WASTE ISOLATION PILOT PLANT

SPALLINGS
CONCEPTUAL MODEL

PEER REVIEW REPORT

A Peer Review Conducted By

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for the

U.S. Department of Energy
Carlsbad Area Office
Office of Regulatory Compliance

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) site has been developed near Carlsbad, New Mexico, by the Department of Energy (DOE) as the United States' first underground repository licensed to safely and permanently dispose of transuranic radioactive waste resulting from the research and production of nuclear weapons. The first shipment of transuranic waste arrived at WIPP on April 6, 1999.

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 Environmental Protection Agency (EPA) in 1996. In accordance with this requirement, the Carlsbad Field Office (CBFO) of the DOE has conducted a peer review of the new spallings conceptual model that has been developed for the Compliance Recertification.

Sandia National Laboratories (SNL) is responsible for the development, maintenance, and conduct of the WIPP performance assessment (PA). As part of the PA methodology included in the Compliance Certification Application (CCA)(DOE, 1996), the DOE identified and developed conceptual models that describe the features, events, and processes relevant to the WIPP disposal system and its subsystems. These conceptual models were peer reviewed by the Conceptual Model Peer Review Panel (CMPRP) and the Panel's results were approved by the EPA during the original WIPP certification (EPA, 1998a).

The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. The spallings conceptual model describes a potential release of degraded solid waste materials when repository gas pressure exceeds the hydrostatic pressure in the drilling fluid at the bottom of an intrusion borehole. The CMPRP found that the spallings conceptual model implemented in the CCA was inadequate to describe the detailed spallings process. However, the CMPRP also concluded that "the spallings volumes used in the CCA are reasonable, and may actually overestimate the actual waste volumes that could potentially be expected to be released by the spallings process at the WIPP"

(Wilson et al., 1997, Section 4). The EPA agreed with the CMPRP that the spallings conceptual model was inadequate but the results were acceptable for use in PA (EPA, 1998b, Section 7).

After the CCA and Performance Assessment Verification Test (PAVT) were completed, work continued on the development of a new spallings conceptual model that would be more technically defensible than the original model. The major elements of the new spallings model include 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/hydrological response of the waste as a porous medium.

This report presents the final results of an independent technical peer review of the adequacy of the new spallings conceptual model representing features, processes, and events involved in assessing the long-term performance of the WIPP.

This independent peer review was conducted by a three-member interdisciplinary team having the requisite broad experience and expertise to address the range of issues associated with the ability of WIPP to successfully isolate waste for the 10,000-year regulatory time frame. The peer review was conducted primarily in Albuquerque, New Mexico, at the DOE Energy Training Center (ETC). The peer review panel was given access to the conceptual model descriptions, scientific reports, briefings, and SNL staff. 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, and the New Mexico Environmental Evaluation Group (EEG) observed the SNL technical presentations and the Panel’s questions and deliberations.

A conceptual model is a statement of how important features, events, and processes such as fluid flow and intrusion scenarios are to be represented in performance assessment (PA). To be used in PA, a conceptual model must be successfully translated into analytical statements and mathematical analogs. The peer review panel reviewed the spallings conceptual model in detail, including the assumptions and scientific information used to develop the model, alternative models considered, uncertainties, adequacy, accuracy, and validity of conclusions. The Panel also made an assessment of the information used and whether the conceptual model is adequate for implementation in an overall WIPP PA.

The spallings model was reviewed in the context of the overall approach to the WIPP PA. The review evaluated the structure of the conceptual model and the mathematics that are used to embody the model in code. The review also included an assessment of the reasonableness of outputs based on sensitivity to parameter inputs.

The Panel has applied the stringent assessment criteria provided in NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories,* and has concluded:

- The new spallings conceptual model appears generally sound in its structure and reasonableness.
- The proposed implementation of the new spallings model appears reasonable.
- Output from sensitivity analyses indicates acceptable results.

1.0 Introduction

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The spallings model was reviewed in the context of the overall approach to the WIPP PA. The review evaluated the structure of the conceptual model and the mathematics that are used to embody the model in code. The review also included an assessment of the reasonableness of outputs based on sensitivity to parameter inputs.

This peer review meets the regulatory requirements of 40 CFR Part 191 and the implementation of those requirements by 40 CFR Part 194. The peer review was conducted in accordance with the Nuclear Regulatory Commission's NUREG-1297, *Peer Review of High-Level Nuclear Waste Repositories*. The adequacy criteria set forth in NUREG-1297 were those used by the peer review panel for reviewing the new spallings conceptual model. The peer review panel followed the DOE CBFO Management Procedure MP-10.5, *Peer Review,* to perform the peer review.

This report documents the results of the new spallings conceptual model peer review. Section 2 of this report details background information relating to the WIPP facility which includes a description of the repository, its geologic and hydrogeologic settings; the review methodology; and the evaluation criteria. Section 3 presents the Panel's evaluation of the new spallings conceptual model. The model was assessed against the requisite predetermined evaluation criteria. Section 4 discusses the integration of the peer reviewed model with the other models used in the overall WIPP waste disposal system PA. Section 5 provides a summary of the evaluations. These sections are followed by appendices that include administrative information and a professional biography for each of the peer review 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 655 meters (2150 feet) below the surface in the bedded salt of the Salado Formation. The underground excavation includes a 12-acre area used for conducting scientific investigations and experiments in which no waste will be placed; an operations area with equipment and maintenance facilities; an area in which the waste 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 independent peer review of the new spallings conceptual model was initiated and sponsored by the DOE CBFO. The DOE CBFO delegated management of this peer review to its technical assistance contractor, known as the Carlsbad Technical Assistance Contractor (CTAC). The CTAC appointed Mr. John Thies as the peer review manager.

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

The selection and training of the peer review panel members and conduct of the review process were governed by DOE CBFO's Management Procedure MP-10.5, *Peer Review*, and the spallings conceptual model peer review plan. Detailed information regarding the review process is further delineated in the peer review records.

Twenty-four conceptual models are used in the WIPP PA. This peer review addressed only the new spallings conceptual model.

2.3 System Overview

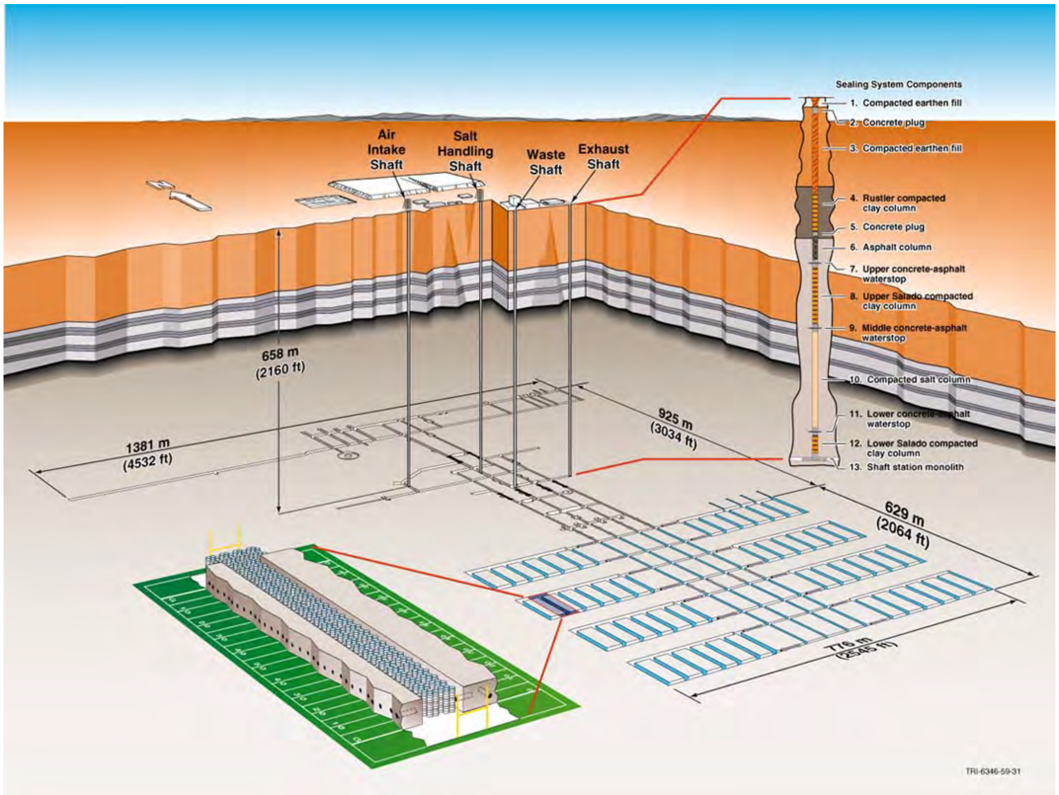
The WIPP disposal system includes the underground repository and shaft system; the geologic host rock; and the local and regional hydrologic system. Figure 2-1 shows the WIPP controlled area, the accessible environment, and the disposal unit boundary.

