WASTE ISOLATION PILOT PLANT

INTERIM REPORT FOR THE REVISED DRZ AND CUTTINGS & CAVINGS SUB-MODELS PEER REVIEW

A Peer Review
Conducted By

William E. Coons, Ph.D.
John F. Gibbons, Ph.D.
Anthony S. Burgess, Ph.D.

For The
Carlsbad Field Office Technical Assistance Contractor
In Support of
The U.S. Department of Energy

December 2007

John A. Thies
Peer Review Manager

SIGNATURE PAGE

On October 23, 2007, a management meeting was held in Albuquerque, New Mexico, between members of the Peer Review Panel, the Department of Energy (DOE), Sandia National Laboratories (SNL), and the Carlsbad Field Office Technical Assistance Contractor (CTAC). The purpose of the meeting was for DOE and SNL to obtain clarification on the Panel's supplementary technical questions. Based on these discussions, DOE and SNL determined that significant resources and time would be required to successfully complete the peer review, and therefore, it was decided to suspend the peer review indefinitely. This interim report was prepared by the Peer Review Panel to document the progress achieved during the peer review of the revised DRZ and Cuttings & Cavings sub-model.

SIGNATURES:

WE Coons — 12/11/07

William E. Coons, Ph.D., Chairman — **Date**

Anthony S. Burgess — 12/11/07

Anthony S. Burgess, Ph.D. — **Date**

12/11/07

John F. Gibbons, Ph.D. — **Date**

Executive Summary

The Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is the world's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste that has resulted from the research and production of nuclear weapons. In 1998 the Environmental Protection Agency (EPA) certified that WIPP met all applicable federal radioactive waste disposal regulations, and it received its first shipment of transuranic waste on April 6, 1999.

The WIPP Performance Assessment (PA) methodology includes twenty-four conceptual models that are used to represent the features, events, and processes involved in assessing the long-term performance of the WIPP. To be used in a PA, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The DOE proposes modifications that affect two of the twenty-four conceptual models in the Performance Assessment Baseline Calculation (PABC), the EPA's current PA baseline from the first recertification of the WIPP (DOE, 2004).

One of the important conceptual models that provides input to PA is the model for the disturbed rock zone (DRZ). The DRZ is the area surrounding an excavation that experiences a change in hydrologic or mechanical properties due to damage caused by redistribution of stresses that accompany excavation. The DRZ conceptual model has been predicated on conservative assumptions that estimate the physical extent and permeability of the DRZ.

The DOE has proposed to modify the representation of the DRZ in the DRZ Conceptual Model: 1) to replace the assumption-based conceptual model with a quantitative model that mathematically links the mechanical responses of salt to the stresses created by excavation and then to changes in permeability that derive from the mechanical responses that occur over time, and 2) to modify DRZ features and parameters that determine the volume of brine stored in the DRZ. These features may include the size and extent, porosity, and brine saturation of the DRZ.

In addition to modifying the DRZ conceptual model, the DOE has proposed to modify the shear strength parameter of degraded waste in the Cuttings and Cavings Conceptual Model. The Cuttings and Cavings Conceptual Model has previously employed a conservative assumption for waste shear strength. The DOE has proposed to replace the assumed parameter value with a shear strength determined from experiments performed on a surrogate waste formulation.

The DOE has proposed these modifications to the WIPP conceptual models at the recommendation of its science advisor, Sandia National Laboratories (SNL), in order to incorporate changes in SNL's understanding of the WIPP underground environment into the WIPP PA. However, based on the significant resources and time required to successfully complete the peer review of the proposed modifications, the DOE has decided to suspend the peer review indefinitely and the proposed modifications have been postponed.

Peer review of conceptual models developed by the DOE for the WIPP is required by 40 CFR Part 194.27, which was promulgated by the EPA in 1996. In accordance with this requirement, the DOE Carlsbad Field Office (CBFO) initiated an independent technical peer review of the adequacy of the proposed changes to the approved conceptual models.

This peer review was conducted by a three-member interdisciplinary panel having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Albuquerque, New Mexico. The peer review panel (or "Panel") was given access to conceptual model descriptions, scientific reports, briefings, SNL staff, and to the SNL Nuclear Waste Management Program Library. The Panel also had access to reports of prior peer reviews and was given the full cooperation of the DOE and SNL throughout the review. Representatives of the EPA, DOE, the New Mexico Environment Department (NMED), and the public observed the SNL technical presentations and the Panel's questions and deliberations.

The proposed changes to the conceptual models were reviewed according to the procedures required by NUREG- 1297, *Peer Review of High-Level Nuclear Waste Repositories* (NRC, 1988) and CBFO MP 10.5 Revision 7, *Peer Reviews* (DOE, 2007), which provide a well-conceived structure that assures a thorough, well-documented review. The Panel's review was conducted within the context of the scientific method, the results of previous WIPP investigations, and the potential impact on the WIPP PA. The scientific method guides the Panel to consider all new findings in the light of previous findings at WIPP and other published scientific works, as well as to assess the reasonableness and completeness of the technical approach, all key assumptions (whether stated or unstated), and the compatibility of the new results with scientifically supportable expectations. Finally, practicality suggests that modifications that logically will produce no significant change in the overall PA need not be reviewed with the same level of scrutiny as changes that might produce a material change in the PA. The Panel has specifically limited their evaluation to the:

- validity of the assumptions,
- alternate interpretations,
- uncertainty of results and consequences if wrong,
- appropriateness and limitations of the methodology and procedures,
- adequacy of the application,
- accuracy of the calculations,
- validity of the conclusions, and
- adequacy of requirements and criteria.

The Panel conducted its review within the strict limitations of the previously-described scope of work. Based on the presentations and technical documents provided by DOE, published articles available in the professional literature, and open interactions with DOE's technical representatives, the Panel arrived at the following preliminary conclusions:

- The recommended change from a conceptual model based on conservative qualitative assumptions to a quantitative model that contains more realism will benefit the WIPP PA;
- Incorporation of the Von Mises flow generation in the salt creep model (i.e., modified M-D model), once validated against documented room closure rates and the production

and healing of dilatant strain, represents a significant improvement that would benefit predictions of DRZ characteristics;

- Although issues remain concerning scale dependence, general aspects of the relationship between permeability and dilatancy in the DRZ conceptual model represent significant progress in coupled damage/permeability calculations;
- The current definition of the DRZ requires additional scientific clarity and should be recast in terms of criteria important to WIPP performance;
- Establishing the physical extent of the DRZ on the basis of the sonic velocity measurements conducted in Room Q lacks sufficient scientific support;
- Changing the shear strength parameter in the Cuttings and Cavings Conceptual Model, based on horizontal flume tests of surrogate degraded waste, lacks sufficient scientific support; and
- The completeness, adequacy and validity of conclusions derived from results of the conceptual models and parameters proposed for both the DRZ and Cuttings and Cavings submodels are not adequately supported at this time.

Although the Peer Review was suspended prior to final discussions and full resolution of questions posed by the Panel, it is the hope of the Panel that the information that follows in this report is beneficial to the DOE.

TABLE OF CONTENTS

ACRONYMS

CBFO	DOE Carlsbad Field Office
CCA	Compliance Certification Application
CTAC	Carlsbad Field Office Technical Assistance Contractor
DOE	Department of Energy
DRZ	Disturbed Rock Zone
EPA	Environmental Protection Agency
NMED	New Mexico Environment Department
NRC	Nuclear Regulatory Commission
PA	Performance Assessment
PABC	Performance Assessment Baseline Calculation
SNL	Sandia National Laboratories
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant

1.0 INTRODUCTION

The subject peer review was suspended indefinitely following a management meeting in Albuquerque, New Mexico on October 23, 2007. The Department of Energy (DOE) and Sandia National Laboratories (SNL) determined that significant resources and time would be required to successfully complete the peer review based on the supplemental questions from the Panel. Because the Panel had already substantially completed portions of their peer review based on the data and information already supplied by DOE, this review information has been compiled within this report for future reference.

Peer review of conceptual models developed by the DOE for the Waste Isolation Pilot Plant (WIPP) is required by 40 CFR Part 194.27, which was promulgated by the Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the DOE Carlsbad Field Office (CBFO) has conducted an independent technical peer review of the adequacy of two of the twenty-four conceptual models representing the features, events, and processes involved in assessing the long-term performance of the WIPP.

This peer review addresses revisions to the representation of the disturbed rock zone (DRZ) in the Disturbed Rock Zone Conceptual Model and the modification of the parameter distribution for a key parameter within the Cuttings and Cavings Conceptual Model. The outputs of both models are important elements in the Performance Assessment Baseline Calculation (PABC), the EPA's current Performance Assessment (PA) baseline from the first recertification of the WIPP (DOE, 2004). Changes to these models have been forwarded for review by the DOE at the recommendation of Sandia National Laboratories (SNL), DOE's science advisor on the WIPP project. SNL proposes to implement these changes to the previously approved conceptual models, and to incorporate the resulting outcomes into the PA baseline.

