PEER 5 - Engineered Systems Data Qualification
Peer Review

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Title: ENGINEERED SYSTEMS PEER REVIEW (ESPR) PLAN 007

(Assistant Manager, Office of Regulatory Compliance, Carlsbad Area Office) 6/25/96 Date:

1. INTRODUCTION

This Engineered Systems Peer Review (ESPR) Plan describes the peer review and documentation the Waste Isolation Pilot Plant (WIPP) Project will use to ensure that the data used in the models describing engineered systems for rock mechanics and shaft/borehole seals in the performance assessment (PA) are qualified for use in the demonstration of compliance.

1.1 BACKGROUND

In accordance with the regulatory requirements specified in 40 CFR Part 191 and implemented in accordance with the criteria specified in 40 CFR Part 194, section 194.22 (b), "Any compliance application shall include information which demonstrates that data and information collected prior to the implementation of the quality assurance program required pursuant to paragraph (a) (1) of this section (194.22) have been qualified in accordance with an alternate methodology, approved by the administrator or the administrator's authorized representative, that employs one or more of the following methods: peer review, conducted in a manner that is compatible with NUREG-1297, "Peer Review for High-Level Nuclear Waste Repositories"; corroborating data; confirmatory testing; or a quality assurance program that is equivalent in effect to ASME NQA-1-1989 edition, ASME NQA-2a-1990 addenda, part 2.7, to ASME NQA-3-1989 edition (excluding Section 2.1 (b) and (c) and Section 17.1)." The DOE has generally opted to employ the peer review methodology to qualify existing data that it cannot demonstrate was collected in accordance with a quality assurance program that was equivalent to the quality assurance defined above. Accordingly, a peer review will be conducted to confirm the adequacy and completeness of data utilized to define parameter values as applied in conceptual models and scenarios that have been determined to be significant to waste containment. To facilitate review of the data, the data qualification peer reviews have been divided into the following three associated waste containment subsystems:

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

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Sandia National Laboratories (SNL) is responsible for the selection and development of conceptual models that reasonably define the WIPP containment system, and for the identification and development of mathematical models, numerical models, and computer codes utilized to assess the performance of the WIPP containment for the statutory confinement period. SNL is responsible for identifying data for which it cannot provide assurance that the information was collected under a qualified quality assurance program (as defined above). These data will then be reviewed under a peer review process conducted in accordance with NUREG-1297. Therefore, to meet the regulatory requirements cited above, this peer review on engineered systems for rock mechanics and shaft/borehole seals will assess the qualification of data used in performance assessment for the WIPP.

1.2 PURPOSE

The purpose of this WIPP peer review plan is to define the peer review process that will be conducted to *determine if (Rev.1)* existing unqualified experimental subsystems data and information *are qualified to be (Rev.1)* used in the demonstration of compliance. As stated above, the DOE has determined the peer review process to be the most appropriate method to demonstrate that all engineered subsystems are qualified for use in the demonstration of compliance. These peer reviews will be conducted in accordance with the requirements of NUREG-1297 that state, "A peer review is a documented, critical review performed by peers who possess qualifications at least equal to those of the individuals who conducted the original work. These individuals must be independent of the work being reviewed; independence from the work reviewed means that the peer, a) was not involved as a participant, supervisor, technical reviewer or advisor in the work being reviewed, and b) to the extent practical, has sufficient freedom from funding considerations to assure the work is impartially reviewed."

1.3 SCOPE

This ESPR Plan describes the peer review process that the DOE Carlsbad Area Office (CAO) will utilize for the review of those existing data and information that form the basis for determining the parameter values of the conceptual models that form the engineered systems subsystems. The peer review will be an in-depth critique of assumptions, alternate interpretations, methodology, and acceptance criteria employed, and of the conclusions drawn in the original work. This ESPR Plan defines the approach, methods, criteria, schedules, deliverables, and resources required for conducting the ESPR to confirm: 1) the adequacy and completeness of the data; and 2) the data and information are qualified for use in the demonstration of compliance. See Attachment A for a description of the data to be reviewed and its intended use in PA.

The conceptual models and codes to be used in the PA of the engineered systems include:

Engineered Systems - Rock Mechanics and Shaft/Borehole Seals

Model	**Code**
Disposal Room Geometry	BRAGFLO
Creep Closure	BRAGFLO
Repository Fluid Flow	BRAGFLO
Shafts and Shaft Seals	BRAGFLO
Disturbed Rock Zone	BRAGFLO

Existing unqualified data and information which was utilized to establish the parameter values will form the basis of this ESPR.

2. PEER REVIEW PLANNING AND IMPLEMENTATION

2.1 APPROACH

The DOE-CAO has prepared the "Office of Regulatory Compliance (ORC) Team Procedure for Peer Review" (TP 10.5) to document the approach for conducting the peer review process. The ESPR Panel will conduct the peer review activities for the qualification of data in accordance with TP 10.5, this Plan and IDI 1.0.

Similarly, SNL has prepared a procedure to provide the data and information necessary to support peer review of the qualification of data. The SNL data packages to be provided to the ESPR Panel will include: 1) identification of the applicable conceptual model parameter(s); 2) assignment of a parameter value or range of values; 3) description of the source of the data used to construct the parameter value or ranges of values; 4) a description of the process whereby the data was scaled up to parameter value(s); and 5) designation of data qualification status.

2.1.1 DATA USED IN THE DEMONSTRATION OF COMPLIANCE

The peer review of existing unqualified SNL data and information (see Attachment A) is to confirm and document its adequacy and completeness. The data and information qualification peer review will confine itself strictly to providing this confirmatory information.

2.1.2 COMPOSITION OF PEER REVIEW PANEL

The ESPR Panel will be composed of a minimum of three individuals who meet requirements identified in TP 10.5. The duration of the ESPR Panel review process is expected to last between three to six weeks. The ESPR Panel may include up to two members of the Conceptual Model Peer Review Panel. The peer review selection committee will appoint the remaining panel member(s) based on his/her technical expertise which will be equivalent to that required to do the original work. Experience areas to be represented on this panel include geotechnical/mining/civil engineering and geohydrology.

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

2.1.3 LOGISTICS AND MANAGEMENT

When the ESPR Panel convenes to perform the peer review process, the intent is to have all the data packages accessible for review. However, not all information necessary to support peer review of the qualification of data for the engineered systems may be available at the beginning of the review. Therefore, it may be necessary to conduct the ESPR in a phased manner, depending upon the availability of information.

2.2 METHODOLOGY

The ESPR will follow the methodology provided in NUREG-1297 as augmented by the specific requirements contained in 40 CFR Part 194.22. The purpose for conducting a peer review of data associated with this WIPP subsystem is to ensure that those data that cannot be qualified by virtue of their collection under a QA program (equivalent in effect to ASME NQA-1-1989 edition, ASME NQA-2-1990 addenda, part 2.7, ASME NQA-3-1989 edition [excluding Section 2.1 (b) and (c) and Section 17.1]) are qualified for use in the demonstration of compliance. To facilitate the conduct of the peer review, a checklist containing potential areas of review is included in this plan as Attachment B. The basis of the peer review will be to determine the adequacy and completeness of specific unqualified data used to demonstrate compliance. Adequacy criteria are provided in Section 2.3.

2.3 ADEQUACY CRITERIA

Adequacy of data associated with the conceptual models that nominally comprise the engineered systems subsystem will be based on the peer review panel's determination that these data meet commonly accepted technical and scientific standards. Criteria utilized to make this determination include:

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

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In evaluating the existing data, the peer review panel shall also consider the following:

- The sources of the parameters and data, e.g., professional judgment, published source material, field tests, laboratory experiments, etc.;
- The processes used to produce the parameters from data are appropriate for the intended use; and
- The assumptions, calculations, extrapolations, interpretations, methods, and conclusions pertinent to the data are appropriate for the development of parameters used as input to the WIPP PA and are traceable.

2.4 SCHEDULE

The PR Manager, working closely with SNL, has developed a preliminary schedule that provides the necessary information on an "as available" basis. Flexibility is required by all supporting organizations, (i.e., DOE-CAO, SNL, the PR Manager, staff, and panel members) to accommodate the peer review schedule and any changes made due to uncertainty in the timing of data availability. Attachment C contains a schedule of ESPR activities and milestones in accordance with the Peer Review Management Plan. This schedule will serve as the baseline schedule from which requested schedule deviations will be evaluated and approved, if appropriate. Revisions to the baseline schedule will not require revision to this plan but will be attached to the plan by reference.

2.5 DELIVERABLES

A final report for the ESPR will be submitted to DOE-CAO. A list of mandatory topics and suggested outline for the final ESPR report is provided in Attachment D. This outline may be utilized to guide the review of each data package to ensure adequate review of the data packages.

3. QUALITY ASSURANCE

The ESPR process will be conducted in a controlled manner and in compliance with TP 10.5.

4. RECORDS MANAGEMENT

Records and documents generated as a result of peer review activities defined in this peer review plan are identified in the CAO Team Procedure, TP 10.5. ESPR records will be assembled and maintained in accordance with the Peer Review Management Plan and the Informatics Desk Instruction, IDI-1.0. Upon completion of the peer review process, a complete set of ESPR records will be delivered to CAO. Ultimately, peer review records will be dispositioned in accordance with DOE-CAO records management requirements.

5. DOCUMENT CONTROL

All plans, procedures, and other documents which require document control will be handled in accordance with applicable DOE-CAO controlled document procedures (MP 4.4).

ATTACHMENT A

PEER REVIEW PANEL DATA PACKAGE DESCRIPTIONS

DATA	INTENDED USE
Salado Mass Concrete Bulk Modulus (Pore Volume Compressibility)	Shaft Seals
Salado Mass Concrete Porosity	Shaft Seals
Crushed Salt Bulk Modulius Analysis Basis	Shaft Seals
Crushed Salt Permeability	Shaft Seals
Concrete Permeability	Shaft Seals
Clay Permeability	Shaft Seals
Waste Densities	Disposal Room
Waste Mechanical Properties	Disposal Room
Initial Waste Water Content	Disposal Room
Waste Intrinsic Permeability	Disposal Room
Cuttings, Cavings, Spallings, including Cementation Strength	Disposal Room
Final Porosity Surface Data	Disposal Room
Halite and Anhydrite	Rock Mechanics
Transition Zone Properties	Disturbed Rock Zone

ATTACHMENT B

SUGGESTED METHODS CHECKLIST

PEER REVIEW CHECKLIST	
STUDY/EXPERIMENT IDENTIFICATION	
	COMMENTS
1.0 Scientific Technical Items	
1.1 Were the technical objectives clearly stated in documents accompanying the data?	
1.2 Are all the stated objectives addressed by the data?	
1.3 Was there any test-to-test interference and/or was the impact of test-to-test interference on results adequately evaluated?	
1.4 Were the tests performed in accordance with: a) nationally recognized standards?	
b) modified recognized standards or specially prepared test procedures?	
c) modified recognized standards or specially prepared test procedures?	
d) If so, are they documented in sufficient detail to be repeatable?	
e) Were they justified, evaluated, and approved by a cognizant individual/organization?	
1.5 Were the test procedures correctly implemented?	
1.6 Were testing irregularities and interruptions described?	
1.7 Was documentation of corrective actions sufficiently detailed?	
1.8 Were data reduction processes appropriate for the objectives of the test?	
1.9 Is the reduced data a true representation of all raw data acquired?	
1.10 Are the interpretations well supported by the data?	
1.11 Is the data quality adequate?	
a) Does the age of the data affect the results?	
b) Were the analytic methods used adequate?	
c) Were detection limits adequate?	
d) Is the range of uncertainty associated with each measurement adequate to satisfy the objectives of the test?	
e) Is the uncertainty associated with the cumulative data low enough to make a decision?	
f) Has invalid data been identified?	
g) Has valid data been characterized by providing qualitative or quantitative statements as to the validity and use?	
h) Is there a redundancy in measurements that provide checks of/on the data?	
1.12 Were the number of data points taken enough to provide an adequate level of confidence in the results?	
1.13 Is there internal consistency between the sets of data for similar tests?	
1.14 Are the data complete?	
1.15 Can credible blocks be improved, or supported by: a) correlation with complementary or confirmatory data?	
b) additional work?	
1.16 Is any source of confirmatory data identified in database documents?	