Figure 2-1 - WIPP Controlled Area

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.

Figure 2-2 - WIPP Facilities



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:

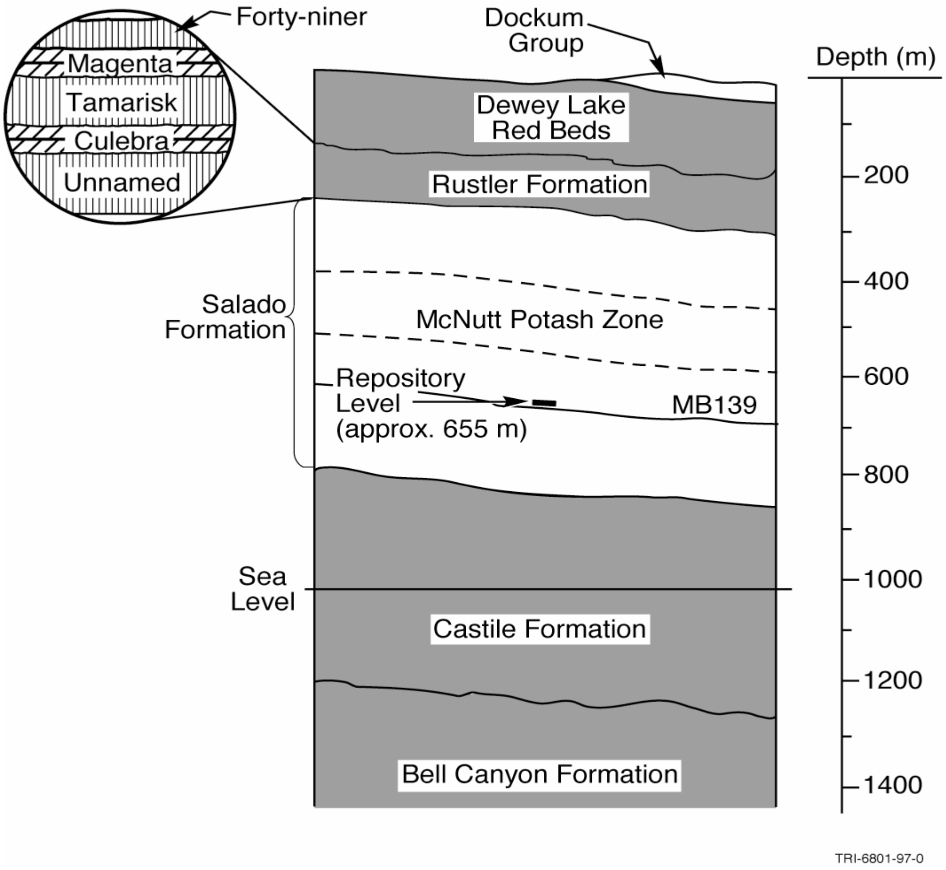
- The regulatory time frame begins at the beginning of disposal and ends 10,000 years after disposal;
- Exploratory drilling may potentially affect the repository;
- Exploratory drilling is inadvertent and intermittent;
- Drilling events occur at random intervals; and
- Future drilling rates will be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

2.3.2 Geologic Setting

The geologic history of southeastern New Mexico and the data collected regarding the subsurface stratigraphy at the WIPP site are important and are discussed extensively in Section 2 of the CCA 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 may be a factor in repository performance and are addressed 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 exist, 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 performance.

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} meters per second and pressures were measured in the range of 12.6 to 13.3 megapascals.

The Castile Formation is of interest to site characterization as a hydrologic barrier between the Salado and Bell Canyon Formations. The Castile is predominantly low-permeability halite which contains anhydrites with greater permeability in zones of fracture and structural deformation. The low permeable halite and high permeable anhydrites (parallel to the bedding plane) form a barrier preventing the transport of brine into the Salado formation.

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 area around the WIPP Site. 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.

2.3.4 Implementation of the “Option D” Panel Closure

The option "D" panel closure is a semispherical concrete closure to be emplaced in drifts and panel exits at several positions throughout the repository. The closure will be emplaced in an enlargement of the drift that will remove some material above the drift and all of the halite and the Interbed #139 below the drift floor. It is presumed that the closure will extend into the ribs of the drift a distance sufficient to remove most of the damaged rock zone (DRZ) in that direction. Back-stress resulting from creep flow in the Salado halite into the repository will immediately begin to heal damage around the closure that may result from construction excavation. It is not expected that the closure will entirely block gas flow in Interbed #139 or the overlaying interbeds, since flow around the closure is not prevented at high gas pressures. Upward gas flow from Interbed #139 into the drift beyond the closure is a possible scenario for bypassing the closure. Rapid gas pressure fluctuations, as in the case of an intrusion into a single panel at a time of high overall repository gas pressures, would be significantly damped in adjacent unintruded repository spaces, but not entirely eliminated by the closure over long time periods.

Reduction in the volume of gas available during a potential intrusion (a single panel isolated by closures) resulting from intrusion may impact a spallings event. Closures between panels imply that a first intrusion may not lower pressure throughout the repository, which may result in several intrusions in several panels having an increased potential for spall events. A drop in gas pressure after intrusion into a panel may accelerate brine flow toward the intruded panel.

2.4 Peer Review Methodology

Review of the conceptual models commenced after orientation and training of the peer review panel members in accordance with MP 10.5, *WIPP Spallings 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 referenced literature relevant to the review;
- Attendance at briefings that addressed development and implementation of the new spallings conceptual model and relevant aspects of the PA process;
- Issue focused presentations with question-and-answer sessions with SNL scientists and engineers;
- Review of literature and documents referenced during the question-and-answer sessions; and
- Formal and informal discussions among the Panel members.

The peer review panel was provided several presentations addressing the new spallings conceptual model being reviewed with respect to whether or not it represents a reasonable view of future states of the proposed disposal system for the WIPP repository. For this review a conceptual model is defined as a set of qualitative assumptions used to describe a system or subsystem for a specific purpose. The peer review panel evaluated the spallings model in accordance with the NUREG-1297 criteria. In addition, the Panel recognized that various aspects of the model may warrant varying levels of review of their mathematical representations, computerized representations, and results. The information gathered by individual members during the review was freely disseminated among all of the Panel members during caucus sessions.

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 new spallings conceptual model as specified 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 Conceptual Model 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 Peer Panel discussions.

Information Used to Review the Conceptual Model. This is an evaluation of data and information used to review the conceptual model. It includes attributes of the disposal system learned by SNL during site characterization activities; exercising the model; and a review of the science and concepts that the model is based upon. It also includes pertinent information gained during the operation of the repository.

Validity of Assumptions. The validity of key assumptions in the model and its application are assessed in terms of how they could affect the validity of the conceptual model. The review addresses the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid.

Alternative Interpretations. This section briefly identifies and assesses plausible alternative conceptual models considered, but not used by SNL, and the rationale why such alternative models were not used.

Uncertainty of Results and Consequences if Wrong. This includes an evaluation of the key uncertainties in the selected conceptual model and a discussion of the consequences if aspects of the conceptual model chosen were inappropriate or incompletely constrained for the site or subject process. This is not an exhaustive evaluation, but it does raise the question, "What if the model is wrong?"

Appropriateness and Limitations of Method and Procedures. Based primarily on the previous four criteria, this is a simple statement of whether the individual conceptual model represents a reasonable approximation of the WIPP disposal system performance.

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

Accuracy of Calculations. This is a statement of whether the results of performance modeling using the conceptual model within the performance system are reliable and accurate to adequately simulate the physical and chemical processes represented.

Validity of Conclusions. This is a judgment of the validity of any key conclusions that have been drawn based on results of the implementation of the conceptual model in the modeling framework. The key question is whether or not conclusions from model implementation appropriately relate to the expected goal of assessing the long-term performance of the WIPP disposal system. This judgment requires an evaluation of output information from the total system PA.

Adequacy for Implementation. This is an overall assessment of whether the conceptual model as implemented in the PA represents a reasonable approximation of the actual disposal system.

3.0 New Spallings Conceptual Model Evaluation

This section presents the results of the peer review panel's review of the new spallings conceptual model. The spallings model is first described and then evaluated for adequacy in accordance with the criteria summarized in Section 2.5. For each evaluation, provision is made for dissenting views. However, there were no dissenting views by any Panel member resulting from this peer review.

3.1 Drilling-Spallings Scenario

Figures 3-1 and 3-2 present the drilling-spallings scenario divided into three stages.