Sandia National Laboratories is responsible for the development, maintenance, and conduct of the WIPP PA. As part of the PA methodology included in the Compliance Certification Application (CCA), the DOE identified processes important to the WIPP waste isolation system and developed conceptual models that describe the features, events, and processes relevant to the disposal system and subsystems. These conceptual models were peer reviewed and the results were approved by the EPA during the original WIPP certification (EPA, 1998). Any significant changes to the previously approved conceptual models must first be peer reviewed to ensure that the disposal system, subsystems, and future state assumptions continue to be adequately represented.

The Peer Review Panel (the "Panel") limited its review to the scope of work provided by the DOE. The DOE has proposed to modify the representation of the DRZ in the DRZ Conceptual Model: 1) to replace the assumption-based conceptual model with a quantitative model that mathematically links the mechanical responses of salt to the stresses created by excavation and then to changes in permeability that derive from the mechanical responses that occur over time, and 2) to modify DRZ features and parameters that determine the volume of brine stored in the DRZ. These features may include the size and extent, porosity, and brine saturation of the DRZ.

In addition to modifying the DRZ conceptual model, the DOE has proposed to modify the shear strength parameter of degraded waste in the Cuttings and Cavings Conceptual Model. The Cuttings and Cavings Conceptual Model has previously employed a conservative assumption for waste shear strength. The DOE has proposed to replace the assumed parameter value with a shear strength determined from experiments performed on a surrogate waste formulation.

The peer review process is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. The peer reviewers are independent of the work being reviewed; i.e., the peer reviewers: a) have not been involved as participants, supervisors, technical reviewers, or advisors involved with the work being reviewed, and b) to the extent practical, have sufficient freedom from funding considerations to ensure the work is impartially reviewed. Therefore, the peer-reviewed subject matter provides additional assurance to the regulator and the public that the subject matter is reasonable, accurate, and valid for its intended use.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. This peer review was conducted in accordance with the NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories* (NRC, 1988). The adequacy criteria set forth in NUREG-1297 were those used by the Panel for reviewing the two conceptual models. In addition, the Panel followed the DOE CBFO Management Procedure MP-10.5, Revision 7, *Peer Review*, to perform the peer review. The Panel has specifically limited their evaluation to the:

- validity of the assumptions,
- alternate interpretations,
- uncertainty of results and consequences if wrong,
- appropriateness and limitations of the methodology and procedures,
- adequacy of the application,
- accuracy of the calculations,
- validity of the conclusions, and
- adequacy of the requirements and criteria.

This report documents the results of the subject peer review. Section 2 of this report details background information relating to the WIPP facility and the review methodology, which includes a description of the repository, its geologic and hydrogeologic settings, the review methodology, and the evaluation criteria. Section 3 presents an evaluation of each of the two conceptual models. Each model was assessed against the predetermined evaluation criteria. These sections are followed by appendices that include management and administrative information, and professional biographies for each of the Panel members.

2.0 BACKGROUND

The DOE was authorized in 1979 (Public Law 96-164) and funded by the Congress to develop a facility for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from national defense activities. The Land Withdrawal Act of 1992 (Public Law 102-579) provided additional authorization to continue the project under a stipulated statutory process. With more than 20 years of scientific investigation, public input, and regulatory oversight, the WIPP facility became the first underground repository licensed to safely and permanently dispose of transuranic radioactive waste from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

2.1 WIPP Overview

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

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

The underground excavation is 655m (2,150ft) below the surface in the bedded salt of the Salado Formation. The underground excavation includes an area used for conducting scientific investigations and experiments in which no waste will be placed, an operations area with equipment and maintenance facilities; an area in which the waste is emplaced for permanent disposal; and four major interconnecting tunnels that are used for ventilation and traffic. The subsurface waste-disposal area is planned to cover approximately 100 acres and will contain eight separately excavated panels, each containing seven disposal rooms, and two equivalent panels.

2.2 Peer Review Management

This Peer Review is an independent review sponsored by the DOE Carlsbad Field Office (CBFO) and delegated to its technical assistance contractor, known as the Carlsbad Field Office Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John A. Thies as the peer review manager.

Early in the peer review process Mr. Thies appointed a technical panel chairperson, William E. Coons, Ph.D., from among the peer review panel members to serve as the technical leader for the peer review and to lead technical development of the peer review report.

The selection and training of the peer review panel members and management of the review process were governed by DOE CBFO's Management Procedure MP-10.5, Revision 7, *Peer Review,* and the Revised DRZ and Cuttings and Cavings Sub-Models Peer Review Plan. Detailed information regarding the review process is further delineated in this document and in the peer review records.

Twenty-four conceptual models are used in the WIPP Performance Assessment (PA). This peer review addressed only the proposed changes associated with the DRZ Model and the BOREHOLE:TAUFAIL parameter, which is used in the Cuttings and Cavings Model.

2.3 System Overview

The WIPP disposal system includes the underground repository and shaft system, the geologic host rock, and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

2.3.1 Repository Setting

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

Present plans call for mining eight panels of seven rooms each and two equivalent panels in the central drifts. As each panel is filled with waste, the next panel will be mined. Before the repository is closed permanently, each panel will be closed. Waste will be placed in the drifts between the panels creating two additional panel volumes and access ways will be sealed off from the shafts. The shafts will then be sealed to isolate the repository from the ground surface. Final closure of the facility will be facilitated by creep closure of the salt.

When considering future intrusion scenarios, the DOE used the following EPA assumptions regarding future penetration of the repository:

- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be the same as the rates of deep drilling in the area over the past 100 years.

Figure 2-1 - WIPP Controlled Area

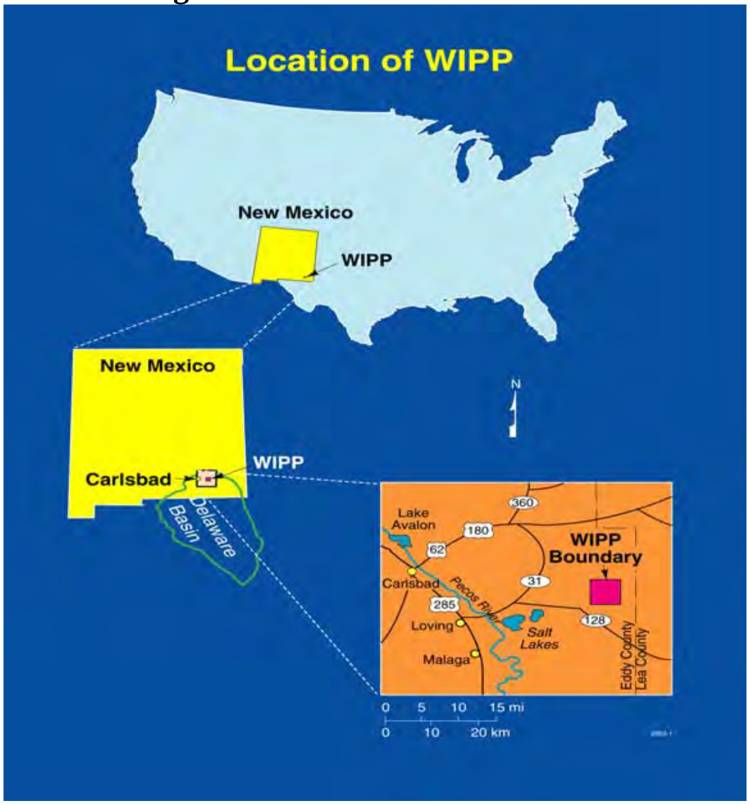
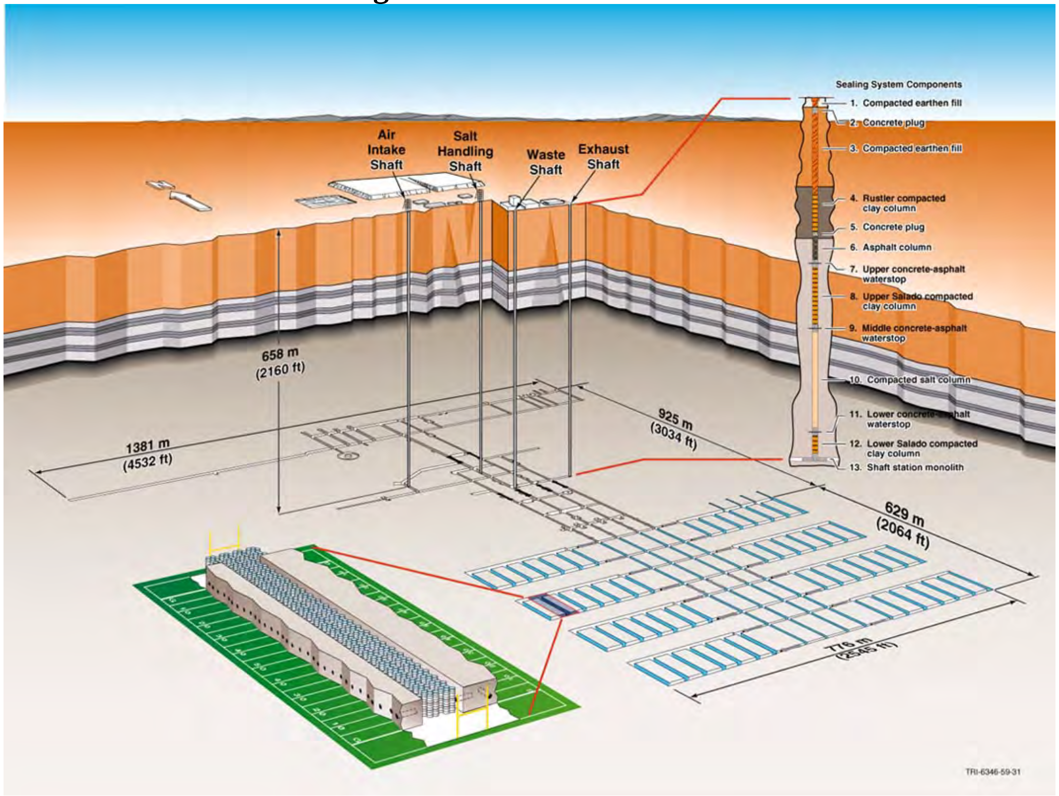