1.17 Is the data good enough to support the intended use?	
2.0 Summary of Conclusions	
2.1 Did the data meet adequacy of requirements and criteria?	
2.2 Did the data show validity of assumptions?	
2.3 Were there alternate interpretations of the data?	
2.4 Was there a discussion of uncertainty of results and consequences?	
2.5 Was there appropriateness and limitations of methodology and procedures?	
2.6 Was adequacy of application demonstrated for the data?	
2.7 Was the accuracy of calculations demonstrated?	
2.8 Was the validity of conclusions demonstrated?	
2.9 Were the sources of the parameters and data considered in evaluating the existing data?	
2.10 Were the processes used to produce the parameters from the data appropriate for the intended use?	
2.11 a) Were the assumptions, calculations, extrapolations, interpretations, methods, and conclusions pertinent to the data appropriate for the development of parameters used as input to the WIPP PA?	
b) Were they traceable?	

ATTACHMENT C

ENGINEERED SYSTEMS PEER REVIEW SCHEDULE

	DRAFT	FINAL
ESPR Plan	3/11	3/29
PR Panel Assigned	NA	4/12
ESData Package to PR Manager	4/5	4/12
Initiate ESPR	NA	4/22
Complete ESPR	NA	5/31
Submit ESPR Report	6/7	6/14

ATTACHMENT D

PEER REVIEW REPORT OUTLINE

Executive Summary

1. Introduction
2. Purpose
3. Description of Work Performed
4. Evaluation Work Performed
   A. Adequacy of Requirements and Criteria
   B. Validity of Assumptions
   C. Alternate Interpretations
   D. Uncertainty of Results and Consequences if Wrong
   E. Appropriateness and Limitations of Methodology and Procedures
   F. Adequacy of Application
   G. Accuracy of Calculations
   H. Validity of Conclusions
5. Conclusions
6. Dissenting Views
7. Summary
8. Signatures
9. Peer Review Members and Acceptability

ENGINEERED SYSTEMS DATA QUALIFICATION

PEER REVIEW REPORT

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FINAL REPORT

WASTE ISOLATION PILOT PLANT
ENGINEERED SYSTEMS DATA QUALIFICATION
PEER REVIEW REPORT

A PEER REVIEW

CONDUCTED BY

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for

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

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FOREWORD

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

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

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

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ACRONYMS AND ABBREVATIONS

SNL	Sandia National Laboratory
SMC	Salado Mass Concrete
DRZ	disturbed rock zone
WIPP	Waste Isolation Pilot Plant
PA	performance assessment
WES	Waterways Experiment Station
IRT	Independent Review Team
SSSPT	Small-Scale Seal Performance Tests
QA	quality assurance
DCCS	dynamic compaction of crushed salt
ASTM	American Society for Testing Materials
PDF	probability density function
CH	contact-handled
TRU	transuranic (waste)
WAC	waste acceptance criteria
INEL	Idaho National Engineering Laboratory
DOE	U.S. Department of Energy
RFP	Request for Proposal
CDF	cumulative distribution function
RM	reduced modulus
MD	Multi-Deformational
MDCF	Multimechanism Deformation Coupled Fracture

1.0 EXECUTIVE SUMMARY

The Engineered Systems Peer Review was conducted by four panel members (Panel), who examined the 14 parameters (or parameter groups) submitted to them for qualification by Sandia National Laboratories (SNL). The 14 parameters are listed in Table 1.1, together with the qualification status for each that resulted from this review.

Table 1.1. Summary of Qualification Status of Parameters, as a Result of the Engineered Systems Peer Review

Subsystem	Parameter Name	Qualification of Parameter
Shaft/Shaft Seal	Porosity of Salado Mass Concrete (SMC)	Qualified
	Pore Volume Compressibility of SMC	Minor change to value suggested
	Bulk Modulus of Crushed Salt	Qualified
	Permeability of Crushed Salt	Requires further analysis by SNL
	Permeability of SMC	Qualified
	Permeability of Compacted Clay	Qualified
Disposal Room/Rock Mechanics	Initial Density of Waste	Qualified
	Mechanical Properties of Waste	Qualified
	Initial Water Content of Waste	Qualified
	Permeability of Consolidated Waste	Minor change to value suggested
	Strength of Waste for "Blowout"	Insufficient data to qualify
	Properties of Halite and Anhydrite	Qualified, based on limited review
	Data on Final Porosity Surface	Qualified, based on limited review
Disturbed Rock Zone	Characterization of Disturbed Rock Zone	Concepts qualified

In summary, the Panel was able to qualify seven of the well-defined parameters, and two of the parameter groups (properties of halite and anhydrite, and data on final porosity surface) based on a limited review. In the opinion of the Panel, minor changes should be made to an additional two parameters (pore volume compressibility of Salado Mass Concrete (SMC), and permeability of consolidated waste).

It is the opinion of the Panel that further analysis by SNL is needed on the permeability of crushed salt, and the strength of the waste for the "blowout" scenario. With regard to the disturbed rock zone (DRZ) around the shaft, the Panel concurred with SNL's general treatment of the DRZ from an engineering point of view.

A summary of the evaluation of the individual parameters follows:

- Porosity of SMC. The Panel is able to qualify the value of 5%. However, this value is not a unique property of SMC; rather it is a property that needs to be controlled in the field during the mixing and placing of the concrete.

- Pore Volume Compressibility of SMC. There were little data in the data package to enable this value to be calculated. The Panel was able to find some new data which SNL should consider in deriving a modified value for this parameter.

- Bulk Modulus of Crushed Salt. The Panel was able to qualify the values for this parameter (ranging from 5.74 to 20.67 GPa) at five different time intervals during the consolidation process.

- Permeability of Crushed Salt. Based on current data, the Form 464 values may be too low; however, new data being analyzed by SNL may establish the validity of these values or lead to their modification. The Panel is unable to form a conclusion until this analysis is completed.

- Permeability of SMC. The Panel concurs with the selected values for this parameter. Up to 400 years this is a triangular distribution with a best estimate of 1.78×10^{-19} m^2. After 400 years the SMC is assumed to deteriorate and acquire the permeability of a dense soil with a best estimate value of 1×10^{-14} m^2.

- Permeability of Compacted Clay. The Panel is able to qualify the value of 5×10^{-19} m^2 for the bentonite seals. The validity of this number depends to a large extent on how the bentonite is emplaced during construction and its consistency, particularly with regard to density.

- Initial Density of Waste. The Panel concurs with the average value of 559.5 kg/m^3, which is used for room porosity calculations of the current inventory.

- Mechanical Properties of Waste. The Panel is able to qualify five elastic-plastic constants for the waste, together with a pressure-relative density table for the waste during the consolidation process. These values are appropriate for use in disposal room closure calculations.

- Initial Water Content of Waste. The Panel is able to qualify the value of 1.5%, which represents the initial waste container saturation by volume.

- Permeability of Consolidated Waste. Based on a review of the data and discussions with SNL, a new value of 2.4×10^{-13} m^2 has been calculated by SNL.

- Strength of Waste for "Blowout." There are little data to support any value for this parameter, and the Panel's opinion is that further analysis be undertaken by SNL.

- Properties of Halite and Anhydrite. The Panel is able to qualify these parameter values for use in mechanical response models for room closure predictions.

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- Data on Final Porosity Surface. The porosity surface is a valid method of describing disposal room closure as an input to BRAGFLO. The Panel is able to qualify the final porosity surface as defined in WPO#35697.

- Characterization of the DRZ. The Panel concurs with the engineering concepts regarding the DRZ and its impacts on effective shaft sealing. The Panel was not asked, however, to qualify any parameter values.

2.0 PURPOSE

The purpose of the Engineered Systems Peer Review was to seek qualification of scientific data by performing a systematic qualifying review of unqualified parameters and subsystems used in the models describing engineered systems for rock mechanics and shaft/shaft seals in the Waste Isolation Pilot Plant (WIPP). This review is one of three recognized methods for providing assurance that scientific data collected are qualified for intended use. A peer review panel (Panel), consisting of four members, was convened to undertake the work. The peer review was conducted in a manner that was compatible with NUREG-1297, Peer Review for High-Level Nuclear Waste Repositories. This report is a documented summary of the Panel's work and of the evaluation performed on selected parameters identified by Sandia National Laboratory (SNL). The report is intended primarily for use by the technical personnel at SNL/WIPP. It may also be included as supporting material in the WIPP Compliance Certification Application submitted to the Environmental Protection Agency.

The parameters evaluated consisted of information used as input to the WIPP performance assessment (PA), which in turn is to be incorporated in the demonstration of compliance. The Panel evaluated existing data and information that form the basis of the parameter values used in the mathematical expression of conceptual models for the engineered systems and subsystems. The parameters selected for evaluation had not previously been fully qualified for use in PA. The conceptual models used in the performance assessment of the engineered systems include components of 1) Disposal Room Geometry, 2) Creep Closure, 3) Repository Fluid Flow, 4) Shafts and Shaft Seals, and 5) Disturbed Rock Zone.

3.0 DESCRIPTION OF WORK PERFORMED

The Engineered Systems Peer Review Panel evaluated 14 parameters, parameter sets and data sets against the eight review criteria cited in NUREG-1297. The review involved selected elements of the following subsystems listed in Table 3.1: 1) Shaft/Shaft Seals, 2) Disposal Room, 3) Rock Mechanics, and 4) Disturbed Rock Zone. In some subsystems, individual parameter values were evaluated and a determination made of their adequacy as used in the WIPP performance assessment program. In several instances, sub-parameters of parameter sets were evaluated to determine their collective contribution to a subsystem concept. This approach resulted in some parameters treated to varying levels of detail in which their intended uses were evaluated with respect to their application in lieu of the effect of their quantitative value.