Figure 3-1: Pre-penetration stage

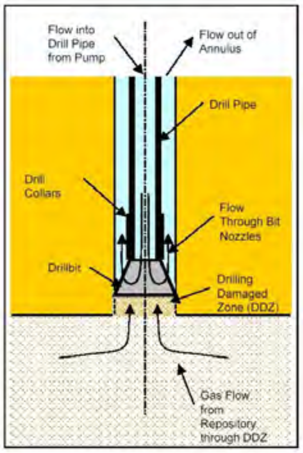
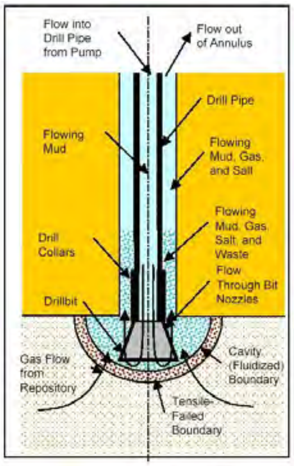


Figure 3-2: Post-penetration stage



Stage One - Pre-penetration Stage: During this stage, the drill bit is drilling from the surface vertically toward the repository as shown in Figure 3-1. This scenario is consistent with current vertical drilling practices. The drilling mud is pumped down the drill pipe and returns to the surface through the annulus carrying chips produced by the drill bit. Material from the wellbore wall can also be dislodged and entrained in the mud column. This is referred to as "cavings", and is caused by friction and chemical alteration between the mud and wellbore wall, stress changes at the wall face, and impact damage due to dynamic loading from the drill string and bit. This scenario is well documented in the literature and will not be discussed further in this report.

Stage Two - Transition Stage: The action of drilling produces a restricted region of relatively higher permeability referred to as the drilling damaged zone (DDZ – see Figure 3-1 above). It is likely that there will be some damage zone just ahead of the bit. However, it is unlikely that the DDZ will extend ahead of the bit much more than a few centimeters. Enhanced hydraulic communication between the wellbore and the repository will commence as the bit approaches near the repository. If the repository pressure is higher than the bottom hole mud pressure, the entrapped gas in the pores of the repository waste will seep through the DDZ mixing with the drilling fluid and be carried to the surface. Though the DDZ is a natural transition zone between the repository and the wellbore, it also serves as a useful feature for numerically coupling the mud motion in the wellbore with the gas motion in the repository.

Stage Three - Post-Penetration Stage: This stage describes behavior of the entire wellbore-repository system after the drill-bit penetrates into the repository. At this point, if the gas pressure in the repository is greater than the bottom hole mud pressure in the wellbore, gas flows through the waste toward the wellbore. If the gas flow velocity is high and the strength of the waste sufficiently weak, the resulting internal stresses may fracture, disintegrate, and fluidize the waste. If the repository pressure is sufficiently high, the mud column with entrained waste could conceivably be pushed to the surface, resulting in a surface release of waste. This is analogous to a wellbore blowout sometimes encountered in the oil industry.

3.2 Governing Equations

The pre-penetration stage has been extensively modeled and studied by the petroleum industry and will not be further discussed here. Instead, we will concentrate our attention on discussing the governing equations describing the transition and post stages. We will start with the gas flow equation in the waste medium in Section 3.2.1 followed by the equations for calculating the stress field in the medium in Section 3.2. The equation for calculating the failure zone in the matrix structure of the compressed waste is addressed in Section 3.2.2, and the equation for fluidizing the failed matrix is discussed in Section 3.2.3. The equation of motion for the rising mud column in the wellbore is discussed in section 3.2.4. Finally, the equations for the transition zone (DDZ) at the onset of the penetration are discussed in section 3.2.5.

3.2.1 Repository Gas Flow Equations

Darcy's equation is used to describe the motion of gas in the compressed porous waste medium. If the gas pressure in the repository is greater than the bottom hole pressure in the wellbore, the compressed gas trapped in the pores of the waste will flow toward the wellbore as shown in Figure 3-1. The equation governing the motion of gas in the medium can be written as Equation 3.2.1:

$$\frac{\partial p}{\partial t} = \frac{\kappa'}{2\phi\eta}\nabla^2\left(p^2\right)$$

Where:

p = gas pressure in the repository
t = time
κ' = effective permeability of waste
ϕ = porosity of waste in repository
η = gas viscosity

The boundary conditions for the equation are:

(1) The pressure at the gas cavity around the drill bit: The magnitude of the pressure is determined by coupling the cavity growth rate near the drill-bit and the mud column movement equation in the borehole to be discussed in a later section, and

(2) No-flow at the outer boundary of the repository. (i.e., q = 0 at $r = r_o$. In the SNL model, the region of computation is modeled as a disk of the compressed waste of thickness 2 m. and radius 50 m.)

Darcy’s equation, Equation 3.2.1, is a commonly used equation for describing the flow of gas in a porous media. A modified permeability (κ’) which includes the effect of turbulence and path tortuosity on flow properties is introduced by applying Forchheimer’s Equation 3.2.2:

$$\kappa' = \frac{\kappa}{1 + F_o}\,, \quad \text{and} \quad F_o = \frac{1.15x10^{-6}\,\rho u}{\mu \phi}$$

Where:

κ = permeability

μ = viscosity

ϕ = porosity

u = flow velocity.

The empirical Forchheimer equation is often used by the industry to extend the range of Equation 3.2.1 from laminar flow to turbulent flow.

A reasonable influence region has been used in the numerical calculation for repository flow, which is modeled as a disk of thickness 2 m. and radius 50 m. The disk has approximately the same volume as a single panel in the repository. The panels are separated by salt-rock walls of 4 m. in thickness. It is reasonable to assume that the gas volume for spallation is from a single panel.

3.2.2 Calculation of the Stress Field

The stress field in the porous medium (positive for compressive stress) is produced from the following two sources:

a. The Elastic Stress Field: The radial stress from the elastic response is shown in Equation 3.2.3:

$$\sigma_r = \sigma_o[1-(\frac{r_w}{r})^n] + p_w(\frac{r_w}{r})^n$$

Where:

σ_0 = far field radial stress
r_w = wellbore radius
p_w = bottom hole wellbore pressure
n = 2 (cylindrical flow) or 3 (spherical flow)

A spherical coordinate system is used at the onset of bit penetration and a cylindrical coordinate system is used when the drill bit has penetrated well into the repository.

The waste material is assumed failed when the radial tensile stress σ_r reaches a critical value. In the SNL model, Mohr-Coulomb criterion is also used to determine the shear failure zone. Shear failure does not affect the disintegration of the waste material, the circumferential stress σ_θ and shear stress τ are not discussed here.

b. The Flow Induced Stress (Seepage Stress) Field: Stresses are produced due to the fluid flowing through the matrix structure of the waste medium. The flow of fluid exerts an equivalent body force on the medium. The effect is similar to the temperature gradient on an elastic medium [ref: Lubinski. A]. By assuming a strong pore structure (i.e., a non-deformable pore) and observing the similarity between the governing equations of the poroelasticity and thermoelasticity, the flow induced radial stress can be written as Equation 3.2.4:

$$\sigma_{fr} = (n-1)\beta(\frac{1-2\upsilon}{1-\upsilon})\frac{1}{r^n}\int_{r_w}^{r}(p-\beta p_o)r^{n-1}dr$$

Where:

$\beta = 1 -$ ratio of bulk modulus of the porous material over the bulk modulus of the interpore material.

ν = Poisson's ratio of the porous material.

p_o = far-field or initial pore pressure.

c. The effective radial stress is the sum of the mechanical stress, seepage stress corrected for the pore pressure effect as shown in Equation 3.2.5:

$$\sigma_r' = \sigma_r + \sigma_{fr} - \beta p$$

It is this effective radial stress that will be used in the calculation of tensile failure zone.

Since the flow of gas is in the radial direction, the procedure for solving Equation 3.2.1 is straightforward. A question may be raised on the use of a strong pore assumption in the calculation of flow-induced stress σ_{fr} (Equation 3.2.4). SNL argues that, based on the experimental study on the properties of surrogate material of the waste (to be discussed in detail in a later section), the change of pore size in range of pressure under investigation is approximately 10%. Therefore, the effect of pore change on the flow-induced stress is included in the permeability (since the permeability is related to the porosity) employed in the sensitivity study. The Panel's opinion is that the argument is basically valid but not quantitative.

Indeed, the use of a strong pore assumption greatly simplifies the stress calculation. This assumption decouples the fluid and the solid motions, and leads to a similarity between the flow-induced stresses and the uncoupled thermal stresses. Equation 3.2.4 can be readily written down by observing the similarity between these two sets of stresses (i.e., poroelastic stresses versus thermoelastic stresses).