Figure 2-2 - WIPP Facilities

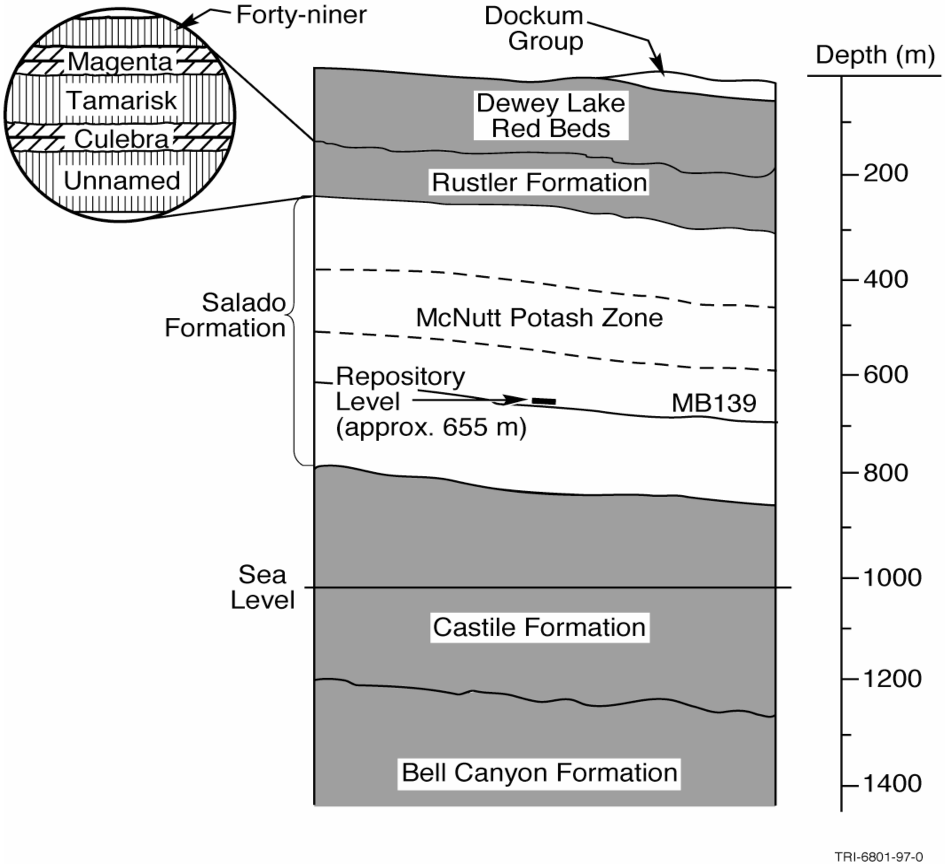


2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the Compliance Certification Application (CCA) and documents referenced in the CCA. The general stratigraphy at the WIPP site is presented in Figure 2-3.

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

Figure 2-3 - General Stratigraphy at the WIPP Site



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

2.3.3 Hydrologic Setting

2.3.3.1 Surface Water

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

2.3.3.2 Groundwater

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

Bell Canyon, Castile, Salado, and Rustler Formations are the units critical to the evaluation of WIPP groundwater issues.

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

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations because it contains isolated pressurized brine reservoirs. The Castile is predominantly low-permeability halite and anhydrite with greater permeabilities in zones of fracture and structural deformation. In the areas of higher permeability brine pressures may exist that are sufficiently above nominal hydrostatic pressure for brine to flow upward through a borehole potentially reaching the surface. The halite and anhydrite rocks of the Salado Formation are relatively impermeable and tests have shown that flows are extremely low to no flow when appreciable pressure gradients are applied. The Salado contains the repository and provides the primary natural barrier for containing radionuclides.

The Magenta and Culebra Dolomite Members of the Rustler Formation are laterally extensive, transmissive, and display hydraulic characteristics sufficient for the lateral transport of radionuclides. Hydraulic conductivities in both members range over five to six orders of magnitude in the WIPP area but the Magenta is generally less transmissive than the Culebra. The Culebra is the most extensive and most transmissive unit above the Salado at the WIPP site.

2.4 Peer Review Panel Methodology

The peer review commenced after panel member orientation and training in accordance with CBFO MP-10.5, Revision 7 (July 2007), the Peer Review Plan, and other relevant information presented in the orientation and training package.

The peer review panel employed the following approaches in their overall method of conducting and accumulating information for the reviews:

- Extensive review of provided and referenced literature relevant to the review;
- Attending presentations of information deemed relevant by SNL and DOE;
- Issue-focused discussions with question-and-answer sessions with DOE technical representatives;
- Review of literature and documents referenced during the question-and-answer sessions, and;
- Formal and informal discussions among the Panel members.

The Panel was provided several presentations addressing the two conceptual models and the key parameters being reviewed with respect to whether or not they represent a reasonable view of future states of the proposed disposal system for the WIPP repository. The Panel evaluated the models in accordance with the NUREG-1297 criteria.

In organizing its work, the Panel established limitations on its review and the content of this report. The Panel members did not review or offer comments on regulations. The Panel confined its review to the DRZ conceptual model and the TAUFAIL parameter, as identified in the Peer Review Plan. To maintain independence, the Panel did not offer recommendations for specific methods and/or approaches to be employed in future work.

2.5 Criteria for Review

The nine criteria used by the peer review members are based on the criteria in EPA regulation 40 CFR Part 194.27, NUREG-1297, the EPA Compliance Application Guidance, and the Peer Review Plan. These nine criteria are:

- Adequacy of information used to review changes in model or parameter,
- validity of assumptions,
- alternative interpretations,
- uncertainty of results and consequences if wrong,
- appropriateness and limitations of method and procedures,
- adequacy of application,
- accuracy of calculations,
- validity of conclusions, and
- adequacy of requirements and criteria.

This evaluation is discussed in the next section.

3.0 EVALUATIONS

This section presents the results of the Panel's review of the two proposed modifications. Each of these modifications is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. Each Panel member was provided an opportunity to document any dissenting views. There were no dissenting views by any Panel members resulting from this peer review.

3.1 Disturbed Rock Zone (DRZ) Conceptual Model Description

3.1.1 The DRZ Conceptual Model in Performance Assessment

In the simplest terms, a conceptual model is a description of the general functional relationship among components of a system. The conceptual model provides a framework for identifying the physical elements and the mechanical or chemical processes that govern how a system operates. During conceptual model development, it is not uncommon for the model to evolve from a qualitative conceptual model to a quantitative conceptual model. For the purposes of this report, qualitative models identify key elements of the system, envision processes or events that might cause elements of the system to interact or alter, and rely on conservative assumptions and/or simplified algorithms to predict limits describing how the system might change. In contrast, in quantitative conceptual models the elements and processes of the system are reduced to an integrated logic and sophisticated algorithms that are mathematically linked. When operated upon, the linked algorithms produce a more realistic prediction of system behavior.

The approved DRZ Conceptual Model is a qualitative conceptual model that has been constructed specifically for the purpose of producing a conservative estimate of the amount of brine that might enter and exit from the WIPP repository during a ten thousand year period. The qualitative DRZ conceptual model is driven largely by conservative assumptions concerning DRZ extent and transmissivity. The proposed quantitative DRZ conceptual model explicitly models the time-dependent mechanical behavior of salt in response to excavation and the consequent effect that mechanical response has on the storativity and permeability of the rock that surrounds the waste at WIPP.