The Panel performed an in-depth critique of assumptions, alternate interpretations, methodology and acceptance criteria employed, and of the conclusions drawn in the original work. In evaluating the existing unqualified data, the peer review panel members considered the following:

- The sources of the parameters and data (e.g., professional judgment, published source material, field tests, laboratory experiments, etc.).
- The appropriateness of the parameters and data for their intended use.
- The assumptions, calculations, extrapolations, interpretations, methods, appropriateness, validity, sensitivities, and conclusions pertinent to the parameters and data used as input to the WIPP performance assessment.

The Panel, in conducting its work, reviewed information packages provided by SNL for each parameter. In addition, technical reports and documents obtained from the SNL waste management library and records center were used to supplement the information in the parameter packages. Both formal and informal technical discussions were held with SNL principle investigators to more fully understand the concepts and parameter derivation and application in the PA. Table 3.1 identifies the subsystems, parameter names, and number of parameters and sub-parameters the Panel evaluated. The Panel collectively devoted about 20 man-weeks of effort to the technical review and this report.

Table 3.1. Listing of Parameters With Approximate Number of Parameters and Sub-Parameters

Subsystem	Parameter Name	Number of Parameters and Sub-Parameters
Shaft/Shaft Seal	Porosity of Salado Mass Concrete (SMC)	1
	Pore Volume Compressibility of SMC	3
	Bulk Modulus of Crushed Salt	6
	Permeability of Crushed Salt	19
	Permeability of SMC	9
	Permeability of Compacted Clay	33
Disposal Room/Rock Mechanics	Initial Density of Waste	6
	Mechanical Properties of Waste	6
	Initial Water Content of Waste	1
	Permeability of Consolidated Waste	3
	Strength of Waste for "Blowout"	1
	Properties of Halite and Anhydrite	94
	Data on Final Porosity Surface	110
Disturbed Rock Zone	Characterization of Disturbed Rock Zone	

4.0 EVALUATION OF SHAFT/SHAFT SEAL PARAMETERS

4.1. Porosity of SMC

4.1.1. General Evaluation

SMC is a specially-designed salt-saturated concrete that is compatible with the salt host rock. It is durable, has low permeability and provides a viable seal in the shaft, with adequate strength to support overlying seal components and promote natural healing processes within the DRZ in the salt around the shaft.

There are three identical concrete components in the Salado shaft sealing system, each one composed of three elements: an upper concrete plug, a central asphalt waterstop and a lower concrete plug. The overall design length of each component is 15m. There is also a 6m SMC plug in the Rustler formation. In addition, SMC is used to construct a concrete monolith at the base of the shaft; however, this is not considered to be part of the shaft sealing system (Sandia WIPP, 1996, pp. 25-29).

The porosity of the SMC is a basic property of the hardened concrete that influences other properties, such as strength and permeability, important to performance assessment of the shaft seal system. Porosity is used also to derive a key BRAGFLO parameter, the pore volume compressibility of SMC (see Section 4.2). The value assigned to the porosity of the SMC is 0.05 or 5% (Form 464, Parameter #2484).

4.1.2. Adequacy of Requirements and Criteria

The requirement is to know the porosity of the concrete, i.e., the proportion of the total volume of the cured concrete that is voids, expressed as a percentage by volume (ASTM C457-90). It excludes the submicroscopic voids within the aggregate and the cement paste. The volume of void space is often measured by absorption (taking a dry specimen, immersing it in water and measuring the increase in weight). Various other procedures can be used that may provide a wide range of results (Neville, 1973, pp. 383-4).

Porosity can also be measured microscopically in both hardened concrete (ASTM C457-90) and freshly mixed concrete by observing the change in volume of a concrete sample with a change in pressure (ASTM C231-91b). Both methods were employed in evaluating SMC at the U.S. Army Corps of Engineers Waterways Experiment Station (WES).

Note that the concrete industry uses its own terminology. For instance "air content" refers to the proportion of air voids in the total volume of concrete, where "air voids" are usually more than a few mm in diameter; the term includes both entrapped and entrained voids. A "water void" is a void occupied by water at the time of setting (ASTM C457-90, p. 1). The terms air content, percentage of air voids, and quantity of air entrainment are often used loosely to mean the same as the definition of porosity given above.

Air entrainment, often induced using pozzolans and special procedures, is a desired feature of mass concrete since it produces a marked improvement in durability, plasticity and workability, together with a reduction in segregation and bleeding. There is also a reduction in strength, which can be minimized in the design process by reducing the quantity of paste, increasing aggregate size and reducing the water-cement ratio. Hence, air entrainment is a desireable quality in concrete, especially in concrete subject to freezing and thawing, provided that the air voids are uniformly distributed within the concrete and the overall air content generally meets recommended values of about 3 to 4.5% (e.g., Table A5.6 in ACI, 1993). The Panel considers that the inclusion of Class F fly ash and the 4.5% porosity obtained from the truck-mixed concrete at WES places SMC in the air-entrained category (ACI, 1993, No. 211.1-91, p. 8).

4.1.3. Assumptions

It is generally implied in the documentation that the different methods of measuring porosity employed at WES yield comparable values of concrete porosity, and that these values are appropriate for correlation with fluid flow as well as strength properties of the concrete. It is also assumed that the test samples are representative of the SMC that eventually will be used to construct the shaft seals.

4.1.4. Alternate Interpretation

As mentioned in Section 4.1.2, there are different levels of porosity in concrete depending upon the measurement scale used. For example, Neville (1973) p. 383, states that the gel pores in the cement paste constitute about 28% of the paste volume, and that capillary pores within the cement paste can vary between 0 and 40% of the paste volume depending on the water/cement ratio and the degree of hydration. In addition, the coarse and fine aggregate particles themselves contain pores. Such measurements of submicroscopic porosity are often valuable in concrete research, but they are not used in normal porosity evaluations.

The definition of porosity discussed in Section 4.1.2 is a purely practical one. It includes only the interconnected pores and the larger entrained air bubbles. It is often used as an index value for correlating porosity with strength and permeability of the hardened concrete under field conditions, although these correlations tend to be imprecise. Despite the limitations mentioned above, the concrete industry has developed a large body of information on concrete porosity and related field behavior, and there are no other practical alternatives to using industry standards at this time.

4.1.5. Uncertainties and Consequences

Due to heterogeneities, measurements of porosity will vary throughout a concrete sample, similar to measurements of porosity in geologic materials such as clay and argillaceous salt. For practical purposes, an average porosity value is usually sufficient for problems at "room scale" or "repository scale."

Different measurement techniques can yield different results, so caution should be taken in comparing results obtained by different methods (Aarre, 1995); comparisons between porosities obtained using the same method are generally more meaningful. In the WES documents, differences in porosity obtained by the different measurement techniques are not discussed. Also, there is little or no discussion as to which measurements of porosity are most meaningful for deriving parameters related to fluid flow, such as pore volume compressibility (see Section 4.2).

Concrete is unlike most geologic materials in that engineers can design the mix to meet specific performance goals; this can include a small, defined range of values for the porosity. Whether these goals are met in practice depends on the care taken to mix and place the concrete during construction. This requires the implementation of a strict process and quality control program, including frequent sampling and testing of the concrete itself, as well as its individual constituents.

The consequences of poor design and poor quality control are that porosities in the field could be highly variable, incompatible with design specifications, and/or unknown. This could lead eventually to loss of function, i.e., the concrete might not be strong enough or impermeable enough to fulfill its function as a sealing component.

4.1.6. Appropriateness and Limitations of Methodology and Procedures

The determination of the porosity of the SMC is largely based on the experimental work reported in Wakeley et al., 1995. This experimental work consisted of measurements on small experimental batches and large volume batches (approximately 5 yd^3) of salt-saturated concrete produced between April 1993 and February 1994.

The small experimental batches ranged in size from 1.5 to 14.0 ft^3 (these are the units reported by Wakeley et al., 1995). Each batch was a variation of SMC mixtures identified in previous studies as being likely candidates for use in shaft seals at the WIPP. Hence, the batches were similar in composition. They were mixed intermittently for two hours using the procedure outlined in Appendix B of Wakeley et al., 1995. Air entrainment measurements were made at two distinct times in each batch, once at the beginning of the mixing and once at the end of mixing (approximately after 2 hours). The values of air entrainment, as summarized in Table 4-2 of RE/SPEC (1996), ranged from 1.1 to 3.3%. Measurements at the start of mixing averaged 2.05% and measurements at the end of mixing averaged 1.91% air entrainment.

Two large-volume batches were prepared from pre-bagged materials and mixed in a truck-mounted concrete mixer, using the procedure described in Wakeley et al., 1995, pp. 22-25. Air entrainment values measured for the 161SM3 and the 231SM3 mixtures during the two-hour mixing period ranged from 1.7 to 2.4%, with an average of 2.03%. This is similar to the air entrainment values measured in the small experimental batches.

A portion of each of these two batches was discharged into separate oval metal tanks approximately 4 ft by 8 ft by 3 ft deep, following the description found in Wakeley et al., 1995, pp. 30-32. Air entrainment data were obtained from concrete cores. The results are summarized in Table 4-3 of RE/SPEC (1996) and Table 4-6 of Wakeley et al., 1995. For batch 231SM3 (which was vibrated 12 times for a duration of 6-8 seconds for each insertion) the air entrainment values ranged from 1.5 to 3.2%, with an average of 2.23%.

For batch 161SM3 (which was vibrated four times for a duration of 3 seconds per insertion) the air entrainment values ranged from 3.3 to 4.5%, with an average of 4.08%; at the far end of this tank the air entrainment values averaged 4.45%.

Based on these tests, the following tentative conclusions may be drawn:

- During mixing, the air entrainment values are about 2% regardless of whether the batches are mixed in a laboratory mixer or in a 10 yd^3 mobile mixer.
- When cast in a monolith, the air entrainment values increased up to 4.5%; the values increased as the amount of vibration decreased and as the flow distance increased.

Hence, it would appear from the data in Wakeley et al. (1995) that the range for air entrainment in SMC is between 2 and 5% for SMC mixed and placed under conditions similar to that for batch 161SM3. In practice, it is expected that flow distances of 2m beyond the discharge point of the tremie line will be representative of flow conditions when the SMC shaft seals are being placed. However, it is not planned to use vibration at WIPP. These issues are discussed further in Section 4.1.7.

Review of Laboratory Records

The two monoliths created from the large truck-mixed batches were cored and analyzed microscopically for total air content and evidence of possible aggregate segregation. These data are summarized in Table 4-6 of Wakeley et al., 1995 (note the typing error in the table; the samples should be labeled 161SM3 and 231SM3).

Since the Independent Review Team (IRT) previously had approved the technical adequacy of the work reported in Wakeley et al., 1995, the review by the Panel of the records package concentrated on the key data pertaining to the field porosity of SMC.