The calculation of flow-induced stress can be made more sophisticated and complete by coupling the fluid and the solid motions (i.e., by assuming a deformable pore). The coupled poroelastic equations are similar to that of the coupled thermoelastic equations [ref: Biot M. A]. It is a difficult problem even in one-dimensional form. The Panel's opinion is that the effort necessary to implement this additional level of detail is not justified. The magnitude of stress from the coupled theory is always lower than the stress from the uncoupled theory. The use of the uncoupled theory would yield a conservative estimation on the release from the repository.

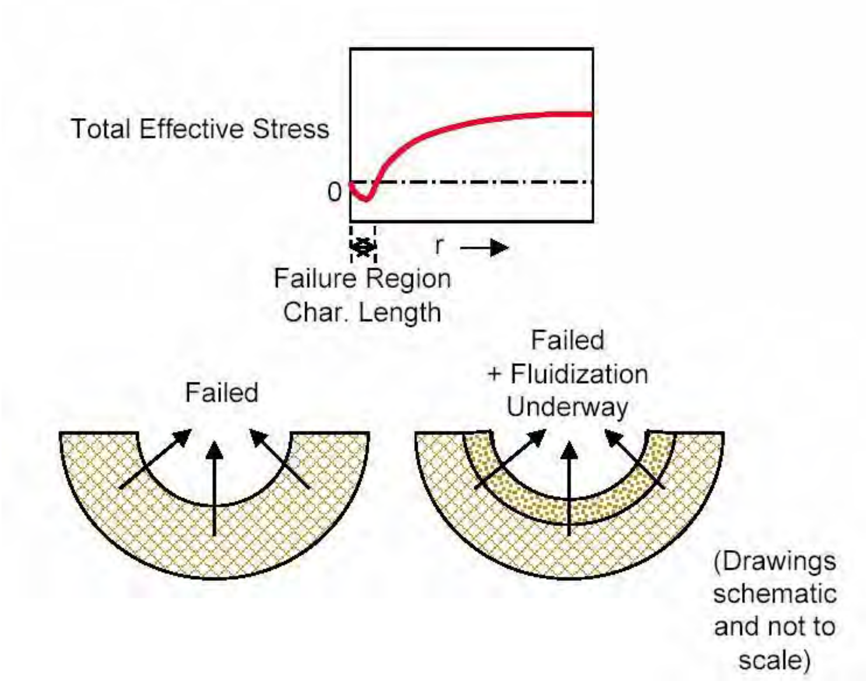
3.2.3. Failure and Fluidizing of the Waste Matrix:

The waste matrix material is assumed failed when the effective radial stress reaches an assumed tensile failure stress $T_{o,}$ Equation 3.2.6:

$$\sigma_r' \geq T_o$$

If this tensile strength is exceeded, the material is assumed to no longer be capable of carrying tensile stresses. This always occurs first at the wellbore surface. In the numerical calculation, the tensile failed material is removed from the calculation. A zero elastic modulus and an infinite permeability are assumed in this tensile failed zone. A tensile failure does not imply that the material will disintegrate and be mixed with the fluid (fluidizing). An assumption is made that the tensile failed materials would be fluidized only when the gas flow velocity reaches or exceeds a critical value, U_f. Figure 3-3 shows this schematically.

Figure 3-3: Failure and Fluidization



The critical velocity U_f for fluidization is calculated from the Ergun's empirical equation, Equation 3.2.7:

$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho}{\eta}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho}{\eta}\right) = \frac{d_p^3 \rho(\rho_w - \rho)g}{\eta^2}$$

Where:

d_p = particle diameter
ρ_w = particle density
a = aspect ratio (shape factor, 1 for sphere)
ρ = fluid (gas) density
η = fluid (gas) viscosity
ϕ = porosity of waste matrix
g = acceleration due to gravity

In the numerical implementation, a characteristic length L_c, that covers several grids (or nodal points) is used to determine the failure zone of the medium. Note that L_{fz} shown in Figure 3.3 is the length of tensile failure zone which may consist of several characteristic lengths. When the average effective radial tensile stress over the characteristic length exceeds the failure stress T_o, the particles inside the length are assumed failed. Therefore, the failure zone shown in Fig. 3.3 may contain several characteristic lengths. The characteristic length is an important parameter in determining the size of failure zone and the volume of spalling release. The effect of characteristic length on spalling volume will be discussed in a later section.

The SNL spalling model does not calculate the particle size of the disintegrated material. It assumes that the material disintegrates to particles of the surrogated material (to be discussed later). Since the particle size of the surrogated material is small, the Panel considers that it is an acceptable and conservative approach for simplifying the problem.

The pressure in the gas column is calculated from the following, Equation 3.2.8:

$$p = \rho R_0 T$$
$$\rho = \frac{M_0 + M(t)}{V(t)}$$

Where:

ρ = gas density
R_0 = gas constant
T = gas temperature
M_0 = initial mass in hemispherical cavity
$M(t)$ = cumulative mass influx to the gas column
$V(t)$ = total volume of the gas column and hemispherical cavity

The total volume V (t) of the gas column includes the free volume created by displacement of the mud and the volume of any cavity that results from tensile failure of the waste. The total mass M_0+M(t) in the gas column includes the initial mass in the hemispherical cavity and the cumulative mass influx from the porous medium, including any mass released during tensile failure and fragmentation of the waste. It is important to note that the volume of the cavity or the material removed by spallation is determined by the value $T_{0,}$ the tensile strength of the waste.

There are three important parameters in this section: the tensile strength of the waste, T_o; the critical flow velocity for waste fluidization, U_f; and the critical length for calculating the failure zone, L_c. In addition, there is an assumption of a perfect-gas law for the gas-particle mixture. The tensile strength of the waste matrix, T_o and the critical flow velocity for fluidization, U_f are determined from experimental studies. The Panel has no reason to doubt their validity. The effect of critical length L_c and tensile failure strength T_o on the final results can be assessed from a sensitivity study. However, the use of a perfect-gas law for the gas-particle mixture is entirely dependent on one’s judgment. The significance and the effect of this assumption on the final results is difficult to determine from a sensitivity study. The assumption appears to be reasonable and would yield a conservative waste release prediction.

3.2.4 Motion of the Mud Column

The equation of mud column motion in the borehole is derived by applying Newton's law of motion as shown in Equation 3.2.9:

$$m\frac{dU}{dt} = F_p - F_f - F_w,$$

where m is the mass and U is the velocity of the mud column; F_p is the pressure force across the mud; F_f is the frictional force retarding the motion of the mud; and F_w is the hydrostatic weight of the mud column. The equations for these quantities are:

$$m = \rho_m(L - x)A$$

$$F_p = (P_{bh} - P_{atm})A$$

$$F_f = \frac{f(L-x)\rho_m U^2 A}{2d_e}$$

$$F_w = \rho_m (L - x)Ag$$

Where:

ρ_m = mud density
L = initial length of mud column
x = displacement of mud column, positive upward
A = cross - sectional area of borehole
P_{atm} = atmospheric pressure
f = Fanning friction factor
g = acceleration due to gravity
P_{bh} = the bottomhole pressure calculated from Eq. 3.2.1
d_e = effective hydraulic diameter of borehole

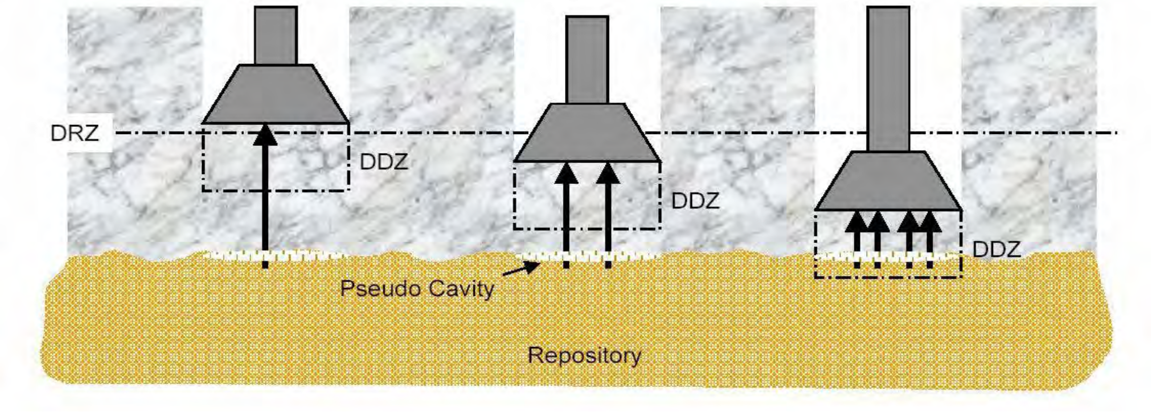
The equation is proper for describing the motion of mud column in the wellbore.