The DRZ is the area surrounding an excavation that experiences a change in hydrologic or mechanical properties due to redistribution of stresses that accompany excavation (after Clayton, “The Disturbed Rock Zone Conceptual Model: Background” in Vugrin et al., 2007). The DRZ has been conceptualized for the purposes of repository performance assessment. The qualitative DRZ conceptual model was reviewed and found adequate during the Peer Reviews conducted in 1996 and 1997 (Wilson et al., 1996A; Wilson et al., 1996B; Wilson et al., 1997A; and Wilson et al., 1997B). That conceptualization was developed by assembling a composite of conservative assumptions based on: 1) subjective observations, and 2) measurements of the experimental facility, access drifts and shafts. The assumptions, observations and measurements have been tempered by general principals adapted from experience in salt mining. No quantitative modeling of the formation or healing of the DRZ has been undertaken in formal WIPP performance assessments (PAs) because in 1996 it was agreed that the mechanical principals governing DRZ development were not sufficiently defined at that time (Wilson et al., 1996). By 1996, the M-D model (Munson and Dawson, 1982) had been modified to better predict convergence rates in the experimental facility (Munson et al., 1989), but a linkage between salt creep, damage, and permeability was not proposed until 2001 (Chan, Bodner, and Munson, 2001). In the mid-1990s, the concept that a time to salt damage and time to ultimate failure could be modeled using deviatoric stress and confining pressure was advanced by Ratigan and Van Sambeek (1991), Chan, Munson, Fossum and Bodner (1995) and Chan, Bodner, and Munson (2001). Relationships derived in these works indicate that dilatant strain only occurs above a threshold ratio of deviatoric stress to confining pressure. No model for DRZ extent and permeability that supersedes the qualitative DRZ Conceptual Model reviewed in 1996 and 1997 (Wilson et al.) has been proposed for use in WIPP PA until the model that is being reviewed under this peer review.

3.1.2 The Proposed DRZ Quantitative Conceptual Model

The proposed conceptual model of DRZ extent and permeability now under review is a quantitative conceptual model developed to replace the qualitative model approved in 1996. It makes use of at least some of the advancements that occurred in the mid- to late 1990s. Its mechanical aspects have been developed by calibrating a modified version of the M-D model against estimates of DRZ damage extent, as determined from sonic velocity measurements (Park and Ismail, 2007; Park et al., 2007). The sonic velocity measurements were completed in an access drift wall twelve years after the drift was opened. The theoretical basis of the model is that damage results from dilational creep (Chan, Bodner, and Munson, 2001); that dilational creep then ceases, and thereafter, no new damage occurs. Healing of damage may begin as soon as secondary creep is initiated, and the healing process greatly accelerates as backstress develops due to gas pressure or contact between the converging surfaces of the opening and the waste. The resulting interpretation of the DRZ has been that it is a thin zone of macro and microfracture (two meters in the horizontal plane and up to five meters thick in the vertical plane) that surrounds the facility openings (Vugrin et al., 2007).

The hydrologic aspects of the DRZ conceptual model have been modeled by deriving a relationship between dilatant damage and permeability. Non-elastic dilatant damage results from production of a network of macrocracks and microcracks in the rock immediately adjacent to excavated openings. This increase in connected porosity increases the local permeability above that of the intact rock. The permeability of the networked fractures has been approximated by a cubic relationship to the volumetric strain (Pfeifle et al., 1998 after Peach, 1991). This relationship essentially couples changes in permeability to the non-elastic deformations calculated by the M-D Model (Chan, Bodner, and Munson, 2001).

The original modeling of transient creep in the Salado formation was done by Munson and Dawson (1982) on the basis of laboratory creep tests performed at Sandia National Laboratories and RESPEC Inc., a rock mechanics contractor. Creep mechanisms and proposed repository conditions were mapped and a generalized flow law (Tresca) was applied. The traditional time dependent relationships among primary, secondary and tertiary creep were not considered at this time since laboratory testing of tertiary creep requires impractically long times, and was assumed not likely to occur during the life of repository openings. A transient creep curve, based on work-hardening and recovery, and a constitutive model were developed and applied to laboratory tests. A creep mechanism map for steady state creep was developed. Estimates of repository conditions were made, and a model of room convergence was constructed.

Measurements of room convergence became available from the north experimental facility at WIPP and it was found that the M-D model under-predicted room closure rates by about a factor of three. Munson et al. (1989) set about resolving the discrepancies between the model and measured room convergence rates in several ways. These included: 1) substitution of the Van Mises flow generalization for the previously used Tresca flow law, 2) compensating for residual strain in core samples used for rock property determinations, 3) considering the effect of impurities in the Salado halite, 4) expanding the repository conditions database, 5) refining the repository stratigraphic characterization, and 6) calibration of the model to measured strain rates. These measures improved the prediction of room convergence to within a few percent of observed rates over a relatively short observation period of 600 days.

Chan, Munson, Fossum, and Bodner (1995) and Chan, Bodner, and Munson (2001) further defined the effects of clay seams and halite impurities on room behavior and refined the relationship between deviatoric stress and dilatant creep. Chan, Bodner, and Munson (2001) proposed a relationship between the equilibrium among dilatant and constant volume creep, damage extent and healing, and permeability of salt during repository room convergence. In the DRZ model being reviewed, a modified version of the MD model that incorporates the Von Mises flow generalization has been included in the rock mechanics code SANTOS, and is the basis for DOE’s subsequent analyses of permeability and damage around Room Q.

The proposed model’s prediction of the extent and permeability of the DRZ (Park, 2002; Park et al., 2007) is based on a calculation outlined in figure 2 from Park et al. (2007). This calculation is based on the application of SANTOS, the relationship between permeability and volumetric strain from laboratory tests (Pfeifle et al., 1998), and calibration to damage measurements based on sonic velocity measurements. A constant (C) representing the limit of dilatant creep is determined by comparing dilatancy contours with the ultrasonic test data. The distribution of C around the exterior boundary of the room is the basis for predicting damage.

Predictions generated by the DRZ Conceptual Model depend on: 1) the basic construction of the mechanical model (3.1.2.1), 2) the use of sonic velocity as the means for establishing the physical extent of the DRZ (3.1.2.2), and 3) completeness of the permeability model (3.1.2.3). To ease complexity of discussion, these three elements will be evaluated separately, using the evaluation criteria contained in NUREG-1297.

3.1.2.1 Evaluation of the Mechanical Model for DRZ Development and Healing

This Section presents the Panel's evaluation of both the creep closure and healing processes with respect to NUREG-1297 criteria. These evaluations pertain to the portion of the Panel's scope that relate to evaluating the proposed model's ability to predict the extent and permeability as a function of time.

Information used to evaluate the DRZ mechanical model

The extensive reference list provided by the USDOE for the reviewers contained more than 100 documents and over 5,000 pages, including several works on the background and historic observations of the WIPP facility, history of the development of the model under review, and observations of other underground structures in salt. The history of the development of the proposed new conceptual model and its observational bases were carefully reviewed from the earliest form of the M-D model (1982) through the modifications of that model (Munson et al., 1989; Chan, Bodner, and Munson, 2001; Park et al., 2007; and others) until it reached its contemporary form. Several documents were reviewed that were obtained from refereed professional publications (e.g., Hu and Hueckel, 2007). In addition, DOE/WIPP Geotechnical Reports documenting the geotechnical monitoring of the repository beginning in 2000 were reviewed. Extensive formal and informal conversations among panel members were held to coordinate understanding and to assure unanimity. A technical summary document was provided to the Panel by SNL on July 16, 2007 that documented DOE's development and technical position with respect to the proposed model changes (Vugrin et al., 2007). Questions were submitted by the Panel to the Sandia National Laboratories (SNL) staff after the technical presentation made on July 3, 2003. Responses provided by SNL to those questions were also consulted.

Validity of assumptions used in the DRZ mechanical model

The Panel has identified four key assumptions within the DRZ mechanical model. The proposed model has assumed displacement according to the Van Mises flow generalization, a change from the earlier versions of the M-D Model that used a Tresca flow generalization. The Panel finds this assumption a valid and significant improvement.

For gas pressurized repository scenarios, the proposed model has assumed that an accumulation of gas in the closed repository will create a backstress that causes healing of fractures in the salt. More specifically, DOE assumes that gas will be trapped in a closing room, and that the trapped gas will create a body force against the enclosing walls. In light of the ability for the gas to enter the fractures in the wall rock, the Panel finds that DOE's assumption that a body force will be created that will cause the DRZ to heal is inadequately supported.

The proposed model is based on a calibration of the DRZ extent determined by sonic velocity measurements. The Panel finds the assumption that the DRZ extent can be adequately determined using sonic velocity to be inadequately supported. This topic is addressed more completely in Section 3.1.2.2 (Sonic Velocity Measurements).

The proposed model may not directly evaluate/address the potential damage that could occur under tertiary creep. The Panel is uncertain if the proposed model includes algorithms that specifically address tertiary creep, or if DOE has assumed that tertiary creep will not occur.

Alternative interpretations to the DRZ mechanical model

The Panel does not know if the proposed DRZ mechanical model has the ability to evaluate the potential for the onset of tertiary creep and its consequences. The acceleration of strain rate in Panel 1 reported in the WIPP Geotechnical Report 2000-2001 (DOE/WIPP, 2002), whether the result of tertiary creep or disturbance, implies the probable disruption of any equilibrium state between dilatant and constant strain creep mechanisms. The potential for renewed enlargement of the DRZ, and its associated impact on permeability, is a significant unknown in the potential of the DRZ to impact performance. It is not clear that the proposed model has the ability to treat the impact of accelerating creep rates in the disposal panels.