For example, the WIPP Records Package (WPO 28380) contains CRD-C42 forms based on ASTM C457 for the microscopic determination of total air in the cored specimens. According to Wakeley et al., 1995, one determination was made at each location, except at the far ends of the monoliths where two determinations were made (and the results averaged for insertion into Table 4-6); this implies the existence of 16 such forms. The Records Package (WPO 28978) appears to contain only 12 completed data forms, however, and the missing forms are those for the far end of the minimally-vibrated concrete (i.e., 161SM3 C&D cores). The missing forms contain the data most relevant to expected conditions when the SMC is placed in the shaft as a seal component.

A memorandum for Dr. Lillian Wakely faxed on 2/15/94 (WPO 28979) gives the total air content at the far end of the batch for 161SM3 C as 6.6% (top) and 6.0% (bottom). This appears to represent data derived from two of the missing sheets.

Other concerns are raised in a memo written by Billy D. Neeley on 1/4/94 (WPO 29097, Item 2). Although these were only preliminary observations by Mr. Neeley, he specifically states that cores taken from the top 4-6 inches of the first placement (161SM3) "indicated large entrapped air voids" and "the cohesiveness of the SMC mixture makes it difficult for the entrapped air to migrate to the top." He also states that "considerable vibration is necessary to eliminate the air entrapped during placing."

The comments of Mr. Neeley need to be considered together with the following previously mentioned facts:

- Four CRD-C42 forms are missing for the total air measured at the far end of the 161SM3 monolith. However, a memorandum exists which refers to the results of two of these data sheets as stating 6% and 6.6% total air content.

- The subsequent decision that was made to use no vibration when placing SMC in the shaft.

The missing forms should be found to support the selected porosity value of 5% for the low vibration situation. The WES data indicate that a porosity value above 5% may need to be selected for the no vibration case, or else vibration must be retained as a option to control the field porosity of SMC (other options include recoring the 161SM3 monolith, or repeating the experiment without vibration). The data examined do *not* conclusively support an overall porosity value of 5%, if vibration is excluded during construction.

4.1.7. Adequacy of Application

The preparation and placement of the SMC in the shaft is described in Appendix A, p. 10, of Sandia WIPP (1996). The concrete will be batched and mixed on the surface in mobile mixers, which will discharge the fresh concrete into a hopper feeding a slick line down the shaft. A tremie line will minimize entrained air by discharging the concrete below the surface level of the concrete already placed. Vibration is not planned (except for the monolith at the base of the shaft) and concreting will be continuous until each concrete segment is complete.

Planned preparation methods in the field are similar to those used at WES up to the point that the concrete is placed in the slick line hopper. What then is the effect on air entrainment of dropping the wet concrete 2000 ft or so down the shaft and emplacing it via a tremie line?

It is reported in the literature that the total air content of air-entrained concrete has been observed to increase, decrease or remain unaffected by pumping (ACI, 1995, No. 92-M48, p. 458). In practice, the final porosity of the mass concrete in the shaft depends on the placement technique. While free fall directly onto the already placed concrete can increase the overall porosity of the concrete, the proposed techniques to break the fall of the wet concrete and place it via a tremie line can be expected to reduce the overall porosity. It is reported that vertical dropping of concrete in a pipeline can reduce the porosity by up to 1.5% (ACI, 1993, No. 92-M48, p. 458). This is particularly true of flowable concrete mixes, discharged vertically downwards in a pipe (NRMCA, 1992, CIP 21).

On the one hand, the planned lack of vibration during placement will tend to produce a porosity higher than the 5% values obtained from the low-vibrated monolith at WES. On the other hand, specifically-planned concrete placement procedures could reduce the air content by up to 1.5% (below the 5% value at WES). These are off-setting effects. This means that a final (in-place) porosity for the SMC of 5% is achievable. In practice it will depend on how the concrete is handled. Therefore, in order to meet the parameter value, it will be necessary to maintain process and quality control in the field, including regular sampling at the truck discharge point (before the concrete enters the slick line) and at the surface of the wet concrete in the shaft away from the discharge point. Handling procedures can be modified, if necessary, to maintain the porosity at around 5% or less. This could include vibration of the wet concrete, as needed.

4.1.8. Accuracy of Calculations

Although the volume of the concrete mass is simple to measure, the volume of air voids is more difficult. (This tends to be the source of differences in porosity values.) The calculation of porosity is merely the ratio of the two numbers. Hence the calculations of porosity are relatively simple and are adequately accurate.

4.1.9. Validity of Conclusions

The value assigned to the porosity of SMC of 5% (Form 464, Parameter #2484) is reasonable and valid for the following reasons:

- The report by Wakeley et al. (1995) and its WIPP Records Package (WPO 28380) demonstrate that a porosity of 2% is typical for small batches of SMC prepared in the laboratory. The porosity of 5 yd^3 batches prepared in a mobile mixer (more representative of field conditions) ranged from 1.5 to 6.6%; lower porosities were achieved with shorter flow distances, and more consolidation through vibration.

- To a large extent, the porosity of SMC in the field can be controlled by careful mixing, transportation, placement and consolidation through vibration. Therefore, a field porosity of 5% for SMC is achievable and reasonable.

However, the WES data do not conclusively prove that a 5% porosity is achievable without vibration. Hence, vibration should be kept as an option to be employed if needed during construction.

In order to produce an SMC shaft seal with a porosity of 5% or less, a rigid process and quality control program will be needed at the site during mixing and placing, which should include frequent porosity testing of the emplaced concrete and timely corrective actions as necessary.

4.1.10. Dissenting Views

None

4.2. Pore Volume Compressibility of SMC

4.2.1. General Evaluation

SMC is a specially-designed concrete that will be incorporated into the shaft sealing system and used to construct a concrete monolith at the base of the shaft. A general description of SMC is included in Section 4.1.1. Further information can be obtained from Wakeley et al., 1995, and Sandia WIPP, 1996.

The Pore Volume Compressibility is a parameter used in BRAGFLO that has to be specified for all materials in the potential flow path. It is a porous material property, defined as the fractional change in pore volume with a unit change in fluid pressure (Kelley et al., 1996, p. 11).

The value assigned to the pore volume compressibility of SMC is 1.2 GPa^{-1} (Form 464, Parameters #2464, 2481 and 3052).

Derivation of Pore Volume Compressibility

The bulk modulus, *K*, is an elastic material property that relates volume changes to changes in mean stress or pressure applied to that material (RE/SPEC, 1996, p. 6). It can be measured directly from a drained hydrostatic compression test in the laboratory or, in isotropic materials, it can be calculated from other elastic properties such as Young's modulus, E, and Poisson's ratio, ν, as follows:

$$K = \frac{E}{3(1-2\nu)}$$

Rock compressibility or bulk compressibility, C_r, is equal to the fractional change in volume of the solid rock matrix with a unit change in pressure (Kelley et al., 1996, p. 11). It is the inverse of the bulk modulus:

$$C_r = \frac{1}{K}$$

BRAGFLO, however, uses the pore volume compressibility, C, as defined above. It can be obtained by dividing the rock compressibility by the porosity of the rock, ϕ:

$$C = \frac{C_r}{\phi}$$

Hence, for WIPP the pore volume compressibility is a derived property of the material, rather than a directly measured value. It is calculated from the following three measured parameters for a material such as SMC:

- Young's modulus, E
- Poisson's ratio, v
- Porosity, ϕ

4.2.2. Adequacy of Requirements and Criteria

The strategy that will be used here to evaluate the pore volume compressibility of SMC will be to evaluate the following three parameters: Young's modulus, Poisson's ratio, and porosity. These will then be combined to derive the pore volume compressibility. (This strategy is similar to the strategy employed by SNL.) Note that there is often a difference in usage between rock mechanics specialists and hydrologists of the terms rock compressibility and pore volume compressibility. Hence, it may be necessary to derive the actual numerical value in each case to see what it represents.

Young's modulus and Poisson's ratio

These parameters are considered together since they both can be derived from the same unconfined compressive strength test in which strains are measured. Several tests are required, however, to obtain reasonable average values. Note that Young's modulus of concrete generally increases with age during the first year, and that Poisson's ratio initially increases with time but then becomes relatively constant after only a few days (Labreche and Van Sambeek, 1988, p. 95). By way of comparison with SMC, ordinary and lightweight concretes have a Poisson's ratio generally in the range 0.15 to 0.20 (Neville, 1973, p. 320).

The U.S. Army Corps of Engineers Waterways Experiment Station (WES) measured Young's modulus from one preliminary batch and one pre-bagged batch of SMC-3 concrete (Wakeley et al., 1995). For batch 153SM3 (trial batch) Young's modulus increased from 15.4 GPa (2.2 x 106 psi) at 7 days to 39.8 GPa (5.7 x 106 psi) at 180 days. For batch 161SM3 (large volume batch) Young's modulus ranged from 18.2 GPa (2.6 x 10-6 psi) at 7 days to 37.0 GPa (5.3 x 106 psi) at 180 days. The full set of test results demonstrate how Young's modulus increases with curing time, at a decreasing rate of gain. These values are of a similar magnitude to those measured in preliminary tests (Mixture 6R, mixed 040692 and 081392) as reported in Wakeley et al. (1993), p. 29.

RE/SPEC performed one triaxial compression test on SMC batched and cast at WES. This test, on specimen No 40 SM4 - 19/2-1/1, produced a value of E=36.3 GPa and v=0.185 (RE/SPEC, 1996, p. 7) listed as test 3 in Table 4.2.1. Later, RE/SPEC conducted three other tests on SMC at various confining pressures; these results are listed as tests 4, 5, and 6 in Table 4.2.1 (Pfeifle, Hansen, and Knowles, 1996).

Table 4.2.1. Measured Values of Young's Modulus and Poisson's Ratio for SMC

Specimen Identification	Young's modulus GPa	Poisson's ratio	Reference
1. Trial Batch 153SM3 at 180 days (WES)	39.8	--	SAND 94-1495, p. 28
2. Large Batch 161SM3 at 180 days (WES)	37.0	--	SAND 94-1495, p. 28
3. 40SM4 - 19/2 - 1/1 (RE/SPEC)	36.3	0.185	RE/SPEC. 1996, p. 7
4. 32SM4- 25/1 - 1/1 σ_3 = 5 MPa (RE/SPEC)	30.5	0.20	Pfeifle, Hansen and Knowles, p. 7
5. 40SM4 - 11/2 - 1/1 σ_3 = 10 MPa (RE/SPEC)	36.7	0.35	Pfeifle, Hansen and Knowles, p. 7
6. 40SM4 - 2/1 - 1/1 σ_3 = 15 MPa (RE/SPEC)	32.2	0.20	Pfeifle, Hansen and Knowles, p. 7
7. MAC 313-2/1 from SSSPT (RE/SPEC)	40.8	0.278	RE/SPEC, 1996, p. 7
8. MAC 314-1/1 from SSSPT (σ_3 = 5 MPa) (RE/SPEC)	41.9	0.264	RE/SPEC, 1996, p. 7

RE/SPEC also conducted several triaxial compression tests on concrete recovered from the WIPP Small-Scale Seal Performance Tests (SSSPT). The two tests at zero confining pressure yielded results close to each other but with values higher than that for SMC, particularly for Poisson's ratio (RE/SPEC, 1996, p. 7). The SSSPT concrete is an expansive salt-water concrete (described in Labreche and Van Sambeek, 1988, p. 8); its expansivity is attributable to the inclusion of Chem Comp III cement and plaster. Due to minor differences in composition, the results from the SSSPT are only indirectly comparable with SMC. They are included in the list of relevant test results (see Table 4.2.1, lines 7 and 8).