3.2.5 The Drilling Damage Zone (DDZ)

Although the DDZ is not mentioned in SAND97-1369, it was presented during the peer review. As mentioned in a previous section, it has been assumed that the action of the drill bit produces a damaged zone (DDZ) in front of the advancing bit. The DDZ serves as a transition zone between the borehole and the repository. It allows the gas pressure at the bottom of the mud column to buildup smoothly reaching the reservoir value (i.e., no pressure discontinuity as the bit penetrates through the interface). In the numerical calculation, a small air cavity is placed at the interface of mud and repository to ensure the continuity condition between these two regions.

The DDZ is assumed to have a higher permeability than the host rock (halite) and the DRZ (Damaged Rock Zone) but a lower permeability than the repository. As the drilling bit approaches the interface between the host rock and the repository, the lower boundary of the DDZ will contact the repository first. At this time, the gas trapped in the repository would flow upward through the DDZ and interact with the mud column. Figure 3.4 shows drilling damaged zone in front of the bit.

Figure 3-4: DDZ in front of the drill bit



The governing equation for mass flow through the DDZ assumes a steady state Darcy flow given in Equation 3.2.10:

$$\frac{\partial m}{\partial t} = \frac{k_{eff} A_{cav}}{2\eta R_0 T} \frac{(P_{cav}^2 - P_{BH}^2)}{L}$$

Where:

k_{eff} = effective permeability

A_{cav} = outer area of pseudo - cavity

η = gas viscosity

T = gas temperature

R_0 = gas constant

L = distance of bit from repository interface

P_{cav} = cavity pressure

P_{BH} = bottom hole pressure

The effective permeability between the wellbore and the repository is represented by a series connection of the DRZ and DDZ.

$$k_{eff} = \frac{L}{\dfrac{L_{DDZ}}{k_{DDZ}} + \dfrac{L_{DRZ}}{k_{DRZ}}}$$

Where:

L_{DDZ} = thickness of DDZ beneath the bit
L_{DRZ} = thickness of DRZ beneath the bit
k_{DDZ} = permeability of DDZ
k_{DRZ} = permeability of DRZ
L = distance between bit and repository ceiling
$= L_{DDZ} + L_{DRZ}$

It is noted that at the instant that the DDZ just begins to intersect the repository, L_{DRZ} is by definition zero and remains so until the bit penetrates the repository.

The mass coupling equation given in Equation 3.2.10 assumes that hydraulic communication between the wellbore and repository is instantaneous, regardless of the distance between the bottom of the wellbore and the repository and regardless of the effective permeability in this region. The effective permeability expression is identical to the thermal analog for steady-state heat flow through stacked layers.

There may be some physical justification for the existence of a DDZ. There will always be some depth below the bit for which there will be formation damage. This depth will under most circumstances be on the order of a few millimeters to a few centimeters. Sometimes the permeability of this damage zone will be greater than the surrounding rock due to the cutting or crushing process beneath the bit. However, it is important to note that under certain conditions this damage zone might have a permeability smaller than the surrounding rock. This permeability reduction is due to fines (mud, drilling) clogging the connected pore space. The latter condition has not been addressed in the model predictions.

We also note that if the DDZ permeability is sufficiently small and the rate of penetration of the bit is sufficiently large, pressure diffusion in the rock in front of the bit will not be able to keep up with the bit. The pressure gradient in the DDZ immediately in front of the bit will get larger the faster this rate of penetration. Within the framework of the pressure diffusion equation, this effect is represented by an advection term. As the rate of penetration increases, the efficiency of the hydraulic coupling between the wellbore and the repository decreases. The simple model given in Equation 3.2.10 does not account for this effect.

The main reason the DDZ was implemented in the model is for numerical stability. It allows for a smooth transition between the wellbore pressure and repository pressure. Without this transition zone, there would be a discontinuity in pressure between wellbore and repository at the instant the bit penetrates the repository. This discontinuity leads to numerical instability.

Under certain conditions, the pre-penetration cavity pressure bleed-off has been predicted to be on the order of 30% or more. Members of the panel were concerned that this pre-penetration bleed-off might result in under-predicting spallings volume. A test run was carried out for which the DDZ thickness was reduced from 16 cm to 2 cm, the DDZ permeability was reduced from $1.0\text{x}10^{-14}$ m^2 to $1.0\text{x } 10^{-15}$ m^2 and the DRZ permeability was reduced from $1.0\text{x}10^{-15}$ m^2 to $1.0\text{x}10^{-19}$ m^2. The reduction in the DRZ permeability probably means little in this test as the bit usually starts at the top of the DDZ in the numerical simulations. The reduced DDZ thickness and permeability will cause the pre-penetration cavity pressure bleed-off to be reduced. It was found that there was no significant change in the predicted spallings volume using this range of input parameters.

The Panel feels that additional justification relative to the following assumptions would improve understanding of the model:

1. The DDZ always has a permeability greater than the DRZ.
2. The flow in the DDZ is steady-state Darcy flow making hydraulic communication between the wellbore and the cavity instantaneous.
3. The effect of bit motion on the state of pressure in front of the bit is ignorable.

Without actually extending the bit-DDZ-repository coupling equations to address items 2 and 3 above and extending the sensitivity analysis to address item 1, the Panel cannot say with any exactitude what these effects may have on predicted spallings volume. It is reasonable to assume, however, that these model restrictions may have only a small effect on the predictions. As discussed previously, there was little effect on predicted spalling volume when the DDZ permeability was decreased by a factor of ten and the DDZ thickness was reduced from 16 cm. to 2 cm. This suggests that predicted spallings volumes may be insensitive to the physical condition and size of the DDZ.

3.3 Material Parameters

There are 26 material parameters used in the DRSPALL code. These include 7 parameters for waste, 13 for drilling (such as drill-bit and collar dimensions, mud weight, etc.), and 6 for environment (such as the far-field in-situ stress, salt rock density, etc.). The parameters for drilling and environment are well studied and documented. They will not be discussed here. The discussion in this section will focus on the material parameters that represent the waste placed in the repository.

The waste is stored in the 55-gallon steel drums, in “standard” waste boxes, or in thick steel pipe “over-packs.” The waste containers are stacked in a panel, and magnesium oxide (MgO) backfill is placed between the barrels and over-packs. The repository inventory by waste category is shown in Table 3-1.

These waste containers are compressed as the salt rock creeps. It is also conceivable that some salt may creep in between the containers. The waste mass in the repository is therefore a highly heterogeneous compressed mass. Since the enclosed repository contains air and would allow some limited intake of brine, it is probable that the process of iron corrosion and microbial activity may result in waste degradation producing a potentially high gas pressure. When material degrades into small particles, they become potential source of spalling release.

Table 3-1

Anticipated Repository Inventory by Waste Category

Waste Category	**Inventory (wt%)**
Iron-based metal alloys	14
Steel container material	12
Aluminum-based metal alloy	1
Other metal alloys	6
Other inorganic materials	3
Vitrified materials	5
Cellulosics	4
Rubber	1
Plastics	3
Plastic container or liner materials	2
Solidified inorganic material (including cement)	4
Solidified organic material (not including cement)	0
Solidification cement	4
Soils	4
MgO backfill	37
Total	**100**

Based on the inventory of wastes placed in the repository and assuming extensive degradation after a long period of time (10,000 years), a recipe (ingredients) for a surrogate product is created. The needed material properties in the calculation of spalling release are determined by testing the surrogate material.

The material properties are compressibilities (i.e., β) of the porous waste and its interpore material, Poisson's ratio, cohesive strength, friction angle, tensile strength, waste particle size, permeability, and waste porosity. The procedures for determining these properties are standard. There is no question about the validity and accuracy of the results. The reasonable question is whether or not the so-constructed surrogate specimen can properly represent the properties of the degraded waste mass. And, would some of the waste material disintegrate into small particles as postulated after 10,000 years of entombment? The Panel has no basis upon which to reject these assumptions and they appear to be reasonable and would yield a conservative waste release prediction.

4.0 Accuracy and Sensitivity of the Code

The equation of motion for mud movement in the borehole is a one-dimensional equation, and the equation for gas flow in the repository can be either axi-symmetric or spherical. A numerical solution of these equations can be obtained by using standard finite-difference methods. The procedures for calculating the tensile failure zone and the fluidization of waste matrix are also standard and straightforward. There is no reason for the Panel to doubt the accuracy of the calculations. The Panel was not surprised by the excellent agreement between the code prediction and predictions from a commercial code, FLUENT, for wellbore flow problems.

The Panel was pleased to see a reasonable agreement between the code prediction and the field measurement in a field-scale coal-bed methane test. This test lends credibility to the robustness of the code.