Uncertainty of results and consequences if the DRZ mechanical model is wrong

The Panel has not quantified the uncertainty of the mechanical model calculations. It is the Panel's judgment that uncertainty attached to the quantitative model results would not produce a DRZ that possessed a greater extent or permeability than was approximated in the qualitative DRZ conceptual model that was previously approved for use in WIPP PA.

Appropriateness and limitations of methods and procedures used to develop the model

The Panel endorses the constitutive elements of the mechanical model, but does not accept the 2m DRZ extent based on sonic velocity tests, used to calculate the damage potential constant C. It is the Panel's opinion that a critical review of alternative creep models and reconciliation of WIPP DRZ model predictions to exploratory and operational field observations made in underground salt facilities would result in a more robust model.

Adequacy of the DRZ mechanical model application

The completeness of the modified M-D model and the geomechanical assumptions contained in the proposed conceptual model have not been adequately supported. The Panel finds the absence or inexplicit use of a tertiary creep component to be a significant weakness in the application of the quantitative DRZ mechanical model.

Accuracy of calculations used in the DRZ mechanical model

The accuracy of calculations developed for the conceptual model as represented by Park et al. (2007) was not independently verified by the Panel.

Validity of conclusions drawn from results predicted by the DRZ mechanical model

Due to unaddressed technical issues, conclusions derived from the proposed DRZ mechanical model are currently precluded.

Adequacy of the requirements and criteria

The Panel finds the requirements and criteria that the EPA and the DOE apply to the acceptance of new or modified conceptual models to be adequate.

3.1.2.2 Sonic Velocity Data

To investigate the extent of the DRZ and determine where enhanced permeability was likely to be encountered, DOE selected sonic velocity measurement. DOE installed ultrasonic transmitters and receivers in boreholes that were drilled in the walls of the S-90 drift, an access drift to Room Q located in the WIPP underground.

Sonic wave velocity is a function of the density of the medium that is carrying the wave, i.e., the greater the density, the faster the velocity. Excavation-related damage in the salt surrounding tunnels and rooms consists of a network of macrocracks and microcracks. In general, the larger cracks are concentrated nearer to the face of the excavation, and the crack aperture, frequency, and connectivity decrease with distance away from the face. This distribution of fractured rock causes the sonic velocity near the excavated face to be slower than the velocity of the less damaged rock.

Sonic velocity tests were conducted in two separate intervals separated in time by about 15 months (2000 and 2001). Excavation of the access drift was completed in January 1988. The first round of sonic velocity tests was performed May 23, 2000, and the second round on August 29, 2001.

Information used to evaluate sonic velocity determinations of the DRZ

Information used to evaluate sonic velocity determinations of the extent of the DRZ included the summary document prepared by Vugrin et al. (2007) and underlying documents. Key underlying documents included the memo by Holcomb and Hardy (2001) that transmitted and interpreted the initial sonic velocity data, the technical document that reported and interpreted the combined first and second round of sonic velocity data (Park et al., 2007), evaluations of the core removed to install the sonic velocity transmitters and receivers (Bryan et al., 2002), and documents reporting the results of field investigations on the extent and characteristics of the DRZ at WIPP (Beauheim and Roberts, 2000; Stormont, 1991).

Validity of assumptions concerning sonic velocity data

A number of assumptions (implicit and explicit) have been made to simplify data interpretation, or establish a foundation for the investigation. The assumptions judged by the Panel to be most significant are:

Sonic Velocity tests are sensitive enough to detect all damage significant to determining the extent of the DRZ. This assumption is unstated, but implicit and unsupported.

For the purposes of determining the extent of the DRZ, changes in sonic velocity measured at increasing depth from the face of a mined opening can be simplified into two linear segments, one horizontal and the other a positive slope. This mathematical simplification is unsupported and appears contrary to multi-zone damage models that might be conceptualized from the observations made on core samples of salt taken from the DRZ (Bryan et al., 2002).

Sonic Velocity data acquired during collection periods separated by more than 15 months can be combined into a single data set. This assumption is unsupported and is questionable given the observation that continuing deformation was observed to have caused salt to intrude into the drift during the interval between the tests.

Alternative interpretations

The extent of the DRZ surrounding excavated openings in the WIPP underground has been determined using a number of techniques. The different techniques have included measuring sonic velocity at increasing depths from excavated faces, evaluating changes in the in situ characteristics that are sensitive to stress relief that accompany excavation (permeability, pore pressure), changes in the in situ stress field (as demonstrated by increasing threshold hydrofracture pressures as a function of distance from the excavated face), and physical observation of rock cores taken from excavation walls (fractures and recrystallization textures). Based on the Panel's review of the sonic velocity data presented, the Panel does not agree that the extent of the DRZ is 2m.

Uncertainty of results and consequences if wrong

The Panel was not presented an evaluation of statistical uncertainty in the sonic velocity data. If the sonic velocity data were misinterpreted or in error, the estimated extent of the DRZ could be wrong.

Appropriateness and limitations of methodology and procedures

The ability of sonic velocity techniques to detect microcracks with apertures in the range of 50 μm has been questioned by Bryan et al. (2002). The Panel has not been supplied with information that resolves this question. Until the sonic velocity measurement technique is demonstrated, practically and theoretically, to have the ability to detect the entire extent of a microfracture network that affects permeability around excavated openings, it should not be used as the sole means for establishing the DRZ extent.

Adequacy of application

The Panel did not explicitly evaluate the adequacy of applying sonic velocity measurement techniques for determining the extent of the DRZ.

Accuracy of sonic velocity calculations

Data interpretations of DRZ extent and consequent estimate of the damage potential constant were quoted to three decimal places. The Panel was not provided the detailed records and data that would provide a basis for evaluating if the data accuracy warrants the use of three decimal places.

Validity of conclusions

The conclusion that the extent of the DRZ is about 2m into the rib is predicated based on interpretation of sonic velocity data. Based on the data presented, the Panel does not agree that the 2m DRZ extent determined from sonic velocity experiments is valid.

Adequacy of the requirements and criteria

The requirements and criteria for acceptance of the sonic velocity data were not presented to the Panel. However, the Panel did note that the sensitivity of sonic velocity tests to detect microcracks with apertures less than 50 μm had not been established.

3.1.2.3 Evaluation of the Quantitative DRZ Permeability Model

Information used to evaluate conceptual model

The permeability (k) of intact and damaged halite has been measured in the laboratory and in boreholes within the repository. Theoretical considerations by Peach (1991) led to the conclusion that permeability was a function of the cube of the volumetric strain (ε). Laboratory tests by Pfeifle et al. (1998) using WIPP salt samples were used to develop a relationship:

$$k = C_p \varepsilon^3$$

$$\text{where } C_p = 2.13 \times 10^{-8} \text{m}^2$$

Testing in WIPP reported by Beauheim and Roberts (2000) in SAND2000-1586J and Beauheim and Roberts (2002) in "Hydrology and Hydraulic Properties of Bedded Evaporite Formation," J. Hydrol, 259; p. 66-88, produced permeability values ranging from 2×10^{-23} to 3×10^{-16}m^2. Some tests showed an increase of permeability at higher test pressure, interpreted as showing fracture aperture increase (Beauheim and Roberts, 2002, p. 25). No correlation was apparent between permeability and normalized radial distance from the room, although this could not be interpreted as indicating that such a relationship did not exist. Permeabilities as high as 1×10^{-17}m^2 were observed at four normalized room radii (Beauheim and Roberts, 2002, Figure 7). This particular test interval was in the floor of the room L4 and was below MB139. Mine-by permeability tests reported by Domski, Upton, and Beauheim (1996) showed a slight increase in permeability between the pre- and post-mining tests, interpreted as a response to the changes in the stress field.

The estimate of the permeability is dependent upon the calculation of the volumetric strain in SANTOS, which is then used with the volumetric strain-permeability relationship developed by Pfeifle et al., 1998. The laboratory testing incorporated carefully controlled loading conditions to ensure only elastic and creep strains were developed. Likewise, the SANTOS code incorporates the M-D Model, an elastic visco-plastic constitutive model.

Validity of assumptions

It has been assumed that the relationship determined at laboratory scale holds at larger scales. The model used to interpret changes in test core permeability was developed by Peach and obeys a fracture flow law. Measured flow in fractures can be highly scale dependent. The Panel noted that where direct comparisons have been made at Asse, the field measured permeability has been lower than what was predicted from the laboratory results.

Alternative interpretations

The DRZ may be conceptually defined as the area that experiences increased fluid permeability and porosity, or it may be defined on the basis of sonic velocity tests. The Panel has noted that Bryan et al. (2002) report that sonic velocity tests are not sensitive to fracture apertures below ~50μm which could result in a significant increase in permeability compared with intact halite, and a DRZ greater than 2m in thickness.

Uncertainty of results and consequences if wrong

The principal uncertainties that the Panel has identified are:

- The sensitivity of sonic velocity tests might be inadequate for the purposes of determining small aperture fractures that might still be significant in terms of increasing halite permeability.
- The applicability of the laboratory-derived damage:permeability relationship is uncertain, primarily due to the lack of confirmatory field scale data, particularly for the WIPP facility.

