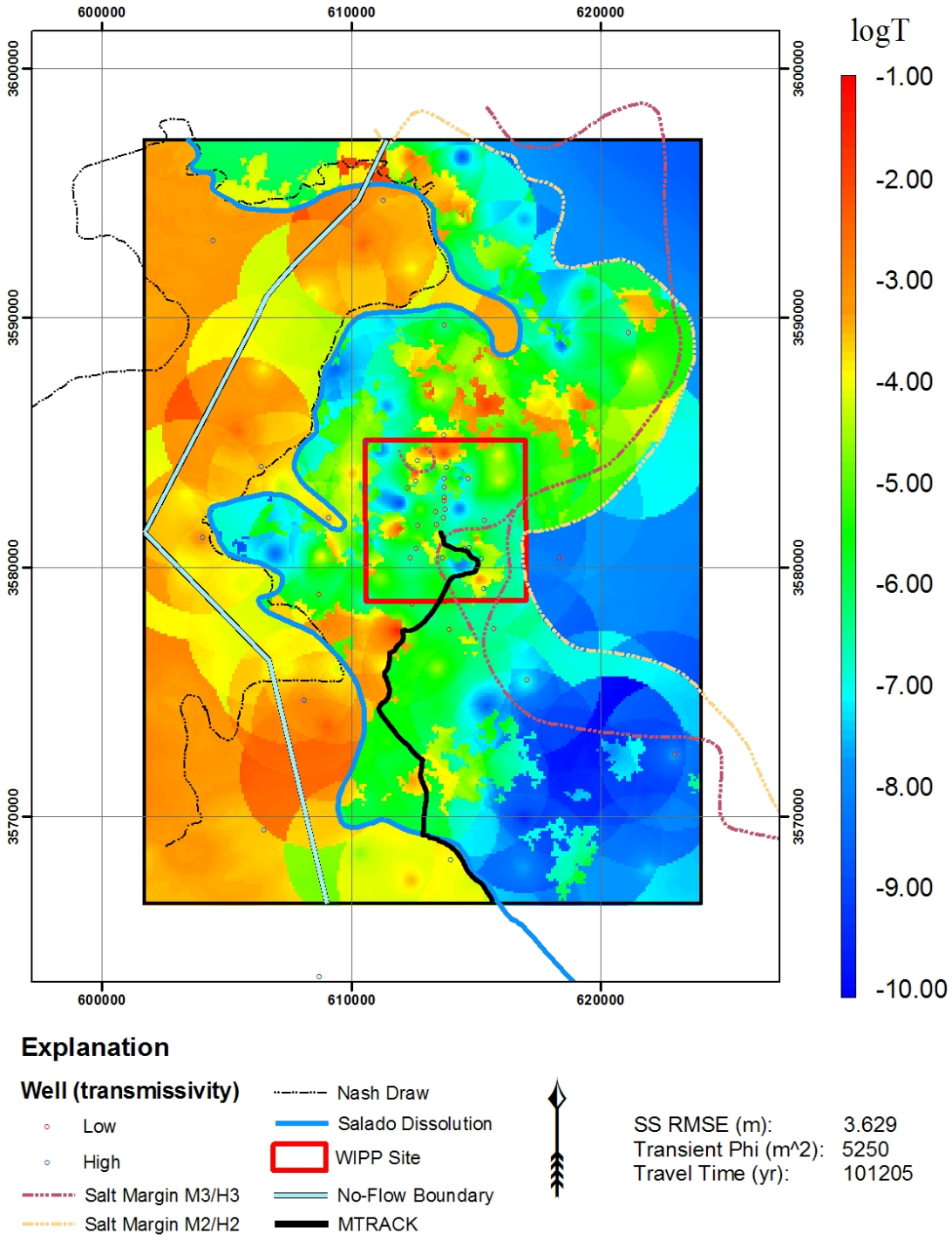
D22R02—Calibrated



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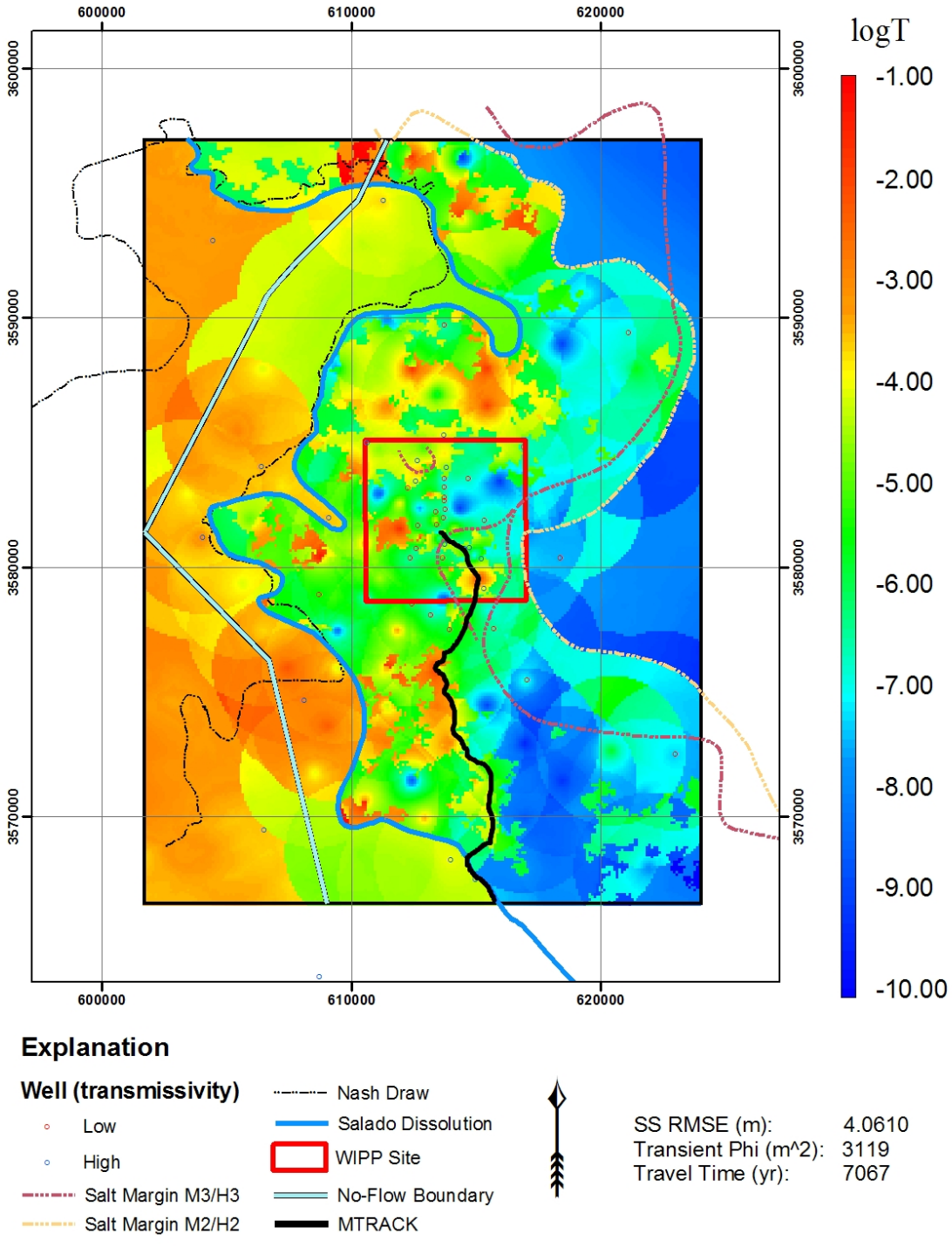
D22R03—Calibrated