Some limited sensitivity analyses have been carried out at the request of the Panel that look at the effect of thickness and permeability of the DDZ on end-state spallings volume. The results indicate that the predicted volumes are rather insensitive to these parameters. Spallings volume increase slightly with decreased DDZ permeability and decreased DDZ thickness. The reason for this is that the pre-penetration reservoir pressure bleed-off due to flow through the DDZ is reduced for both of these conditions. This results in a higher repository pressure when the bit actually penetrates the waste. It should be pointed out here, however, that DDZ permeability has been assumed to always be greater than the permeability in the DRZ. We expect that as the DDZ permeability approaches zero (e.g. no drilling damage), the spallings volumes will increase. To what degree they will increase, however, is unknown. It is the Panel's belief that the increase will probably be small, although this assumption is somewhat speculative.

Another issue that may affect the predicted spallings volume is the choice of characteristic length over which the radial stress is averaged to determine if the waste fails or not. If this length is zero, waste will not fail because at the cavity surface, radial stress is identically zero. If too large, waste will not fail because the average radial stress will be dominated by compression and not tension. Somewhere between these extremes lies the correct averaging length. The characteristic averaging length is an artifice required to get non-zero spallings volume. Without this averaging process, there would never be spalling. The base case characteristic length is taken to be 20 cm.

There has been some attempt to associate this averaging length with some average size of waste material particulates. There may be some validity to this concept but, similar to the invocation of the existence, size, and characteristics of the DDZ, this identification was not substantiated by measurement. It was driven more by requirements of the numerical model rather than physical reality. We would expect that there would be some value of the characteristic length that maximizes spallings volumes. This "optimal" characteristic length will likely be different for each unique simulation and therefore it is probably unrealistic to expect for all simulations an estimate of this optimal length. The Panel understands this limitation but points out that fixing a characteristic averaging length may bias spallings volume predictions. A limited number of simulations have been carried out that halve, double, and quadruple the base case characteristic length. These results suggest that, although the characteristic length does effect final cavity radius (and thus, spallings volumes), this effect may be small.

The Panel has identified that the most sensitive parameters in the model are repository initial pressure, waste permeability, and the waste tensile failure strength. At the request of the Panel, a sensitivity study on the relationship between the spalled volume and these parameters was carried out using the following input: Repository initial pressure from 8.0 to 14.9 MPa, Waste permeability from 1.7×10^{-14} to 1.7×10^{-12} m^2, and Waste tensile failure strength from 0.01 to 1.0 MPa. The Panel realizes that the value of 0.01 MPa for the waste tensile failure strength is too low and unrealistic. However, this would serve as a test of the robustness of the code.

The spalled volume is related to the above parameters in a complex manner. In general, the repository initial pressure is the primary parameter controlling the spalling process because pressure controls the velocity of gas flow in the medium. A high pressure produces a high velocity gradient near the cavity face causing tensile failure of the waste. This high pressure and velocity gas also fluidizes the disintegrated waste and pushes the fluidized waste through wellbore to the surface causing a spalling release. The permeability of the waste also plays an important role in the spalling process. A high waste permeability would allow a relatively higher gas velocity in the medium. In addition, the size of waste particles (and shape factor) also has an effect on this process. A disintegrated waste with large particle size would require a higher gas velocity to fluidize. The conditions for producing a high gas velocity in the waste are therefore a high repository initial pressure and a waste medium with high permeability. The tensile failure strength of the waste may simply be regarded as a mark point for spalling release. A low waste tensile strength implies that a spalling release could occur at a relatively low gas velocity. This implies that, at a low tensile strength, spalling could occur at a relatively low repository pressure and waste permeability. The result from the sensitivity study confirms the above observation. It has demonstrated that if the gas velocity in the waste, which depends on the repository initial pressure and waste permeability, is sufficiently high, a “runaway” spalling would occur at a very low waste tensile strength.

In conclusion, the Panel considers that the SNL’s spall prediction code contains all of the elements necessary to model this highly complex problem. The Panel also feels that these elements are adequately implemented in the software to yield robust and accurate solutions over a wide range of input parameters.

5.0 Summary Findings of the Spallings Peer Review Panel

This section focuses on the findings of the peer review panel as related to the review criteria discussed in Section 2.5. The spallings conceptual model is one of 24 conceptual models used in the WIPP PA. The list of the twenty-four WIPP conceptual models is provided in Table 5-1 with the spallings model identified by yellow highlight so as to put it in the context of the total WIPP waste disposal system modeling effort.

Table 5-1

WIPP Conceptual Models

Disposal System Geometry	Not Addressed During This Peer Review
Culebra Hydrogeology	Not Addressed During This Peer Review
Repository Fluid Flow	Not Addressed During This Peer Review
Salado Flow	Not Addressed During This Peer Review
Impure Halite	Not Addressed During This Peer Review
Salado Interbeds	Not Addressed During This Peer Review
Disturbed Rock Zone	Not Addressed During This Peer Review
Actinide Transport in the Salado	Not Addressed During This Peer Review
Units Above the Salado	Not Addressed During This Peer Review
Transport of Dissolved Actinides in the Culebra	Not Addressed During This Peer Review
Transport of Colloidal Actinides in the Culebra	Not Addressed During This Peer Review
Exploration Boreholes	Not Addressed During This Peer Review
Cuttings/Cavings	Not Addressed During This Peer Review
Spallings	**Addressed During This Peer Review**
Direct Brine Release	Not Addressed During This Peer Review
Castile and Brine Reservoir	Not Addressed During This Peer Review
Multiple Intrusions	Not Addressed During This Peer Review
Climate Change	Not Addressed During This Peer Review
Creep Closure	Not Addressed During This Peer Review
Shafts and Shaft Seals	Not Addressed During This Peer Review
Gas Generation	Not Addressed During This Peer Review
Chemical Conditions	Not Addressed During This Peer Review
Dissolved Actinide Source Term	Not Addressed During This Peer Review
Colloidal Actinide Source Term	Not Addressed During This Peer Review

Information Used to Review the Conceptual Model.

The data and information available to support the review of the spallings conceptual model allowed a thorough technical review. Necessary attributes of the disposal system are well characterized and understood. The science and concepts upon which the model is based are sound. The model has been benchmarked against other quantified experience in coal fields, and sensitivity analyses indicate the model is valid within the range of its intended use.

Validity of Assumptions.

The validity of key assumptions in the model and its application have been assessed in terms of how they might affect the validity of the conceptual model. The review addressed the comprehensive inclusion of important features, events, processes, and other key assumptions. Examples are the assumption of Darcy flow, use of the ideal gas law at high pressures, and the mathematical method chosen to develop the model grid. The essential assumptions used by SNL in development and exercise of the spallings model were found to be appropriate and valid. Additional justification addressing the supporting assumptions in Section 3.2.5 would be helpful.

Two assumptions of the model were imposed by the requirements of successful numerical implementation of the model. These were: (1) the existence of the DDZ and (2) the requirement of a characteristic averaging length required for tensile failure. The former was required for numerical stability of the code as the bit approaches and intersects the repository and the latter is required for spalling to occur at the face of the cavity. Both of these assumptions are reasonable and have been shown, based on a limited sensitivity analysis, to likely have little effect upon model predictions. It must be emphasized, however, that the inclusion of these mechanisms was motivated primarily for numerical purposes and have not been substantiated by laboratory measurement.

Alternative Interpretations.

During the spallings peer review, information presented and considered by the Panel did not include alternatives or options for the spallings conceptual model. The original spallings conceptual model can be considered an unacceptable alternative. In the present model development, it appears that SNL has employed the simplest and the most straightforward approach in modeling this complex and highly coupled problem. Each individual scenario is described by applying the basic physical equations. The Panel considers that this approach would provide a conservative estimation of spalling release.

Uncertainty of Results and Consequences if Wrong.

The Panel feels that the conceptual model contains all of the necessary components to adequately represent the physics of the spalling problem. This is a highly coupled and nonlinear problem that involves a fluid-filled wellbore, pre-penetration leak-off from the repository, post-penetration depressurization of the repository, and resulting tensile failure of waste and transport of that waste to the surface.

Obviously, there will be uncertainty in the predictions. This uncertainty can be categorized as follows:

1. Uncertainty in the physical model
2. Uncertainty associated with numerical implementation of the model
3. Uncertainty associated with the input parameters to the model

The Panel is comfortable with the adequacy of the physical model used to represent the process. The uncertainty associated with the numerical implementation of the model falls within the category of features invoked for numerical stability or other reasons that have little justification in terms expected physical processes or actual laboratory measurement. These include principally the existence and characteristics of the DDZ and the requirement of a characteristic averaging length near the cavity wall necessary for tensile failure to occur. Probably the largest effect on prediction error will be the uncertainty associated with the input parameters to the model, most notably the waste properties.

All of these uncertainties will have an effect on the predicted spallings volume. Some limited sensitivity analyses have been carried out at the panel's request to look at the effect of DDZ parameters and tensile stress averaging length on predicted spall volumes. These analyses suggest that, even though these parameters do affect the volumes, the effect is probably small.