- The appropriate time for assigning decreased DRZ permeability appears uncertain, based on review of data from Asse.
- The vertical extent of the DRZ appears to be strongly influenced by the presence of non-halite units.

Appropriateness and limitations of methods and procedures

The overall method of using a numerical model calibrated by actual observations is appropriate. However, the Panel recommends more complete model validation using empirical data and operational observations. Field testing methods for determining the extent of the DRZ should be capable of detecting changes in halite properties at a scale that is appropriate to the magnitude of the properties and conditions contemplated for WIPP.

Adequacy of application

The Panel considers the proposed model to determine the extent and permeability of the DRZ as not adequate. The principal areas requiring further work are:

- Improvement of the method for determining the extent of the DRZ from field tests,
- Confirmation of the laboratory derived relationship between volumetric strain and permeability at the field-scale, including the time-dependent effect of healing, and
- Model validation, including quantification of the variability of constitutive parameter values and sensitivity to lithological changes, using underground observations at WIPP.

Accuracy of calculations

The calculation of the permeability is developed from a relationship with volumetric strain. Thus the accuracy of the calculations is dependent upon (i) the ability to accurately define the volumetric strain in the model domain, as a function of time and repository conditions, and (ii) the accuracy of the function relating permeability to volumetric strain. The accuracy of the model could be quantified by using it to forecast operational room deformations (volumetric strains) and permeabilities, and comparing predictions with observations. Without these comparisons, the accuracy of the model calculations cannot be fully evaluated.

Validity of conclusions

The general conclusion that there is a relationship between permeability and volumetric strain appears reasonable.

Adequacy of the requirements and criteria

The Panel does not consider the requirements and criteria for model validation to have been sufficiently documented.

3.2 Evaluation of the Shear Strength Parameter BOREHOLE:TAUFAIL

3.2.1 Parameter Description

The Cuttings and Cavings Model estimates the volume of solids removed as a consequence of a borehole penetrating waste disposed in a waste emplacement room. The term “Cuttings” is applied to materials removed directly by the cutting action of the drill bit. The term “Cavings” is applied to materials that are removed from the sidewalls of the borehole by the shearing forces of drilling fluids that lubricate the drill bit and carry cuttings to the surface.

The conceptualization behind Cavings is that the velocity of the injected drilling fluid is highest near the drill collar, where all fluids must escape through a narrow annulus between the drill collar and the borehole wall, prior to spiraling up the borehole and carrying entrained solids toward the surface. The narrowness of the annulus creates a higher flow velocity than occurs within the unobstructed borehole. The hydrodynamic shear forces introduced by the high velocity flow produce enhanced erosion of the borehole wall (Cavings) in the vicinity of the drill collar.

The Cuttings and Cavings conceptual model estimates the total volume of Cavings by determining where the shear stress imparted by the drilling fluids equals the shear strength of the borehole wall. For the purposes of a WIPP PA, the salient shear strength for the borehole wall is the shear strength of aged and degraded WIPP waste, at the strength that resists erosion by the flowing drill fluid.

The shear strength of soils and like materials is usually represented by τ or Tau. Heretofore in WIPP PAs, the τ associated with WIPP wastes has been estimated very conservatively, so as to over-predict releases attending a borehole intrusion. Most recently, an expert elicitation assigned the lower bound of τ at 0.05Pa, a value that is similar to the shear strength measured for Bay Area muds.

The upper bound for the shear strength parameter was estimated as 77Pa based on a relationship between particle size and shear strength (Wang, 1997; Wang and Larson, 1997). During WIPP PA, the shear strength of the waste is sampled statistically across the range from the upper bound to the lower bound. The current range in values between the lower and upper bounds for shear strength exceeds 3 orders of magnitude. As a result of this span, WIPP PA assumes a log uniform distribution when sampling shear strength.

3.2.1.1 Shear Strength Measurement

DOE is proposing to replace the conservative lower bound estimate, derived through elicitation, with a more realistic shear strength value, determined empirically through tests conducted on a surrogate waste material. The formulation for preparing the surrogate waste test material has been modeled closely after the surrogate formulation used to derive the tensile strength parameter for the WIPP Spallings model.

The tests conducted to derive an appropriate shear strength for the surrogate waste are not classical geotechnical shear strength tests such as direct shear, triaxial shear, or vane shear tests. Instead, the shear strength for the waste has been measured by subjecting samples to water flowing at varying rates in a horizontal flume. Such flume tests have been adopted by entities such as the US Army Corps of Engineers (see Parchure and Mehta, 1985; Parchure et al., 2003) as the most direct means for determining the “erodibility” of sediments.

3.2.1.2 Hydrodynamic Shear

Hydrodynamic shear is a term that has been adopted to distinguish shear strength measured by flowing water from classic geotechnical shear strengths. A given material may exhibit several different hydrodynamic shear strengths depending on such characteristics as the thickness of the bed, the degree of heterogeneity of the bed and the compaction history of the bed.

Hydrodynamic shear measurements have also been found sensitive to as many as 60 parameters, including such parameters as the salinity and pH of the pore liquid and flowing medium; the degree of turbulence of the flowing fluid; moisture content of the sample; mineralogy of the soil; and so on (Parchure, Sobecki and Pratt, 2003). There are multiple hydrodynamic shear strengths, including definitions for the initial (or incipient motion) shear strength, operational shear strength, characteristic shear strength, and aggregate shear strength (or bed shear strength). The different shear strengths apply to different situations and have different applications.

The initial shear strength (commonly τ_i) refers to the lowest energy where flowing water lifts and carries material off the surface of the sample. Typically this erosion is associated with mobilization of fluidized mud particulates in the uppermost sections of deposited sedimentary beds. The shear stress required to carry particles of the bedded sediments typically increases linearly above τ_i with increasing depth from the surface.

Deeper in the beds, where some compaction has occurred, the shear stress: required erosional energy relationship changes, and erosion requires higher energy. This transition creates a second linear segment in shear stress versus erosion rate plots. The shear stress at which this transition occurs is referred to as the characteristic shear strength (τ_{ch}).

At still deeper horizons where such phenomena as layering may induce armoring in the sediment bed, even greater energy is required for erosion. That shear strength, when exceeded by applied stress, can result in a sudden mobilization of a significant portion or all of the bed, and it is sometimes referred to as the aggregate bed shear strength (see Parchure and Mehta, 1985).

The operational shear strength (τ_c) is a practical shear strength that has been adopted by engineers. Operational shear strength is determined from the empirical data by geometric construction. The second line segment (the line between characteristic shear strength and aggregate shear strength) is extended to the abscissa, thereby defining a shear strength that is intermediate to the initial shear strength and the characteristic shear strength. The operational shear strength introduces a margin of engineering conservativism to designs that might otherwise be based on the characteristic shear strength.

3.2.2 Review of Proposed TAUFAIL Shear Strength

Information Used to Evaluate the TAUFAIL Shear Strength Parameter

The information consulted to evaluate the proposed shear strength parameter for TAUFAIL included literature on hydrodynamic shear testing and interpretation (e.g., Partheniades, 1965; Partheniades and Paaswell, 1970; Mehta et al., 1982), changes in PA outcomes produced before and after the proposed parameter change, reports of prior peer review panels and reviewers concerning the Cuttings and Cavings Conceptual Submodel (e.g., Wilson et al., 1996A), and borehole logging data obtained from borings at the WIPP site and surroundings (e.g., Powers and Holt, 1987).

For the most part, the documents reviewed by the Panel were outgrowths of the work of Partheniades (1965) and Parchure and Mehta and coworkers (post-1982). Most all of the documents were provided to the Panel as background reading by DOE. One additional reference (Parchure, Sobecki and Pratt, 2003) was used by the Panel. The documents were reviewed in detail in order to gain an understanding of the utility and limitations of the test method used to develop a more realistic value for the shear strength parameter used in WIPP Cavings calculations. The documents that were reviewed discuss hydrodynamic shear test set-ups, how the data are acquired and interpreted. Parchure, Sobecki and Pratt (2003) discuss the dependence of results on control of parameters, representativeness of the sample, and it clarifies sediment thicknesses where erosion may be controlled by critical shear strength.

The Panel reviewed the results for Cavings calculations that were undertaken as part of the 2004 WIPP recertification (DOE, 2004). Those results were then compared with an outcome produced in 2007 in which the proposed change in waste shear strength was implemented. The Panel's focus was on the volume of Cavings produced and not on radioactive releases. The Panel reviewed and compared the released volumes and incident of releases to gauge the significance of the change to the PA and to assess the reasonableness of the change.

The Panel was provided and reviewed pertinent sections of reports and memos produced for WIPP's initial license application and subsequent recertifications. The Panel also was provided and reviewed memos and reports on the Cuttings and Cavings Submodel that were prepared by previous peer review panels and reviewers. These documents were reviewed in order to learn how the submodel has evolved, and determine what concerns, reservations, or perceived limitations might have been identified by previous participants.