Porosity

The porosity of SMC is an independent parameter that appears on the WIPP Parameter list as Parameter #2467. It has an assigned value of 0.05 (Form 464, Parameter #2467).

This Panel has investigated this parameter (see Section 4.1), and determined that the value of 0.05 is reasonable and achievable. This value, however, is not a unique property of a particular SMC mix, rather it is dependent on the procedures employed in mixing, transporting, placing and compacting (through vibration) the concrete under field conditions. This is a property largely under the control of field personnel at the time of concrete placement. In the Panel's opinion, the likely range of porosities that could be achieved in the field varies from about 0.03 to about 0.07.

Derivation of Pore Volume Compressibility

For purposes of deriving pore volume compressibility, the porosity value for SMC of 0.05 selected by SNL (Form 464, Parameter #2484) is accepted and treated as a constant. It should be noted, however, that pore volume compressibility is quite sensitive to the porosity value.

Experimental measurements of Young's modulus and Poisson's ratio for SMC and SSSPT concrete are included in Table 4.2.1. Since the SSSPT represents a similar but different data set, the SSSPT results are included for comparison purposes only. The first six test results in Table 4.2.1 for Young's modulus of SMC are not widely scattered and average 35.4 GPa. There are four measurements for Poisson's ratio of SMC, which average 0.235.

Table 4.2.2 lists three data sets for the measured or assumed parameters (E, ν, ϕ) from which the derived parameters bulk modulus (K), rock compressibility (C_r), and pore volume compressibility (C) are calculated. Line A includes the elastic constants selected by RE/SPEC in Calculation No. 325/13/02 (RE/SPEC, 1996, p. 7, line 4). From these values, the pore volume compressibility value of 1.2 GPa-1 is derived, which corresponds to the Form 464 value for this parameter.

Table 4.2.2. Sensitivity of Pore Volume Compressibility to Variations in Elastic Constants

Basis for Measured Parameters	Measured Parameters			Derived Parameters		
	Young's modulus (E) GPa	Poisson's ratio (ν) --	Porosity (ϕ) --	Bulk modulus (K) GPa	Rock Compressibility (Cr) Gpa^{-1}	Pore Volume Compressibility (C) GPa^{-1}
A. Calc. No 325/13/02	30.0	0.20	0.05	16.67	0.060	1.2
B. SMC Sample 40SM4-19/2-1/1	36.3	0.185	0.05	19.21	0.052	1.04
C. All 6 SMC samples	35.4	0.235	0.05	22.26	0.045	0.89
D. Average of 2 SSSPT samples	41.4	0.271	0.05	30.13	0.033	0.66

In reviewing Table 4.2.1 it appears that the values of E and ν in RE/SPEC (1996) may be somewhat low. Hence, three other data sets were selected from Table 4.2.1 to see how sensitive the pore volume compressibility is to variations in the elastic constants. Line B takes the data from the SMC sample in which both E and v were measured at zero confining pressure. This gives a pore volume compressibility value of 1.04 Gpa^{-1}. Line C is based on the averages from all six tests on SMC; this gives a pore volume compressibility value of 0.89 Gpa^{-1}. What happens if the SSSPT elastic constants turn out to be more representative of the SMC than the SMC tests? This scenario is investigated in Line D. It yields a pore volume compressibility of 0.66 GPa^{-1}, approximately half of the Form 464 value.

Based on the limited data set for the elastic constants (Table 4.2.1), the Panel has concluded that the pore pressure compressibility for SMC lies in the range 0.7 to 1.2 GPa^{-1}, with the most probable value at about 0.9 GPa^{-1}. Thus, SNL's selected value of 1.2 GPa^{-1} represents a value close to the upper bound for this parameter. The difference between the Panel's value and SNL's value is due to the inclusion of recent data from Pfeifle, Hansen, and Knowles (1996). The Panel's conclusion is that a value of 0.9 GPa^{-1} for the pore volume compressibility of SMC is a more reasonable number to use in future PA calculations.

4.2.3. Assumptions

The assumptions used in deriving the pore volume compressibility of SMC include treating SMC as an elastic material in which the structural components are effectively incompressible and strain occurs only through reduction in pore space. It is also assumed that SMC is relatively homogeneous (with uniform porosity), and that it is reasonable to average the pore volume compressibility and treat it as a constant in BRAGFLO calculations. For SMC these are not unreasonable assumptions.

4.2.4. Alternate Interpretation

Alternate interpretations include treatment of pore volume compressibility as a spatially distributed parameter, since the value will change to the extent that porosity changes. In fact, the pore volume compressibility is quite sensitive to changes in porosity but, from a practical point of view, it is not possible to measure porosity changes within a large mass of concrete without destroying the concrete itself (the same also holds for Young's modulus and Poisson's ratio). Hence, it will be necessary to rely on good process control to ensure that a uniform concrete is emplaced in the shaft. In the Panel's opinion, it is reasonable to use average values of porosity, Young's modulus, and Poisson's ratio to determine an average value of pore volume compressibility. This is because SMC is relatively homogeneous and isotropic when compared to the geologic materials that also are in the potential flow path from the emplaced waste to the accessible environment.

4.2.5. Uncertainties and Consequences

There were four measurements of Poisson's ratio for SMC, with bounds of 0.19 and 0.35. SNL's selected value of 0.2 (see Line A in Table 4.2.2) could understate Poisson's ratio by up to 35% (compare with Line D in Table 4.2.2). This, together with uncertainties in the other measured parameters in Table 4.2.2, could reduce the Form 464 value of the pore volume compressibility by up to 50%, although 25% is more likely (Line C, Table 4.2.2).

The consequences of making an error of 25% or 50% in the average value of pore volume compressibility to the results of the BRAGFLO calculation is beyond the scope of this investigation.

4.2.6. Appropriateness and Limitations of Methodology and Procedures

The methodology used in calculating pore volume compressibility is straightforward. It is calculated from three other measured values, as demonstrated in Table 4.2.2. The limitations of the methodology are due mainly to limitations in determining the averages of the individual parameters, rather than in the method of measurement. Several measurements are needed to obtain meaningful averages. The average for Poisson's ratio is the least well-defined parameter.

4.2.7. Adequacy of Application

The application of the concept of pore volume compressibility appears to be appropriate. It is frequently used in hydrologic modeling. The concept appears to be appropriate for SMC to the extent that it is appropriate to apply it to the geologic materials that are in the potential flow path from any pressurized zones to the repository, and from the repository to the accessible environment, taking into account human intrusion scenarios. The Panel, however, has not investigated how and where this parameter is utilized in WIPP performance assessment calculations. Such an investigation is beyond the scope of this review.

4.2.8. Accuracy of Calculations

The value of pore volume compressibility of $1.2\ \mathrm{Gpa}^{-1}$ on the Form 464 was checked by the Panel, using the formulae listed in Section 4.1 (see Line A, Table 4.2.2), and the calculation was found to be accurate, based on the data used.

4.2.9. Validity of Conclusions

The pore volume compressibility is derived from three other measured parameters. Two of the three parameters, Young's modulus and porosity, are reasonably well defined. Only four measurements were made of Poisson's ratio for SMC, however, so its accuracy is not as well known as the other two parameters.

The Panel's best estimate of pore volume compressibility based on the available data is 0.9 GPa^{-1}. This is reasonably close to the 1.2 GPa^{-1} value chosen by SNL (Form 464, Parameter #2464), but the Panel's estimate includes new data taken from Pfeifle, Hansen, and Knowles (1996). SNL's value likely lies close to the upper bound for SMC.

In addition to its use as a shaft seal in four main locations, SMC also will be used to construct the monolith at the bottom of the shaft. The concrete in the monolith will be vibrated during placement and it is assumed that quality control of concrete during construction will ensure that a porosity of about 5% is maintained. Hence, for practical purposes, a value of pore volume compressibility of 0.9 GPa^{-1} can be applied to all three applications of SMC (this value applies to Parameters #2464 (CONC__T1), #2481 (CONC__T2), and #3052 (CONC__MON)).

4.2.10. Dissenting Views

None

4.3. Bulk Modulus of Crushed Salt

4.3.1. General Evaluation

The parameter evaluated here is the bulk modulus of salt, which is used in the PA calculation of crushed salt shaft seal pore volume compressibilities and permeabilities at specified times after emplacement. The bulk moduli developed for these calculations are presented in Table 4.3.1 (RE/SPEC, 1996).

Bulk modulus is the property that relates volume changes of a material to changes in mean stress or pressure. Bulk modulus can be measured directly from a drained hydrostatic compaction test in which the mean stress is increased and changes in volume are measured, or it can be calculated from other elastic properties such as Young's modulus and Poisson's ratio. In the sealing materials studies for WIPP (RE/SPEC, 1996), bulk moduli for salt have been estimated by fitting a curve (Figure 4.3.1) to hydrostatic test results of compaction of crushed salt from Holcomb and Hannum (1982) and RE/SPEC

(1996), and to a bulk modulus for intact WIPP rock salt recalculated from values given in Sjaardema and Krieg (1987) on the basis of new density measurements by Brodsky (1994B). The model employed for curve fitting is from Sjaardema and Krieg (1987). The constitutive relationship represented by the model was used to calculate bulk moduli for mid-seal depths (515 m) for times after emplacement of 0, 50, 100, 200, and 400 years for calculation of permeability values for handoff to the performance assessment (Table 4.3.1).

Table 4.3.1. Best Estimators for Bulk Modulus of Compacted Crushed Salt at a Depth of 515 m

Time After Seal Emplacement (Years)	Density[a] ($kg\ m^{-3}$)	Bulk Modulus (GPa)
0	1,944	5.74 [b]
50	2,038	10.60 [b]
100	2,121	18.22 [b]
200	2,160	20.67 [c]
400	2,160	20.67 [c]

[a] After Chieslar [1996].

[b] Calculated from Equation 5-1 (after Sjaardema and Krieg [1987]).