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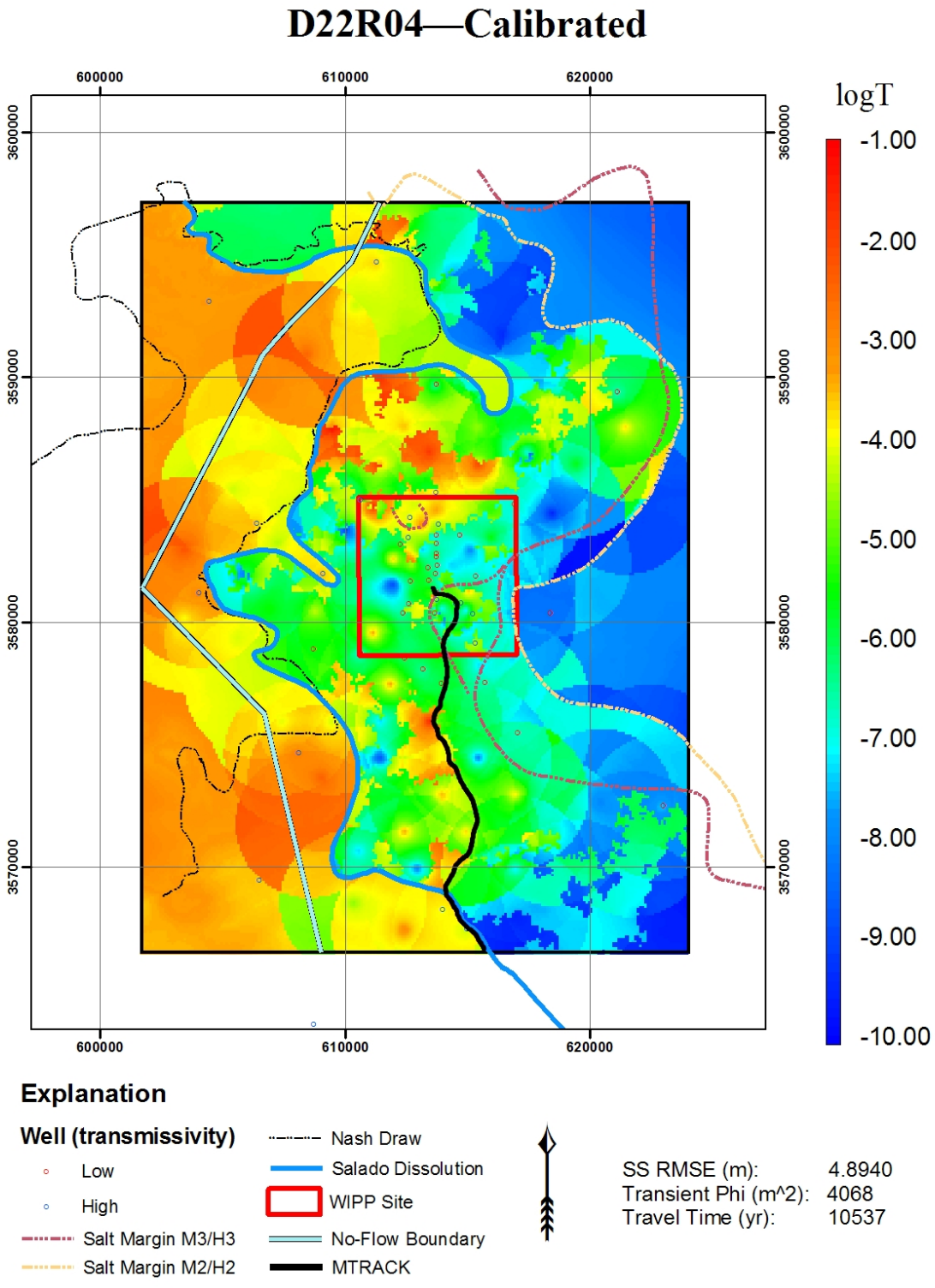
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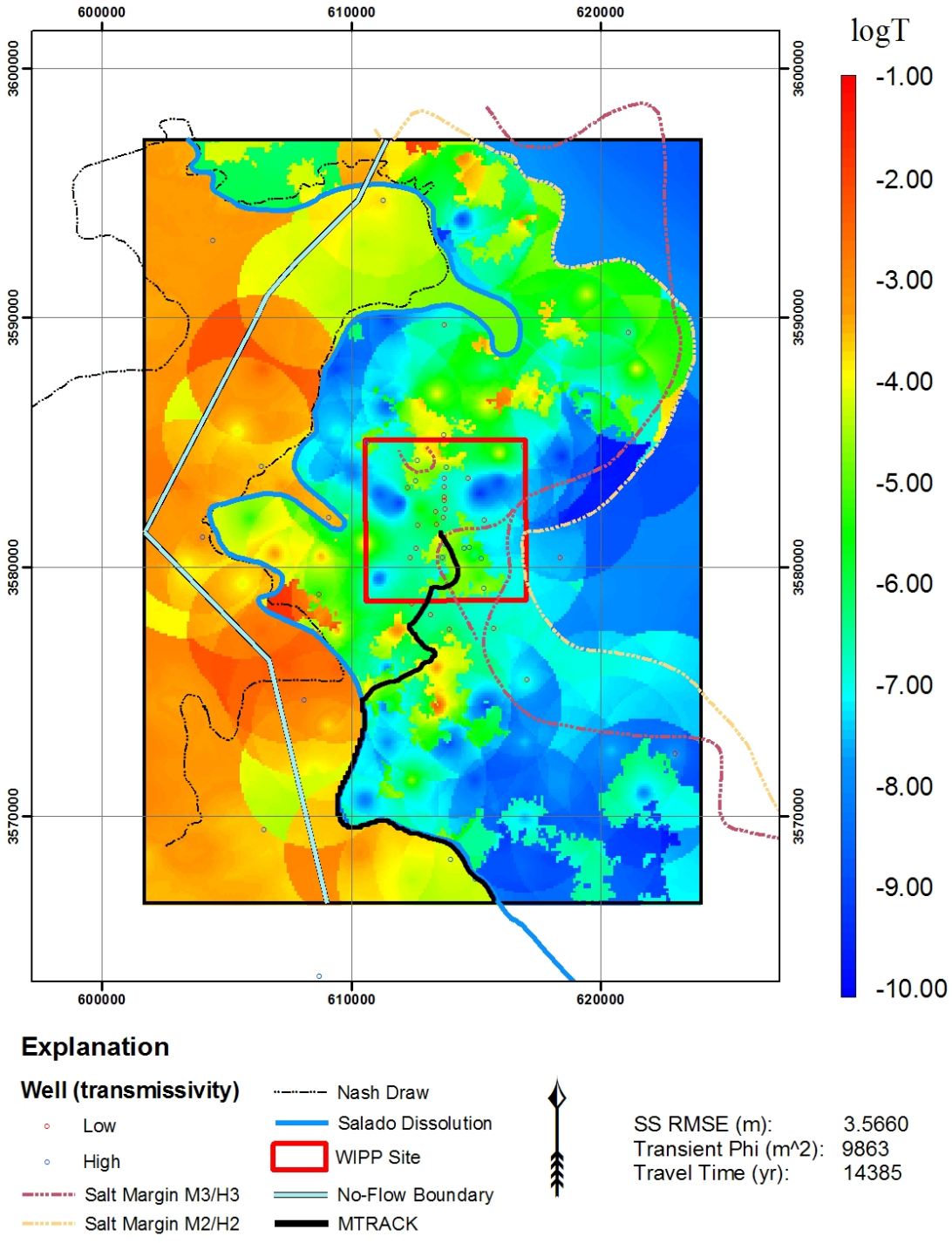