The Panel requested, received and reviewed several borehole logs for borings on and around the site. The data were reviewed by the Panel to establish a context for comparing borehole characteristics and assist assessing the reasonableness of PA calculations that incorporated the proposed change in the shear strength parameter.

Validity of Assumptions

The method used by DOE to arrive at an improved estimate of the minimum shear strength for aged, degraded waste entails conducting hydrodynamic experiments on a surrogate waste material. The surrogate was prepared to simulate a representative sample of the most erodible materials likely to result from physical and chemical weathering of WIPP waste. Use of a surrogate waste material has been reviewed and approved by a peer review panel for the purpose of determining the tensile strength of weathered WIPP waste and providing important input to the Spallings conceptual submodel (Yew et al., 2003).

The Panel agrees that under certain circumstances, tests performed on surrogate materials may be an acceptable alternative to expert elicitation for illuminating the performance characteristics of WIPP materials. In the current review, the Panel has not been convinced that use of a surrogate material has been adequately supported. The principal concern derives from a caution provided in the professional literature (Parchure, Sobecki and Pratt, 2003) that warns that results from hydrodynamic shear tests are extremely sensitive to the characteristics of the test sample. It goes on to warn against testing apparently "similar" materials, or materials taken from locations near the location of concern, in lieu of samples taken from the exact location and from the actual material ("actual sample") where the results of the test will be applied. It appears to the Panel that hydrodynamic test results from a surrogate formulation for a future material with uncertain properties would necessarily be significantly less reliable than test results obtained from a material known to be "similar" to a well-characterized, actual sample.

Alternative Interpretations

Operational shear strength as opposed to initial shear as the parameter to be used by PA is one possible alternative interpretation. The expert elicitation that resulted in the assumed properties of Bay Area Mud is another very conservative interpretation. Analysis of surrogates based on assumed future waste conditions may provide a different interpretation. However, the current shear strength parameter (0.05 Pa) has been reviewed and found to be acceptably conservative and the Panel has seen no compelling evidence to justify a different parameter at this time.

Uncertainty of Results and Consequences if Wrong

DOE determined operational shear using graphical constructions (or mathematical algorithms to produce such results). The operational shear parameter was determined by plotting the flume data for erosion rate and shear stress and constructing two linear line segments through the data points. The intersection of the two line segments, when projected vertically to the abscissa, identifies the characteristic shear. The projected intercept of the lower line segment with the abscissa determines the initial shear strength, and an extension of the upper line segment to the abscissa determines the operational strength.

For the B2 tests, there are four data points used to define two straight lines. This is the minimum amount of data that makes it possible to define two straight lines. The two points assigned to the lower line segment (data points 1 and 2) clearly apply to the line segment that connects the initial strength to the characteristic strength. The data point farthest from the origin (data point 4) clearly applies to the line segment that connects the characteristic strength to the aggregate strength (off the scale of the plot). Data point 3 is ambiguous. It could be associated with the lower line segment because it is approximately on the trend defined by data points 1 and 2. If, in fact, data point 3 lies on the lower line segment, then the characteristic strength and operational strength are not defined. The characteristic shear strength could lie anywhere between 2 and 2.5 Pa, and the operational shear strength could lie anywhere between ~1.9 and 2.4 Pa.

The consequences that would result if an interpretation error has been made would be favorable to the WIPP performance assessment because the shear strength parameter for the degraded waste would increase.

For test B3 there are only 3 data points, a number generally considered insufficient for defining 2 straight line segments. DOE has defined a single straight line through all data points. Again the consequence with respect to determining the operational shear strength is that if an error has been made, then the correct value would be a higher shear strength than DOE has defined.

DOE conducted eight hydrodynamic shear tests, using two surrogate waste formulations: Category 1 (representative of 50% degraded waste), and; Category II (representative of 100% degraded waste). There were five Category I tests and three Category II tests. Parameters determined included initial shear strength, characteristic shear strength and operational shear strength. During some tests, only the operational shear strength was reported. DOE did not report the statistical uncertainty of parameters determined and instead used the mean value in their PA calculations. The mean value for the five Category I operational shear strength is 1.5Pa.

The standard deviation of the five Category I shear strength determinations is 0.531. For 95% confidence, the lower bound of the mean shear strength would be 0.44 Pa. This value is about 3.4 times smaller than what was used in the 2007 PA, and about 8.8 times greater than what was used in the 2004 PA. DOE reported only one value each for the initial shear and characteristic shear of Category I materials. As a result, direct statistical analysis of the data is not possible.

The standard deviation of all three shear strength parameters may be calculated from the three Category II test results. The mean value for the initial shear strength is 0.24Pa, with a standard deviation of 0.05. At 95% confidence the lower bound of the initial shear strength is 0.14Pa. That value is 10.7 times smaller than the value used in the 2007 PA and about 2.8 times greater than what was used in the 2004 PA. The mean value for the characteristic shear is 0.58Pa with a standard deviation of 0.19. At 95% confidence, the lower bound of the characteristic shear is 0.2Pa. That value is about 7.5 times smaller than the value used in the 2007 PA and about four times greater than what was used in the 2004 PA. The mean value of the operational shear strength of the Category II tests is 0.48Pa with a standard deviation of 0.12. At 95% confidence, the lower bound of the operational strength of the Category II tests is 0.24Pa. That value is about 6.25 times smaller than the value used in the 2007 PA and about 4.8 times greater than the value used in the 2004 PA.

The experimental uncertainty of the measurements or erosion rate and shear stress were not reported for the experiments. Possible sources of experimental error include variability in the flow rate of the water in the flume, measurement error in the mass of material removed from the sample at each time step, estimates of sample area, variability in sample composition and water composition, and so on. Whether or not these sources of possible error are significant is unknown to the Panel.

One of the most common tests applied to data derived from empirical tests is to answer the question: “Are the results reasonable?” Many times, it is not possible to answer that question until the derived data are put to use. If the results produced by the input do not appear to be reasonable, then either a new discovery has been made, the data are faulty, or the application of the data is faulty.

The Panel compared the output from the Cuttings and Cavings Submodel of the 2007 PA with the output of the 2004 PA. In the 2004 PA, approximately 91% of the realizations from the Cuttings and Cavings Submodel produced at least some amount of cavings. In the 2007 PA, only about 51% of the realizations produced cavings. That means that 49% of intrusion boreholes that penetrated degraded waste produced absolutely no volume of cavings. The Panel then examined borehole logs for drilling records recording how the sedimentary materials at the site responded to drilling. Caliper logs showed significant and consistent pocketing in horizons rich in clay. For these reasons, the Panel lacks confidence in the predicted result of no cavings in 49% of the realizations. Because the only change that occurred in the Cuttings and Cavings calculation from the 2004 PA to the 2007 PA was a change in the shear strength parameter, the Panel lacks confidence in the proposed shear strength parameter. The Panel notes that the size of the change in the parameter has caused function used for stochastic sampling of shear strength to change from a log uniform to uniform. This change removes the weighting toward finer particle size, and undoubtedly contributes to the new result.

Appropriateness and Limitations of Methods and Procedures

On the basis of technical considerations, the Panel agrees that hydrodynamic shear tests are an appropriate means for determining shear strength for bedded particulate materials, such as might be produced at WIPP after more than 1000 years of degradation of the waste. As noted above, the method may add considerable complexity to shear strength parameter determination because of the sensitivity of the test results to a large number of variables, and the uncertainty surrounding the form and composition that the degraded waste might take. As far as the Panel has been able to determine, all hydrodynamic test data developed by any scientist for any application has been acquired through tests conducted in a horizontal flume. A horizontal configuration poses some questions about application to erosion occurring on the face of vertical boreholes. In addition, the test method may not be entirely compatible with a basic assumption of the Cuttings and Cavings Submodel, i.e., that the amount of cavings produced by an intrusion borehole is independent of the conditions that prevail in the repository at the time of the intrusion.

The one additional limitation noted by the Panel is the geometry of the test setup when compared to the geometry of an intrusion borehole penetrating degraded waste in a WIPP repository. The hydrodynamic shear tests were conducted in a straight, horizontal flume, with water across the surface of a sample. This geometry is generally appropriate for determining the shear strength of deposited beds of sediment, such as those washed over by currents and tides in bays, or channel flow in rivers and streams. In vertical boreholes the horizontal geometry of the test flume does not appear optimum for an empirical determination of initial shear strength in a borehole. The initial shear strength is equal to minimum stress required to lift and mobilize a particle. Some particles are lifted but fall back onto the bed, where friction between the particle and the bed surface keep the particle from becoming mobilized. In a vertical borehole configuration, once a particle is dislodged from the surface of the borehole wall, gravity will not return the particle to the bed. As a result, tests conducted in a horizontal flume may overestimate the initial shear strength to an unknown degree. The Panel's intuition is that the difference would likely be small between initial shear strengths measured using horizontal and vertical configurations. However, the characteristic shear strength differs from the initial shear strength in that the characteristic shear strength represents the resistance to erosion of aggregated particles in the bed while the initial shear strength is more a measure of the erosion of individual particles. The effect of geometry on the aggregated particles could be more significant than the effect on individual particles because the forces of gravity on a larger mass might be more obvious. The operational shear strength, DOE's preferred parameter for calculating release of degraded waste, is defined by the rate of change in the bed shear strength under conditions of increasing erosion after the characteristic shear strength has been exceeded. The extent to which the operational shear strength might be affected by a vertical geometry has not been considered by the Panel.