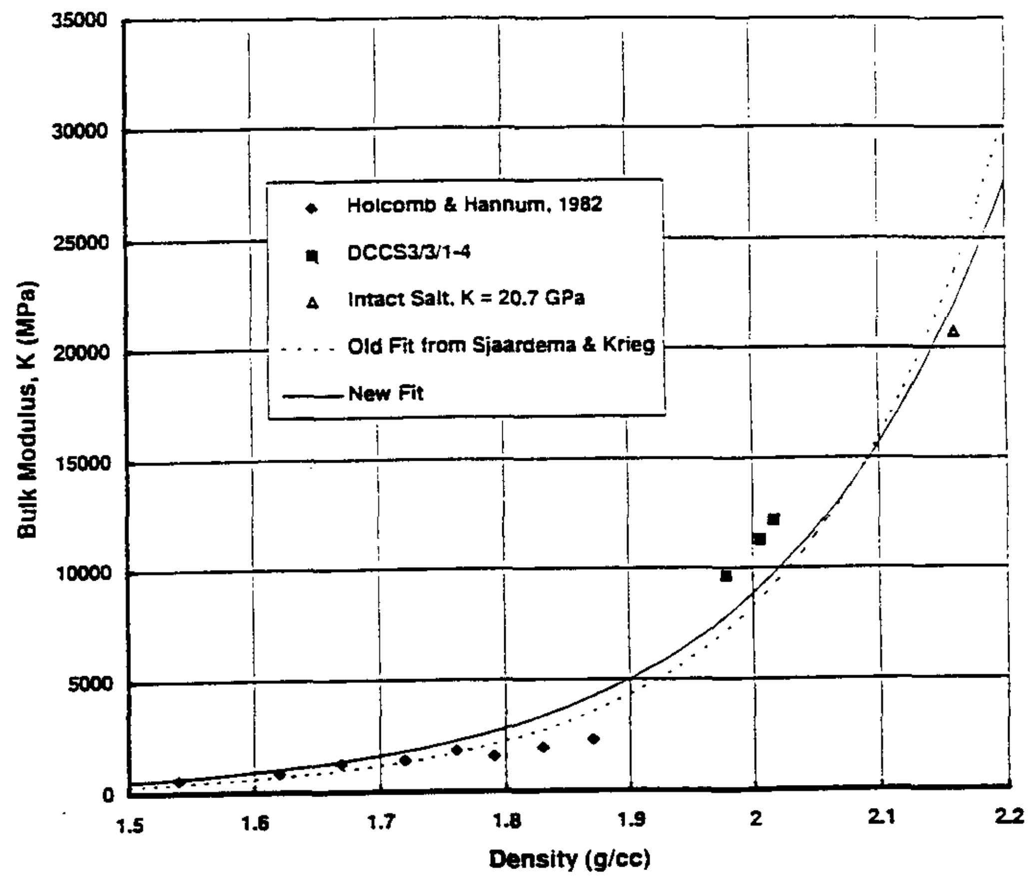
[c] Bulk modulus of intact salt.

From RE/SPEC 1996

Densities for this calculation are from Chieslar (1996). The fit of the experimental data to the curve predicted by the modified Sjaardema and Krieg model displays some systematic scatter (Fig. 4.3.1). Callahan et al. (1996) attributes this misfit between the model and experimental results to the absence of shear compaction data in the Sjaardema and Krieg model and considers two alternative models (Zeuch 1990, Speirs and Brzesowsky 1993) using some yet-to-be qualified data and some recent (qualified) experimental data. The Zeuch and Spiers models (modified) and the modified Sjaardema and Krieg models are not greatly different in terms of predicted strain versus time behavior. None of the models fit the strain/time curves for shear compaction well, perhaps reflecting the inclusion of questionable data from the Zeuch tests. It appears that the Sjaardema and Krieg model fits the hydrostatic test results acceptably and the resultant constitutive equation is an acceptable and conservative basis from which to predict moduli for seal consolidation.

4.3.2. Adequacy of Requirements and Criteria

The bulk moduli are intermediate parameters in the calculation of seal permeabilities. The methodology is to fit a curve to preexisting data (Figure 4.3.1) and use the resulting empirical constitutive relationships to calculate moduli. The quality of the plotted data and scatter about the fitted curve must be acceptable



from RE/SPEC, 1996

Figure 4.3.1. Bulk Modulus Versus Density for WIPP Crushed Salt

for the results to be credible. Only the Holcomb and Hannum data were not developed under acceptable SNL quality assurance (QA) protocol.

The objectives of the Holcomb and Hannum (1982) Quasistatic (Hydrostatic) tests were to determine whether saturated crushed salt was impeded in its consolidation by trapped pore brines. It is apparent from the results of the tests conducted under excellent scientific protocols that some reduction in the rate of compaction occurred at higher fractional densities due to trapped pore waters. This condition occurred when drainage stopped during a drained test before all the water which had been added to the crushed salt specimen was expressed. Compaction did proceed, however, at a reduced rate. This reduction of rate may account for the deviation of bulk moduli at the higher densities achieved during testing from the Sjaardema and Kreig curve (Figure 4.3.1). The results were consonant with Holcomb and Hannum's objectives and provide an understandable basis for evaluating their results relative to the constitutive model of Sjaardema and Kreig.

4.3.3. Assumptions

Sjaardema and Krieg (1987) have developed a nonlinear elastic model and fitted it to the Holcomb and Hannum (1982) data to define material constants for use in an empirical exponential relationship [$K = K_o \exp(K_1 \rho)$] to define bulk modulus, where K_o and K_1 are empirical material constants based on curve fit and ρ is density. This relationship was subsequently fit to the results of laboratory determinations of the bulk modulus of compacted salt from the Dynamic Compaction of Crushed Salt (DCCS) Experiment (RE/SPEC, 1996, and Hansen and Ahrens, 1996) and a newly determined value based on a new determination of the bulk density of intact Salado salt (RE/SPEC 1996, Brodsky 1994B) (Fig. 4.3.1). The primary assumption in the development of the moduli (RE/SPEC, 1996) is that the modified curve fits the experimental data well enough to validate the use of the derivative equation and materiel constants to adequately calculate the needed bulk moduli for handoff to the performance assessment. Holcomb and Hannum's (1982) data fit the curve very well at low densities but the trend of the data diverge from the curve at the middle of the density range (Fig. 4.3.1). The DCCS results lie significantly above the curve at densities around 2g/cc. The corollary assumption that the data are valid and adequately represent the variability of distribution of bulk moduli of compacted crushed salt for the defined conditions is central to the acceptance of the calculated moduli (Table 4.3.1) and their usefulness in predicting shaft seal consolidation.

The assumption that the Holcomb and Hannum data are representative is central to modulus development and those data are subject to some qualifications. Holcomb and Hannum's (1982) data were rejected by the IRT review primarily on the grounds of the absence of complete QA documentation. The quasistatic tests excerpted from the data for bulk modulus calculation were developed under adequate scientific protocol and controls which are equivalent to the general requirements of the current QA structure. Technical comments from that review show that some concern exists about specimen homogeneity. The specimens were constructed by loading "mine run" salt below the size of 1 mm into the sample sleeves (14 mm) without regard for sorting. The blockage of specimen drainage at a late stage of the test may also have affected results.

The DCCS data were developed under the current SNL QA plan and are fully qualified. The data are, however, from an experiment which consisted of weight-drop dynamic compaction of a large volume of crushed salt (Hansen and Ahrens, 1996). This compaction methodology may not have produced homogeneous compaction of the highly unsorted salt used in the experiment. Compaction under strong dynamic loading may have significantly changed grain size distribution. The relatively central fit of the curve and the existence of data over much of the range of densities from densities of 1.5 g/cc to 2.16 g/cc implies a reasonably good fit to the model of data having potentially significant variability as a result of experimental procedure and the calculation of the intact salt bulk modulus from non-Salado literature values (see Section 4.3.2).

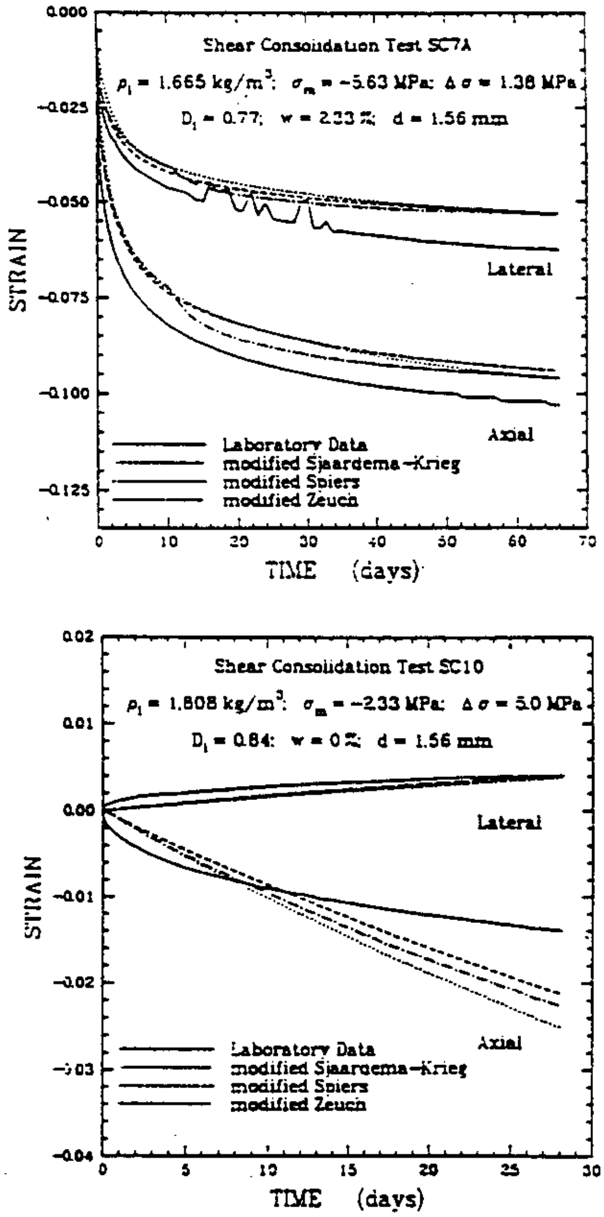
4.3.4. Alternate Interpretation

Callahan et al. (1995, 1996) have considered alternative models to the Sjaardema and Krieg model, principally models that incorporate shear compaction (Zeuch 1990, and Spiers and Brzewowski 1993) and that specifically identify micro-mechanical strain mechanisms such as pressure solution. Modeling results from Callahan et al. (1996) imply relatively small differences between the predicted behavior of the alternative models and a poor fit between all the models and the experimental results (Fig. 4.3.2). The poor fit to the experimental data may be due to the inclusion of shear test data from Zeuch (1990) which Zeuch identifies as aberrant and internally contradictory. The consideration of alternative models does not indicate that the Sjaardema and Krieg model is inadequate or erroneous, nor is there any apparent advantage in using the alternative models.