3590000
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 4.8940
Transient Phi (m^2): 4068
Travel Time (yr): 10537

1

D22R05—Calibrated



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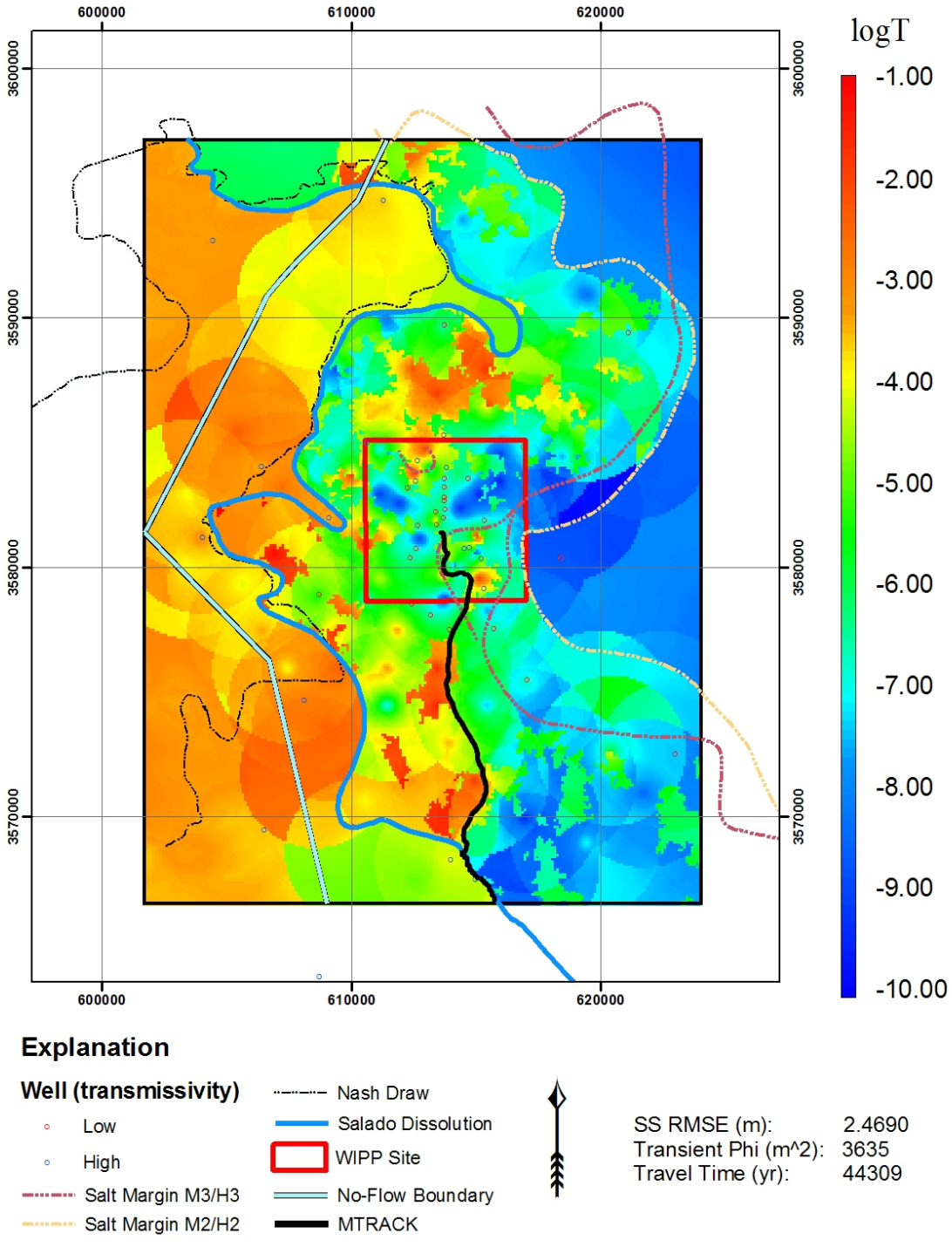
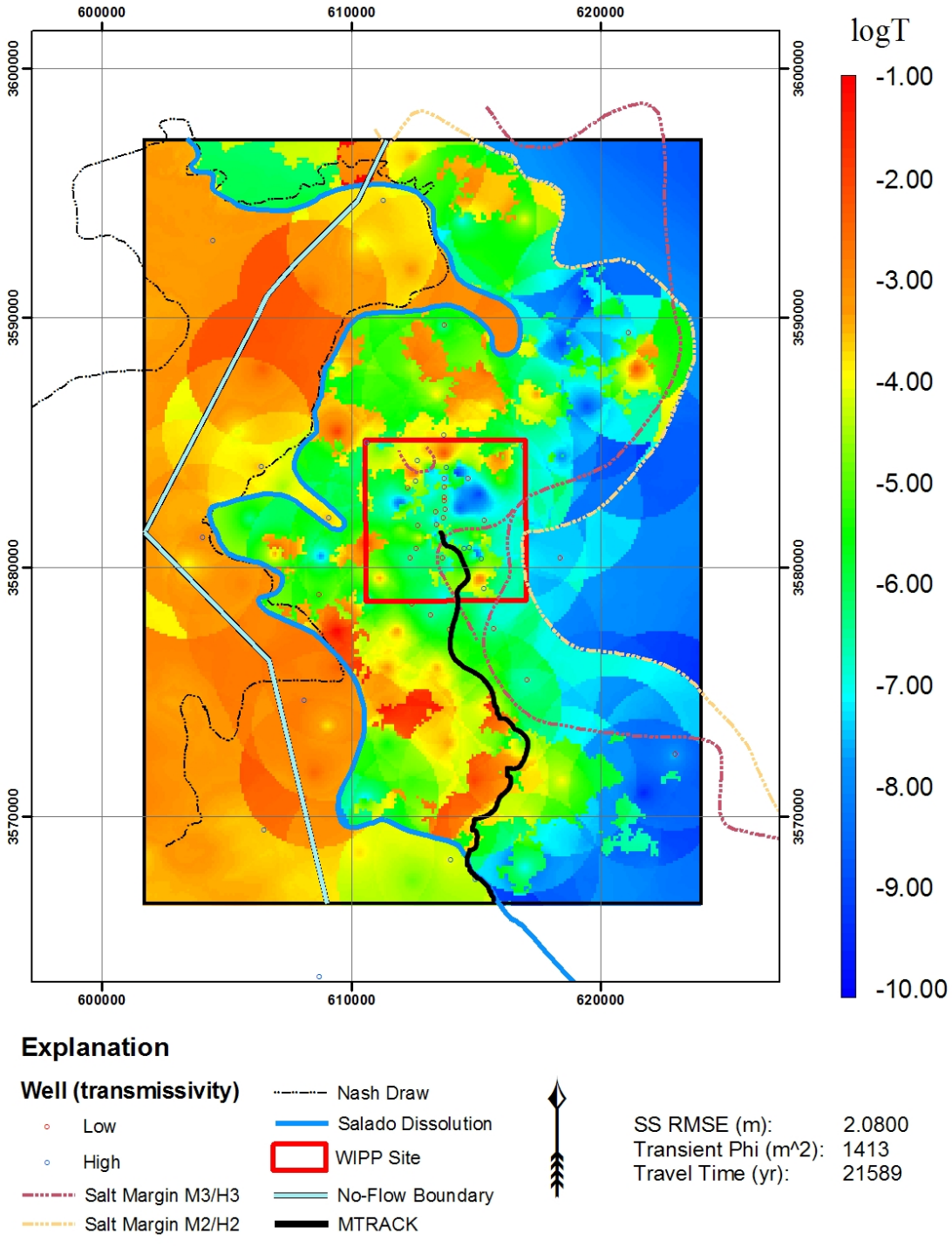
D22R06—Calibrated



1

D22R07—Calibrated