The largest uncertainty will be associated with assumed material parameters of the waste that serve as input to the model. These include tensile strength, porosity, permeability, particle size, and so on. Extensive laboratory measurements of these parameters have been carried out on simulated waste material under predicted in situ conditions. The uncertainty in these parameters is associated with the uncertainty in how these parameters may be modified due to degradation over time in the in situ environment. This cannot be predicted with any degree of certainty. Therefore, one must make a reasonable estimate of the possible range of these parameters and look at the variability of the model output due to this range of input.

The Panel feels that the range of waste material properties used is reasonable based on our current understanding of these parameters and how they may change in time under in situ conditions. This is not to say that the Panel feels that this range is necessarily conservative. The latter would suggest knowledge of the end state condition of the waste.

Based on these arguments, the Panel believes that the combined uncertainty in the model, implementation, and input will necessarily lead to some level of model prediction error. This error, however, is expected to be small and acceptable within the context of best practices.

Appropriateness and Limitations of Method and Procedures.

Based primarily on the previous four criteria, the Panel did find that the methods and procedures used by SNL to develop and present the spallings model to be acceptable and reasonably representative of future repository performance.

Adequacy of Application.

The peer review panel found the new spallings conceptual model to be adequate. The model structure is technically sound in mathematical formulation and numerical implementation. The Panel also found that the model represents a reasonable approximation of what is expected to be the WIPP disposal system performance. The Panel's assessment did not address the relationships among conceptual models in detail, but rather whether the significant components of the spallings conceptual model are appropriately implemented in support of performance assessment. For example, the various geometrical systems and representations of the conceptual model appear to be adequately applied within the performance modeling system, and there appear to be no significant inconsistencies in the application of the conceptual model in its application to modeling the WIPP waste disposal system.

Accuracy of Calculations.

The results yielded using the spallings conceptual model appear reliable and reasonably accurate to adequately simulate the physical processes that must be represented to adequately model the WIPP waste disposal system.

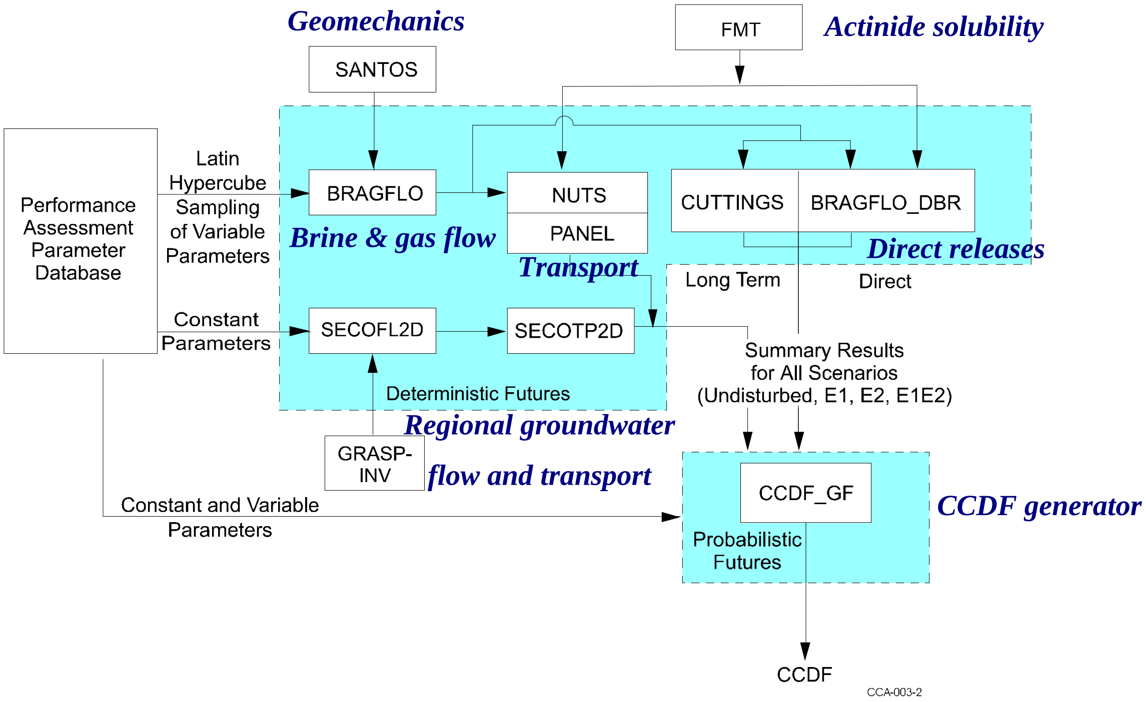
Validity of Conclusions.

There are no specific conclusions drawn, with respect to the spallings conceptual model, other than its ability to characterize appropriate properties, processes and features of the repository during a potential spallings event. The Panel concludes that the spallings conceptual model reasonably represents future repository performance.

Adequacy for Implementation.

The overall assessment of whether the spallings conceptual model as implemented in the PA represents a reasonable approximation of the actual disposal system is addressed by Figure 5-1 which is a simplified illustration in which selected conceptual models represent a system or subsystem within the CCA, PA code sequence. BRAGFLO DBR, as illustrated, is a special, short-term application of BRAGFLO related to a drilling intrusion and includes the conceptual model system representations listed under BRAGFLO plus the Direct Brine Release model. The direct brine release element illustrates that the calculated brine volume removed from the repository by a drilling intrusion is input directly to the CCDFGF.

Figure 5-1. Illustration of Conceptual Model Integration



As shown in figure 5-1, the WIPP conceptual models, as interpreted through the various codes, are ultimately integrated at the CCDFGF where results are prepared. The figure ignores many preparatory and post-process codes and relationships between codes that are not linear and in a single direction. For example, while SANTOS is related to BRAGFLO and receives system representation from the Creep Closure conceptual model, creep closure results from an iterative relationship between gas pressure, compaction, and brine characterizations from BRAGFLO and the porosity surface in SANTOS. The integration of the conceptual models, therefore, identifies the overall WIPP PA model as a complex structure that represents 24 conceptual models through preparatory, process, flow and transport, presentation, and enabling codes.

Applying evaluation criteria to the integration of a given conceptual model, as a step in the assessment of model adequacy, results in most of the discussion focusing on the review criteria discussed in Section 2.5. For example, evaluation of information used in the integration, assumptions, uncertainties, adequacies, accuracy, and validity are all based on the conceptual model being evaluated or the implementing mathematical representation or code.

Because a total and complete system PA was not available for the Peer Review Panel to review, the overall adequacy for implementation of the spallings model integrated with the other conceptual models can only be judged at this time relative to the criteria discussed earlier in this section. Based on the review of the spallings conceptual model, the supporting assumptions, and mathematical, implementation, integration of this conceptual model with the other conceptual models is expected to be adequate.

6.0 Dissenting Views

There were no dissenting views for this model.

7.0 References

40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes,(Peer Review applicable to Subparts B and C),* November 1985 (amended December 1993)

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* Attachments to the Zone Size Sensitivity Report:
CAVRAD history for BC1 spherical
RADEFSTR profiles for BC1 cylindrical geometry
RADEFSTR profiles for BC1 spherical
RADEFSTR, POREPRS, etc for BC1 spherical
CAVRAD history for DR2 spherical

RADEFSTR profiles for DR2 cylindrical geometry
RADEFSTR profiles for DR2 spherical geometry
RADEFSTR, POREPRS, etc for DR2 spherical
CAVRAD history for DRH
RADEFSTR profiles for DRH cylindrical
Geometry
RADEFSTR profiles for DRH spherical
RADEFSTR, POREPRS, etc for DRH spherical
CAVRAD history for LT2
CAVRAD history for LT4
CAVRAD history for LTH
SPLVOLEQ history for LT2
SPLVOLEQ history for LT4
SPLVOLEQ history for LTH
SPLVOLEQ history for BC1

Appendix A - Panel Member Technical Qualifications

Ching Yew, Ph.D.

Dr. Yew is currently a Consulting Engineer with over 40 years experience in mechanical engineering. He worked for the University of Texas at Austin providing research and teaching for 32 years. He is now a Professor Emeritus in the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin. Dr. Yew is a fellow of the America Society of Mechanical Engineers (AMSE) and a member of the Society of Petroleum Engineers (SPE).

Dr. Yew has provided professional consultation for businesses such as Shell Oil Company, Aerospace Corporation, The University of Texas Medical School at Galveston, Traco Inc., Exxon Production Research Company, IBM at Austin, British Petroleum Inc., Oryx Energy Company, Sandia National Laboratories, ARCO Oil and Gas Company, Maurer Engineering Inc., Japan Geothermal Research and Development Inc., and Japan National Oil Company.