M

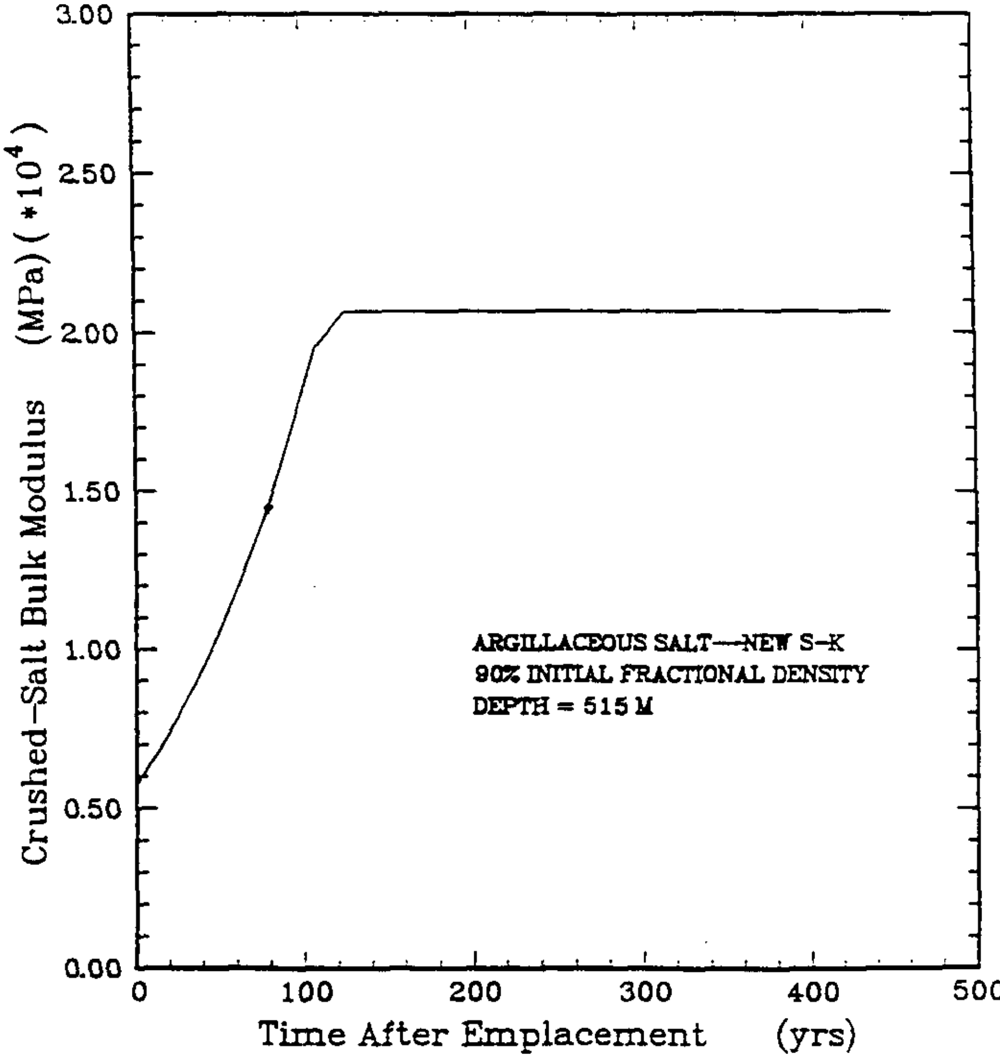
4.3.5. Uncertainties and Consequences

Uncertainty in this parameter is represented by the scatter of measured bulk modulus/density plots about the corrected (new fit) curve shown on Figure 4.3.1. At low and high densities the fit is very good, with increasing uncertainties in the mid-range of the curve. The intact salt bulk modulus in this plot was re-calculated from rock salt bulk modulus values from the literature for non-Salado salt (Hume and Shakoor, 1981) and densities measured for Salado salt by Brodsky (1994). Bulk moduli predicted by the modified Sjaardema and Krieg model, combined with fractional density predictions from Chieslar (1996) imply that the crushed salt-seal material at the midshaft region (515m depth) will reach *in situ* salt densities (and perhaps permeability) in about 140 years (Fig. 4.3.3). This is very early in the predicted brine-inflow and gas-generation histories predicted for the repository. Further, the sense of the uncertainty represented by the DCCS data in the mid-range of the model is toward more rapid densification. It appears that the consequence of uncertainty is not great if compaction were a little slower than predicted and the only available indicator of uncertainty (relative weight of data scatter)



from Callahan et al., 1996

Figure 4.3.2. Comparison of Model Predictions and Experimental Data



from RE/SPEC, 1996

Figure 4.3.3. Bulk Modulus Versus Time for the Compacted Crushed Salt Column at a Depth of 515m

implies that the consequence of uncertainty in the region of most uncertainty is toward more rapid compaction.

4.3.6. Appropriateness and Limitations of Methodology and Procedures

With regard to the Holcomb and Hannum data, specifically the quasistatic tests, there are no recognized standards such as ASTM. These tests were among the first of their kind. The quasistatic tests were performed according to appropriate methods and met the needs of the intended use of the data.

4.3.7. Adequacy of Application

The test procedures were correctly implemented and irregularities were identified and described. Predictable variation in the behavior of late stages of Holcomb and Hannum's testing may have resulted in departure of the calculated bulk moduli from the Sjaardema and Kreig curve. These departures were related to elevated pore pressures caused by the entrapment of brine in the interstices of the crushed salt specimens. This was an expected experimental result and the influence on the data was noted. Data points were sufficient, traceable and consistent. The data are adequate to the intended use and their PA application is appropriate.

4.3.8. Accuracy of Calculation

Calculations of bulk moduli from the data (Table 4.3.1) were simple and accurately made. A revision of the curve resulting from the constitutive model shown in Figure 4.1 was appropriately made when a critical parameter (density of intact rock salt from WIPP) was revised.

M

4.3.9. Validity of Conclusions

The relationship represented by the analyses of data from Holcomb and Hannum and other qualified sources (Hansen and Ahrens, 1996 and Chieslar, 1996, and Brodsky, 1994B) are purely empirical in nature. Some scatter of the data is apparent, but the sources of scatter appear to be inherent in the testing and the calculation of the intact modulus from non-Salado literature values and probably do not represent significant sources of error in the basic constitutive relationship (Sjaardema and Kreig, modified) used to calculate parameters for performance assessment. The moduli shown in Table 4.3.1 are valid for their intended use.

4.3.10. Dissenting Views

None

4.4. Permeability of Crushed Salt

4.4.1. General Evaluation

The parameter being evaluated is the permeability of crushed salt, which is time dependent. The Form 464 values are given in the last three columns of Table 4.4.1.

Table 4.4.1. Crushed Salt Permeabilities

	RE/SPEC, 1996, m^2			RE/SPEC, 1996, $\log_{10} m^2$			Form 464, $\log_{10} m^2$		
Time	**lower**	**"best"**	**upper**	**lower**	**"best"**	**upper**	**lower**	**median**	**upper**
0 to 10							-17.301	-14.7825	-12.2652
10 to 25							-17.301	-14.7825	-12.2652
25 to 50							-17.301	-14.7825	-12.2652
0 to 50	5.00E-18	1.65E-15	5.43E-13	-17.301	-14.7825	-12.2652			
50 to 100	1.33E-23	6.83E-18	1.12E-14	-22.8761	-17.1656	-13.9508	-22.8761	-17.1656	-13.9508
100 to 200	1.33E-23	5.27E-20	3.75E-16	-22.8761	-19.2782	-15.426	-22.8761	-19.2782	-15.426
200 to 10,000	1.33E-23	5.35E-21	2.15E-18	-22.8761	-20.2716	-17.6676	-22.8761	-20.2716	-17.6676

Crushed salt will be used as a major component of the shaft sealing system over a 170m depth interval in the Salado formation. Screened (for elimination of coarse material) mine-run salt will be dynamically compacted along with a small amount of added water (about 1% by weight) and then allowed to compact further with time by the natural forces of creep closure of the shaft walls. This is all for the purpose of creating a very low-permeability shaft seal. Because the crushed salt interval is an important part of the seal system, its permeability as a function of time is an important part of PA calculations.

Crushed salt permeability as a parameter is described as a log triangular distribution of values over six time intervals: 0-10 years, 10-25 years, 25-50 years, 50-100 years, 100-200 years, and 200-10,000 years. Full consolidation (and the lowest permeability) is assumed to be reached at 200 years. A recent compilation and explanation of the crushed salt permeability values to be used by WIPP is provided by RE/SPEC (1996), although some work is still ongoing. The values in the RE/SPEC document (p. 47) correspond exactly to the values in the WIPP PA Form 464 for ID Numbers: 2940-2942, 2948-2950, 2956-2958, 2964-2966, 2972-2974, and 2980-2982. The values from both of these sources are listed in Table 4.4.1. Note that although six time intervals are listed in the table, the values for the first three

Form 464 intervals (times up to 50 years) are identical, so only four unique intervals are actually used by WIPP.

The method of determining crushed salt permeability vs. time involves several steps. In the first step, various measurements of crushed salt permeability versus "relative density" (sometimes called fractional density) are obtained (Brodsky, 1994A; Hansen and Ahrens, 1996; and Brodsky et al., 1996). Relative density, as defined here, means the density of the crushed salt as tested, divided by the density of the "intact" salt, determined to be 2160 kg/m^3 by Brodsky (1994B). (The actual measured densities of the intact salt had variations of about +10/-30 kg/m^3 from this value.) Intact salt, as defined here, may contain pore space (about 1% or less), may be either clean or argillaceous, and is assumed to be at the equilibrium long-term density of salt at the site. In the second step, crushed salt density versus time is predicted by a creep compaction model as outlined in RE/SPEC (1996) (but not itself a subject of this review). In the third step, the time-dependent densities thus obtained are expressed as time-dependent permeabilities by assuming that density and permeability are uniquely related. Finally, error analysis is used to assign a probability distribution to the results. The values finally reported also appear in Sandia WIPP, 1996.

Several different types of permeability measurements and samples were used to obtain the raw data. These included brine permeabilities on laboratory-made and compacted specimens, and gas permeabilities on field-precompacted specimens from three different dynamic compaction demonstrations. One permeability measurement was actually made *in situ* in the dynamic compaction chamber. In all, 27 measurements are represented, as shown in Figure 4.4.1. The values in Figure 4.4.1 are from RE/SPEC (1996).

The power-law trend line in Figure 4.4.1 (created for this review using the Excel spreadsheet) is similar to the trend line used to generate the current permeability values used by WIPP, as shown in the references. Statistical analysis by WIPP then gives the maxima and minima used to generate the final parameter values. (Please note that the trend line shown in Figure 4.4.1 is derived independently of WIPP analyses and is shown for purposes of the present discussion only.)

Since both the sample preparation and test methods are distinctly different for the two types of permeability tests, it may be legitimate to develop two independent trend lines for the two sets of test results. These lines are shown in Figure 4.4.2. Although the multiple trend lines are close to falling within the overall limits for permeability specified by WIPP, they do not actually fall within those limits. Furthermore, the long-time low permeability trends, corresponding to the highest fractional density values, are especially different from those specified by WIPP. In particular, the higher value implied by the gas permeabilities is above the WIPP range. The causes and ramifications of this discrepancy will be discussed further below.