Adequacy of the Application

The Panel has not seen adequate evidence for a modification to the shear strength parameter in the Cuttings and Cavings Submodel.

Accuracy of Calculations

The Panel has not independently checked DOE's calculations.

Validity of Conclusions

At this time, the Panel cannot endorse the conclusions that future borings into the repository would fail to produce any Cavings in nearly 50% of the boreholes.

Adequacy of Requirements and Criteria

The Panel finds the requirement for a conservative elicited shear strength parameter to be reasonable in the absence of a defensible experimental set-up and known representative surrogate material.

4.0 REFERENCES

Beauheim, R.L., and Roberts, R.M. 2000. Hydrology and Hydraulic Properties of a Bedded Evaporite Formation. SAND2000-1586J. Carlsbad, NM: Sandia National Laboratories.

Beauheim, R.L., and Roberts, R.M. 2002. Hydrology and Hydraulic Properties of Bedded Evaporite Formation, *J. Hydrol*, 259, pp. 66-88.

Bryan, C.R., Powers, D.W., Chapin, D.W., and Hansen, F.D. 2002. Observational studies of halite salt cores extracted from a disturbed rock zone/excavation damage zone at the Waste Isolation Pilot Plant. North American Rock Mechanics Symposium (NARMS-TAC) 2002, Toronto, Canada.

DOE. 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. Carlsbad, NM: U.S. Department of Energy, Waste Isolation Pilot Plant Carlsbad Area Office. DOE/CAO-1996-2184.

DOE. 2004. Title 40 CFR Part 191 Compliance Recertification Application for the Waste Isolation Pilot Plant. Carlsbad, NM: U.S. Department of Energy Waste Isolation Pilot Plant, Carlsbad Field Office. DOE/WIPP 2004-3231.

DOE. 2007. CBFO MP 10.5, Revision 7, Peer Review. Carlsbad, NM: U.S. Department of Energy, Waste Isolation Pilot Plant Carlsbad Area Office.

Chan K. S., Bodner S., and Munson, D. E. 2001. Permeability of WIPP Salt during Damage Evolution and Healing, *International Journal of Damage Mechanics*, 10, 347-375.

Chan, K.S., Munson, D.E., Fossum, A.F., and Bodner, S. 1995. Inelastic Flow Behavior of Argillaceous Salt. SAND94-3017J. Albuquerque, NM: Sandia National Laboratories.

Domski, P.S., Upton, D.T., and Beauheim, R.L. 1996. Hydraulic Testing around Room Q: Evaluation of the Effects of Mining on the Hydraulic Properties of Salado Evaporites. SAND96-0435. Albuquerque, NM: Sandia National Laboratories.

EPA, 1998. 40CFR Part 194 Final Rule. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Part 191 Disposal Regulations: Certification Decision, U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, D.C.

Holcomb, D., and Hardy, R. 2001. Status of Ultrasonic Wave Speed Measurements Undertaken to Characterize the DRZ in the Access Drift to Q Room Memorandum to F. Hansen, January 22, 2001.

Hu, L.B., and Hueckel, T. 2007. Creep of Geomaterials due to Coupled Damage and Spontaneous Mineral Dissolution. European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering C.A. Mota Soares et al. (eds.), Lisbon, Portugal, 5–8 June 2006.

Mehta. A.J., Parchure, T.M., Dixit, J.G., and Ariathurai, R. 1982. Re-suspension potential of deposited cohesive sediment beds. In Kennedy, V. (Ed.). Estuarine Comparisons, Academic Press, New York, pp. 591-609.

Munson, D.E., and Dawson, P.R. 1982. A Transient Creep Model for Salt during Stress Loading and Unloading. SAND82-0962. Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Fossum, A.F., and Senseny, P.E. 1989. Advances in Resolution of Discrepancies between Predicted and Measured, In Situ Room Closures. SAND88-2948. Albuquerque, NM: Sandia National Laboratories.

NRC. 1988. NUREG-1297, Peer Review for High-level Nuclear Waste Repositories: General Technical Position. U.S. Nuclear Regulatory Commission, Washington, D.C.

Parchure, T.M., and Mehta, A.J. 1985. Erosion of Soft Sediment Deposits, *J. Hydraul. Eng.*, 111(10), 1308-1326.

Parchure, T.M., Sobecki, T.M., and Pratt, T.C. 2003. Fine Sediment Parameter Measurement for Sedimentation Studies. Appendix 4, Extended Abstracts of U.S. Geological Survey Circular 1276, Proceedings of the Federal Interagency Sediment Monitoring and Instrument Analysis Workshop, September 9-11, 2003.

Park, B.Y. 2002. Analysis Plan for the Structural Evaluation of WIPP Disposal Room Raised to Clay Seam G, AP-093, Revision 1. Carlsbad, NM: Sandia National Laboratories.

Park, B.Y., and Ismail, A.E. 2007. Analysis Plan for Prediction of the Extent and Permeability of the Disturbed Rock zone around a WIPP Disposal Room, AP-133, Revision 0. Sandia National Laboratories, Carlsbad, NM: Sandia National Laboratories.

Park, B.Y., Ismail, A.E., Holcomb, D.J., and Herrick, C.G. 2007. Analysis Report for Prediction of the Extent and Permeability of the Disturbed Rock Zone around a WIPP Disposal Room, Revision 0. Sandia National Laboratories, Carlsbad, NM: Sandia National Laboratories.

Partheniades, E. 1965. Erosion and deposition of cohesive soils, *ASCE, Journal of the Hydraulics Division*, 91, 105-139.

Partheniades, E., and Paaswell, R.E. 1970. Erodibility of Channels with Cohesive Boundary, *ASCE, Journal of the Hydraulics Division*, 96, 755-771.

Peach, C.J. 1991. Influence of Deformation on the Fluid Transport Properties of Salt Rocks. Geologica Ultra Iactna, 77, Instituut voor Aardwetenschappen der Rijksuniversiteit Utrecht, Netherlands.

Pfeifle, T.W., Brodsky, N.S., and Munson, D.E. 1998. Experimental Determination of the Relationship between Permeability and Microfracture-Induced Damage in Bedding Salt. Albuquerque, NM: Sandia National Laboratories. SAND98-0411C.

Powers, D.W., Holt, R.M., and Hoffer, J.M. 1987. Preliminary Studies of Near-Surface Sediments, Salt Flat Graben, West Texas: Guidebook 18, El Paso Geological Society, p. 184-194.

Ratigan, J.L., and Van Sambeek, L.L. 1991. The Influence of Seal Design on the Development of the Disturbed Rock Zone in the WIPP Alcove Seal Tests, Topical Report RSI-0400, prepared by Parsons Brinckerhoff, San Francisco, CA, and RE/SPEC Inc., Rapid City, SD, for Sandia National Laboratories, Albuquerque, NM.

Stormont, J.C., Howard, E.L., and Daeman, J.J.K. 1991. In-Situ Measurements of Rock Salt Permeability Changes Due to Near-By Excavations. SAND90-3134. Albuquerque, NM: Sandia National Laboratories.

Vugrin, E. D., Clayton, D. J., Dunagan, S. C., Herrick, C. G. Kirchner, T. B., Nemer, M. B., and Park, B.Y. 2007. Summary Report for the 2007 Performance Assessment Conceptual Model Peer Review. Carlsbad, NM: Sandia National Laboratories.

Wang, Y., and Larson, K.W. 1997. Estimate Waste Critical Shear Stress for WIPP PA Caving Model. Memorandum to M.S.Y. Chu and M.G. Marietta, June 27, 1997.

Wang, Y. 1997. Estimate WIPP Waste Particle Sizes Based on Expert Elicitation Results: Revision 1. Memorandum to M.S.Y. Chu and M.G. Marietta, August 5, 1997.

Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and Caporuscio, F. 1996A. Conceptual Models Peer Review Report, U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, July 1996.

Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and Caporuscio, F. 1996B. Conceptual Models Supplementary Peer Review Report, U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, December 1996.

Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and Caporuscio, F. 1997A. Conceptual Models Second Supplementary Peer Review Report, U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, January 1997.

Wilson, C., Porter, D., Gibbons, J., Oswald, E., Sjoblom, G., and Caporuscio, F. 1997B. Conceptual Models Third Supplementary Peer Review Report, U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance, April 1997.

DOE/WIPP. 2002. Geotechnical Analysis Report for July 2000 – June 2001, Supporting Data. DOE/WIPP-02-3177. U.S. Department of Energy, Carlsbad Area Office.

Yew, C., Hanson, J., and Teufel, L. 2003. Waste Isolation Pilot Plant Spallings Conceptual Model Peer Review Report, U.S. Department of Energy, Carlsbad Area Office, Office of Regulatory Compliance.