Dr. Yew has two patents; Method and Apparatus for Analyzing Sucker-rod Wave Motions (June, 1967) and Over-Pressurized Well Fracturing Method (December, 1993). Dr. Yew has published twenty articles related to oil and gas industries, twelve publications related to penetration, perforation and fragmentation, and thirteen publications related to wave motions and non-destructive testing, and authored a book on mechanics of hydraulic fracturing.

<u>EDUCATION:</u>

B.S. (1956): Mechanical Engineering, National Taiwan University, Taipei, Taiwan, China
M.S. (1958): Mechanical Engineering, Cornell University, Ithaca, N.Y.
Ph.D. (1962): Mechanical Engineering, University of California at Berkeley, Berkeley, CA.

Jonathan Hanson, Ph.D.

Dr. Hanson has over 18 years experience as a Consulting Geophysicist. His primary focus as consultant is the development, and subsequent software implementation, of research and analysis tools used in the earth sciences, engineering, and technology. Areas within which this work has been carried out include oil field drilling dynamics and drill bit design and performance optimization, methane desorption in coal, tailored pulse loading for well stimulation, VSP (Vertical Seismic Profiling) acoustic data analysis, and CMM (Coordinate Measurement Machine) analysis software for manufacturing quality assurance. He has also done work in the software development for and subsequent geophysical interpretation of combined gravity, magnetic, and heat flow data in geothermal systems.

Dr. Hanson was employed by the University of California Lawrence Livermore National Laboratory from 1978 to 1985, where he worked in the Earth Sciences Division. He has published over fifty related articles and reports. He is a member of the Society of Petroleum Engineers.

Dr. Hanson has provided professional consultation to the UC Lawrence Livermore National Laboratory, Chamber of Mines Research Organization (South Africa), Science Applications International Corporation, Rockwell International Corporation, Baker Hughes, Inc. (Hughes Christensen), TOTAL Austral, S.A., Resource Enterprises, Inc., Terra Tek, Inc., Utah Geophysical, Inc., Norton Company, Inc., and Valtek, Inc

EDUCATION

Ph.D., Geophysics, Oregon State University, 1977
M. S., Physics, Oregon State University, 1974
B. S., Physics, Oregon State University, 1969

Lawrence Teufel, Ph.D.

Dr. Teufel is currently a Langdon Taylor Professor in the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology in Socorro, New Mexico. Dr. Teufel has over 24 years experience in petroleum and natural gas industry. He was chairman of the Petroleum Engineering Department at the New Mexico Institute of Mining and Technology Department from 1997 to 2000. Dr. Teufel has recently provided professional service for the following: SPE Cedric K. Ferguson Medal Committee (Member 1992-1995), U. S. National Committee for Rock Mechanics (Member 1993-1998), AAPG Committee on Development Geology (Member 1992-2000), SPE Geology and Geophysics Committee (Member 1994-1998, Chairman 1998), SPE Geology and Geophysics Committee (Member 2000-2003, Chairman 2003), and Chairman of Strategic Research Institute Conference on Tight Gas (2003).

Dr. Teufel has received many honors and awards, including the U. S. National Committee for Rock Mechanics Applied Research Award (1985); Federal Laboratory Consortium Award for Excellence in Technology Transfer (1993); U. S. National Committee for Rock Mechanics Case History Award (1993); Distinguished Lecturer for American Association of Petroleum Geologists (1994-1995); and Distinguished Lecturer for Society of Petroleum Engineers (1995-1996).

Dr. Teufel was employed by Sandia National Laboratories as a member of the Technical Staff, Geomechanics Department, from 1979 to 1986, Senior Member from 1986 to 1993, and Distinguished Member from 1993 to 1999. He has thirty five refereed publications to his credit, has written sixty two conference proceeding papers and six contract reports.

EDUCATION

Ph.D.	Geology, 1979, Texas A&M University
M. S.	Geology, 1976, Texas A&M University
B. S.	Geology, 1973, Syracuse University

Appendix B

Determinations of Peer Review Member Independence

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/[✓ No]

Were you employed by DOE or a DOE Contractor <u>previously</u>? Yes/[✓ No]

(If yes, give dates, location, organization, position, and type of work performed).

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/[✓ No]
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/[✓ No]
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/[✓ No]
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Ching H. Yew

Print Name: Ching H. Yew

Date: July 7, 2003

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE_ or a DOE contractor___? Yes/[✓ No]

Were you employed by DOE or a DOE Contractor <u>previously</u>? [✓ Yes]/No

(If yes, give dates, location, organization, position, and type of work performed).

1978-1982, Livermore, CA
Lawrence Livermore National Laboratory
Earth Sciences Division

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/[✓ No]
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/[✓ No]
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/[✓ No]
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature:

Print Name: JONATHAN HANSON

Date: 7/7/03

Determination of Peer Review Panel Member Independence Form

Are you currently employed by DOE____ or a DOE contractor___? Yes/[✓ No]

Were you employed by DOE or a DOE Contractor previously? [✓ Yes]/No

(If yes, give dates, location, organization, position, and type of work performed).

Sandia National Labs from 1979-1999, Member of Technical Staff
Geomechanics primarily for oil + gas studies

Do you have or have you had any direct involvement or financial interest in the work under review? Yes/[✓ No]
(If yes, describe the involvement)

Is there any reason why you cannot perform an impartial peer review? Yes/[✓ No]
If yes, state the reason(s))

Is there any aspect of your past that may lead to a perception of bias in the results of your peer review? Yes/[✓ No]
(If yes, describe)

I pledge that my review of this work will be completely impartial and based solely on the information available during the review.

Signature: Lawrence W. Teufel
Print Name: Lawrence W. Teufel
Date: 7/7/02

Statement of Unbiased Peer Review of the Spallings Model by Lawrence W. Teufel

Before accepting my current position in 1994 as the Langdon Taylor Professor of Petroleum Engineering at the New Mexico Institute of Mining and Technology I was a member of the technical staff at Sandia National Laboratories from 1979 to 1999. From 1994 to 1999 I had a joint appointment at Sandia Labs and New Mexico Tech. During my 20 year career at Sandia Labs I was involved with several cooperative DOE/Industry oil and gas projects and worked almost exclusively on petroleum-related rock mechanics studies on hydraulic fracturing, fluid-flow in natural fracture systems, *in situ* stress measurements, and reservoir compaction and subsidence. In my very early career at Sandia Labs I was involved in only one small WIPP related project, which was a rock mechanics study of the mechanical properties of anhydrite in the Salado Formation at WIPP. Colleagues at Sandia were involved with various geotechnical studies at WIPP. Over the years I have had many technical discussions with them on these projects. Since leaving Sandia Labs in 1999 I have had limited technical contact with Sandia staff members and these have been related only to tight gas projects with industry. When I was a member of the U.S. National Committee for Rock Mechanics I was asked and provided unbiased peer review of WIPP and Yucca Mountain geotechnical studies. At that time I was employed by Sandia Labs. I have no vested interest in any of the technical studies at WIPP conducted by Sandia Labs (other than my small anhydrite rock mechanics study, which went through peer review) or by any other group. I can and will provide an unbiased peer review of the Spallings Model.

Lawrence W. Teufel

Lawrence W. Teufel

Appendix C

Certifications Regarding Organizational Conflicts of Interest

I have reviewed each of the selected peer review panel member's (Jonathan M. Hanson, Lawrence W. Teufel, and Ching Hsie Yew) backgrounds and employment histories. I have also interviewed each of them to determine if they have any organizational conflict of interest or a bias for, or against, the WIPP facility as a nuclear waste repository. Through these background investigations and interviews I have determined that none of the selected peer review panel members has a bias or an organizational conflict of interest related to the Spallings Conceptual Model Peer Review. Please note that in the case of Lawrence Teufel having worked for Sandia National Laboratories, I requested a written statement by him attesting to his independence. That signed statement is attached.

John A. Thies,
Peer Review Manager

Appendix D

Signature Page

I acknowledge by my signature below that I concur with the findings and conclusions documented in this spallings conceptual model peer review report.

Ching Yew

Ching Yew, Ph.D., Chairman

Jonathan Hanson, Ph.D.

Lawrence Teufel, Ph.D.

Appendix D

Signature Page

I acknowledge by my signature below that I concur with the findings and conclusions documented in this spallings conceptual model peer review report.

Ching Yew, Ph.D., Chairman

Jonathan Hanson, Ph.D.

Lawrence Teufel, Ph.D.

Appendix D

Signature Page

I acknowledge by my signature below that I concur with the findings and conclusions documented in this spallings conceptual model peer review report.

Ching Yew, Ph.D., Chairman

Jonathan Hanson, Ph.D.

Lawrence Teufel

Lawrence Teufel, Ph.D.