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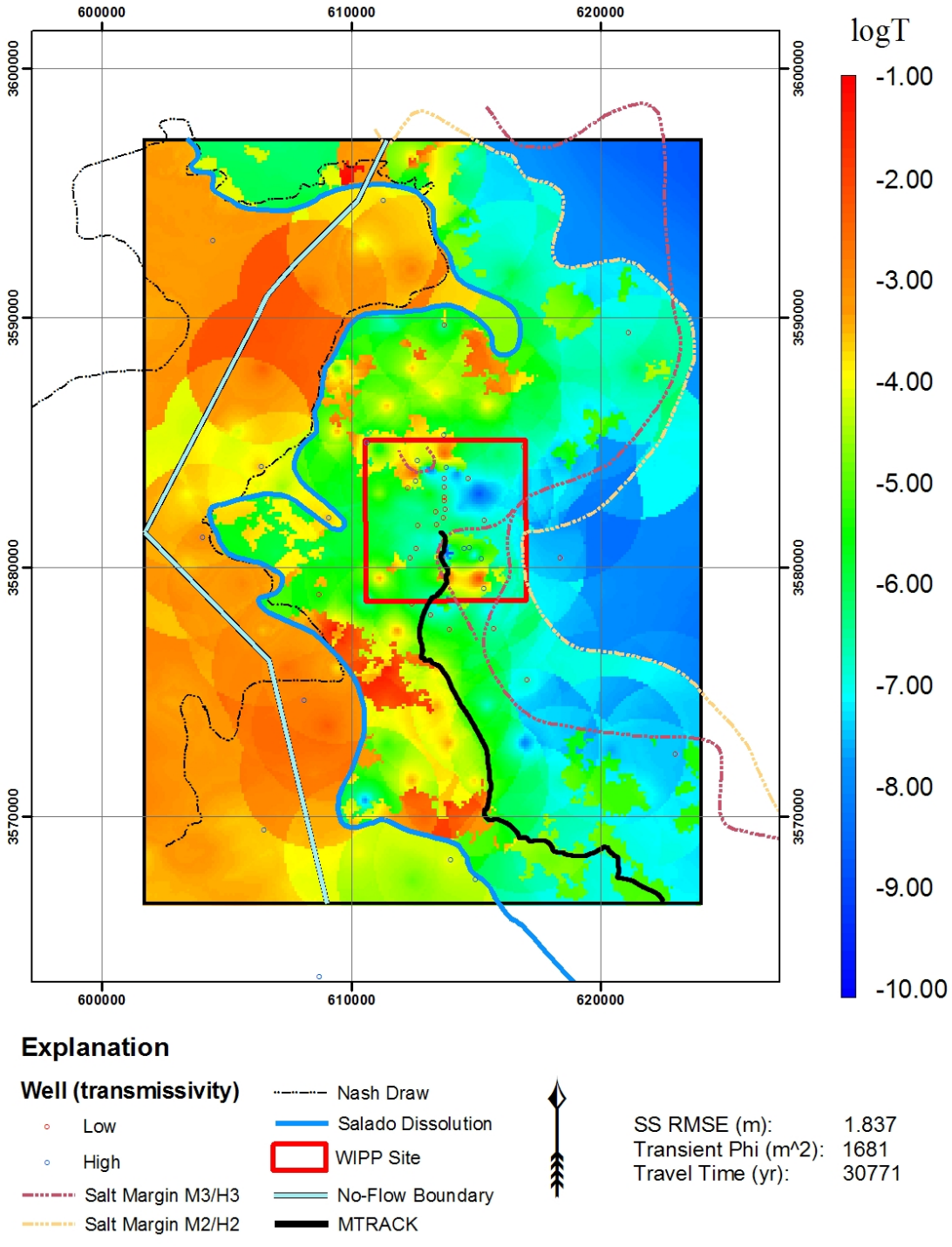
D22R08—Calibrated



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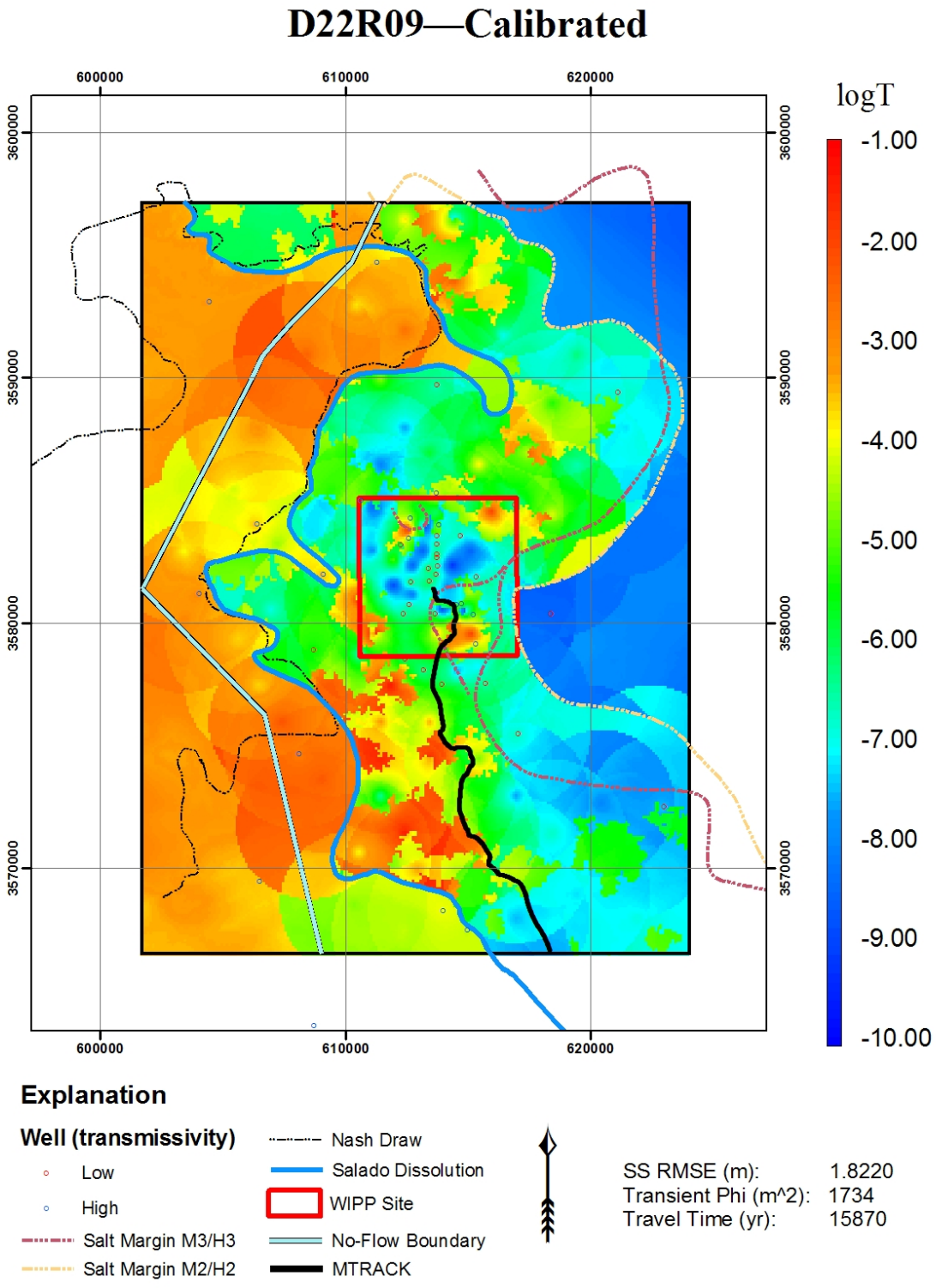
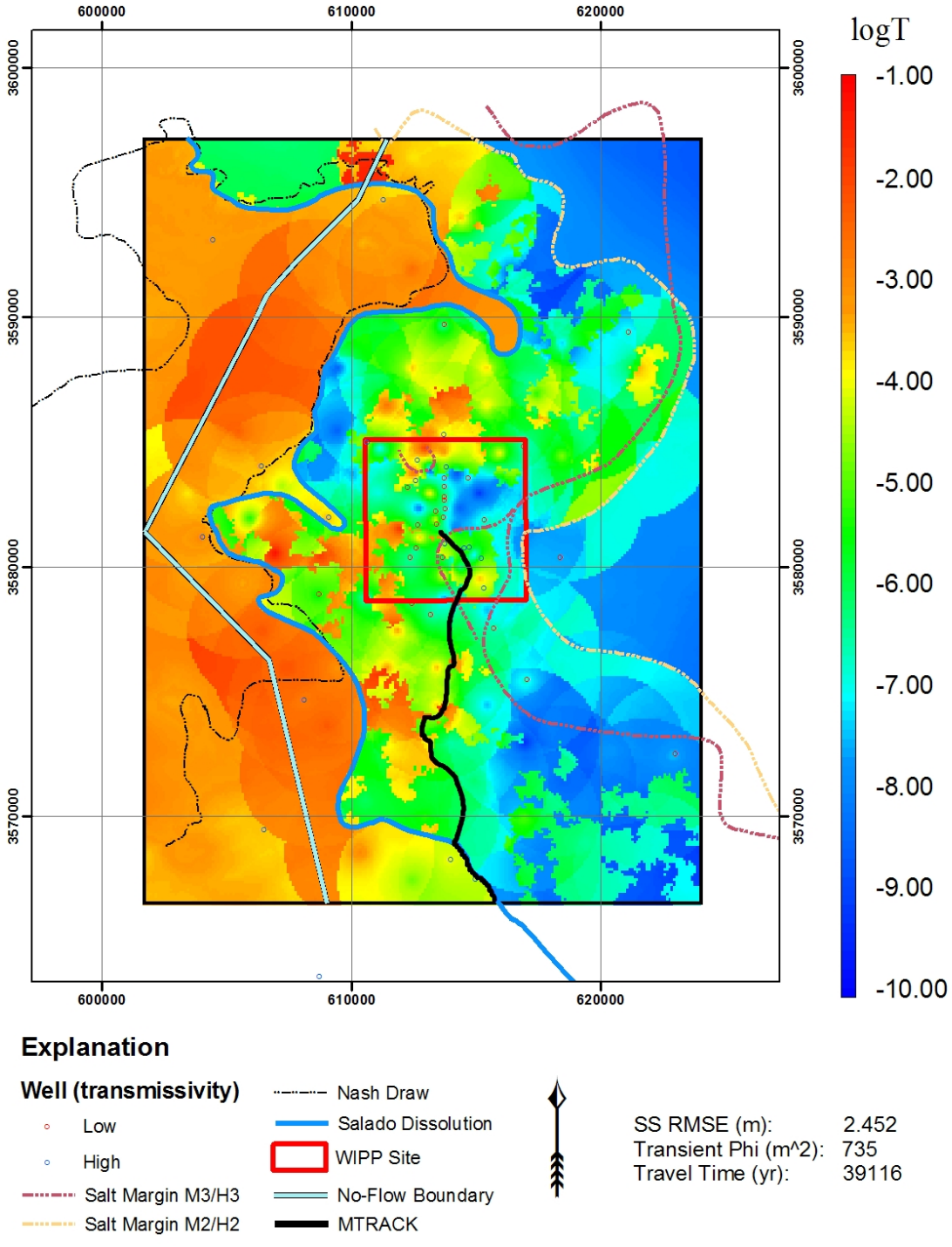

D22R09—Calibrated
600000
610000
620000
3600000
3590000
3580000
3570000
logT
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
Explanation
Well (transmissivity)
Low
High
Salt Margin M3/H3
Salt Margin M2/H2
Nash Draw
Salado Dissolution
WIPP Site
No-Flow Boundary
MTRACK
SS RMSE (m): 1.8220
Transient Phi (m^2): 1734
Travel Time (yr): 15870

1

D22R10—Calibrated



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