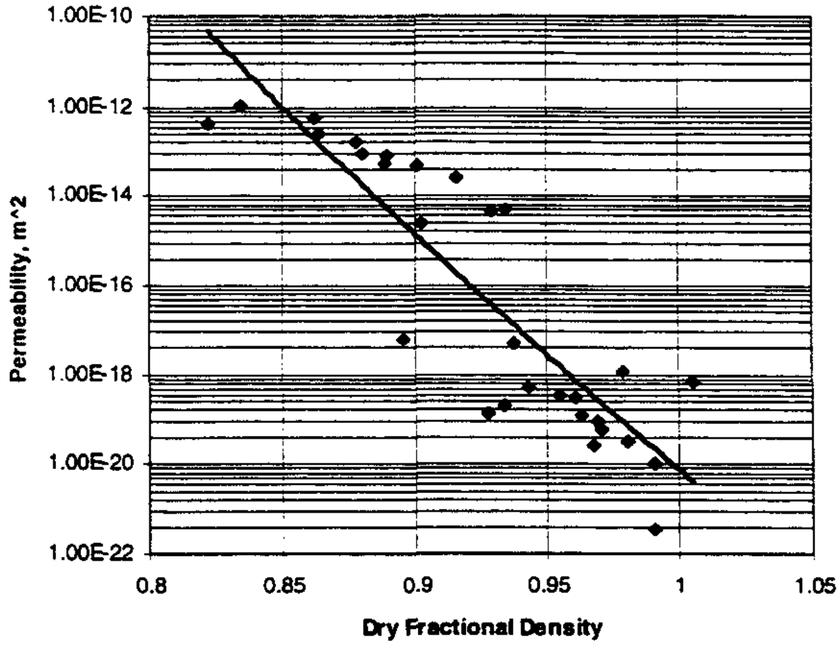


Figure 4.4.1. Crushed Salt Permeability Data, With Single Power-Law Trend Line

The brine permeability test results reported by Brodsky, 1994A, and emphasized at the bottom of Figure 4.4.2, had considerable variability and were questionable with regard to reproducibility because of time-changing values. The majority of these test specimens were prepared by screening and saturating mine-run WIPP salt, followed by hydrostatic pre-consolidation in the pressure vessel. Most of the permeability tests (to brine) showed a high initial flow rate, which then decreased after a number of days. Discounting storage mechanisms (which were not discussed but should have ceased within this period of time), solution/precipitation was identified as the likely cause of the decrease, and only the early time (higher values for permeability) were suggested for use (and shown in Figure 4.4.1), although all were reported in the original document. Another mechanism of systematic error not discussed is that flow during permeability measurements in granular specimens is frequently hindered by the motion and or rotation of grains. The relatively high confining pressures and long times of these tests may restrict this effect, but it cannot be completely discounted.

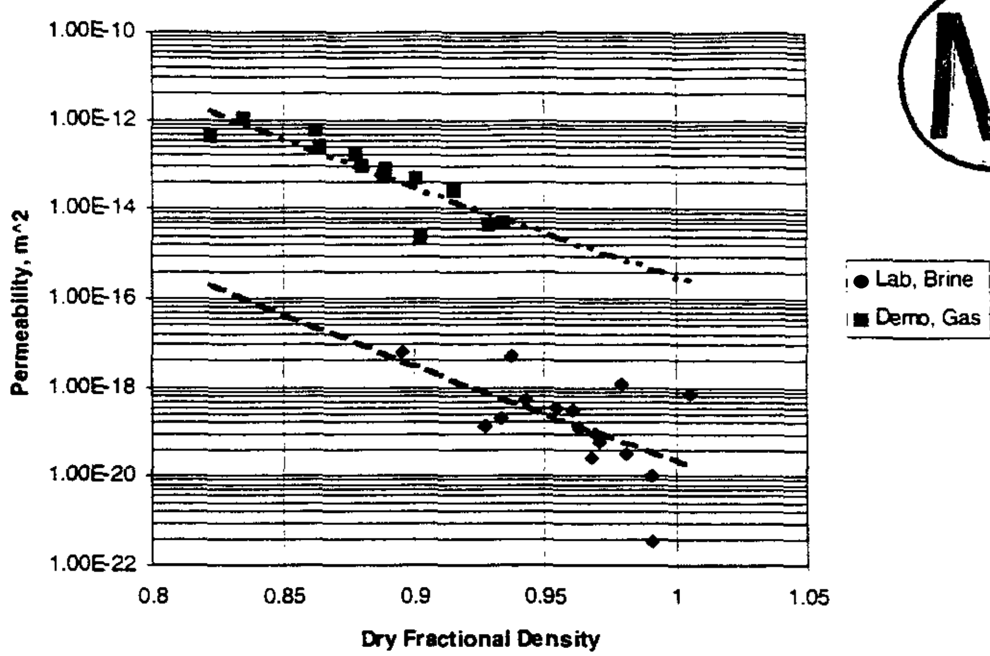


Figure 4.4.2. Crushed Salt Permeability Data (Same Data as Figure 4.4.1), With Two Power-Law Trend Lines Representing Brine Permeabilities on Lab-Prepared Samples and Gas Permeabilities on Field Demonstration Samples

The gas permeability test results reported by Brodsky et al. (1996) and emphasized at the top of Figure 4.4.2, seem to have less variability and were possibly more reproducible than the brine permeability tests, although the raw data were not made available for this review. These test specimens were prepared (preconsolidated) by SNL in several medium- to large-scale field dynamic consolidation demonstrations from which intact samples were taken and cored. In all of these specimens, larger particles would have been present in the original mixes, and extreme particle size distribution changes would have been caused by the method of preconsolidation (as compared to the laboratory hydrostatic method). The laboratory tests then consisted of further dry consolidation under hydrostatic conditions, along with gas permeability tests. These values appear high as compared to the brine values. A possible reason for this is that the field-compacted specimens might have been unusually dry when finally tested in the laboratory (Pfeifle and Hansen, 1996), and therefore not representative of the permeability/density relation that would be obtained by damp compaction of the field specimens, as will actually occur in the shaft.

4.4.2. Adequacy of Requirements and Criteria

Specifying crushed salt permeability versus time is an important part of the shaft seal performance assessment, and may be used elsewhere in WIPP as well. This requirement is therefore adequate.

Specifying that predicting a density-time relationship is sufficient to predict a permeability-time relationship via density-time coupling, without full experimental or theoretical justification, may not be adequate, although recent work (Pfeifle and Hansen, 1996) suggests that positive progress is being made to support this adequacy.

4.4.3. Assumptions

The main assumptions of the current analysis appear to be that (a) intact density is the same everywhere, (b) the experimental results using very different sample preparation and test techniques may be treated as part of the same data population, and (c) the relationship of permeability to fractional density is unique and is time- or structure-independent. Assumption (a) is weak but not damaging since density variations are not large. Assumptions (b) and (c) have strong effects which could lead to results outside of the currently stated range of crushed salt permeability values.

4.4.4. Alternate Interpretation

The alternate data interpretation issue centers around whether the single trend line in Figure 4.4.1 or the multiple trend lines in Figure 4.4.2 are most appropriate. The WIPP project has chosen a trend like the single one shown in Figure 4.4.1. The reasons for the approach chosen by the project is not well-established in the current documentation. New data (Pfeifle and Hansen, 1996) may indicate that the extreme dryness of the original gas permeability specimens may make those results (the upper trend line in Figure 4.4.2) by themselves uncharacteristic. This would tend to support the single-trend line. Another argument in favor of the single-trend approach is that all available data should be considered without bias. However, a counter argument also can be made that the sample preparation and test technique for the two types of data are so different that the existence of two completely separate sets of results must be considered seriously, as suggested by the two trend lines shown in Figure 4.4.2. If new data then become available, they should be assigned to the most appropriate population. The Panel could identify no overwhelming scientific or engineering reason why a single-trend line should be chosen instead of the two based on the current published documentation. This is not to say that the WIPP-chosen interpretation is wrong, but simply to say that there may be a reasonable alternative, or that more data should be examined.

If the upper-trend line in Figure 4.4.2 were chosen instead of the single-trend line in Figure 4.1.1, the crushed salt permeabilities at long times would be higher than are used now to provide the parameter values. This interpretation might be questioned, in that the consolidated permeabilities from this trend are much higher than most measurements of undamaged intact halite permeabilities. This either means that the data are suspect, or that the method of consolidating crushed salt to near *in situ* densities by the method used and in the time period involved does not create the same decrease of permeability as natural consolidation over longer time periods. That is, although the porosity is reduced as expected by the laboratory tests, narrow flow channels do not close as compared to intact salt. One would expect such flow channels to close eventually with time, but then the assumed method of using density/time predictions to directly create porosity/time predictions is brought into question. Perhaps a safer method of data interpretation, lacking additional data, would be to use both trend lines in Figure 4.4.2 to establish a new range of crushed salt permeability values. Or, an alternative method of correlating permeability with time other than the unique permeability/density relationship might be considered. Certainly, one reasonably expects near-intact permeabilities to be reached at some time. The question is whether this occurs by the 50-200 years currently modeled, or after a longer period. Recent data (Pfeifle and Hansen, 1996) may suggest that the upper trend drops to much lower permeabilities at high relative densities in damp specimens. Perhaps a third trend line might exist (were there enough data) for field dynamic compaction samples that are maintained at the appropriate water content of about 1% by weight. This third trend line might resemble the first trend line in Figure 4.3.1 and thus justify the current WIPP parameter choice.

Even if the data population interpretation issue were settled on the above grounds, the issue of alternate interpretation remains, stemming from WIPP's assumption that density-time uniquely relates to permeability-time. In support of this assumption are the photomicrographs (Brodsky, 1996A) showing that flow channels close by pressure solution in the dynamically compacted specimens as they are further compacted in the laboratory, but this interpretation has not been discussed or supported in the documentation.

4.4.5. Uncertainties and Consequences

Based on the original assumptions and analyses presented in the documentation, uncertainties in the data are appropriately carried through to create the PA parameter ranges. In this sense, the uncertainties and their consequences in terms of a distribution are clear. However, alternate interpretations, as discussed above, may introduce larger uncertainty ranges. In particular, a higher mean and upper limit of crushed salt permeability may exist for longer times than is now currently used, unless new data, now forthcoming, decrease this uncertainty. Without new data and further data analysis, the crushed salt seal may have to be assumed to be more permeable with time than currently specified. Only PA calculations can determine the ultimate importance of this change, should it be made.

4.4.6. Appropriateness and Limitations of Methodologies and Procedures

Permeability/compaction testing on these types of specimens is very difficult. The work to date is appropriate and is apparently state-of-the-art but, as discussed above, this may not yet be enough. Limitations exist in determining the best methods of permeability sample selection, sample handling compaction method, and test method, in showing data accuracy and reproducibility, and in determining the best method of data analysis and parameter prediction. Therefore, although the fully published work done to date is appropriate, it is overly limited in its quantity and scope. Work underway would seem to be addressing this problem.

4.4.7. Adequacy of Application

Based strictly on the original assumptions (which here have been brought into question), the application is adequate. When the questioning of assumptions is allowed, the presently published data are not sufficient to support the application of current permeability-time predictions. Emerging data and interpretations may resolve this issue.

4.4.8. Accuracy of Calculations

The calculations in the original brine-flow test program, based on the reports, appear accurate. The conversions to relative density relationships are somewhat adversely affected by the assumption of only one intact density, but this does not appear critical. The Panel cannot assess accuracy of the latest gas-flow tests because detailed data reports were not available. The accuracy of final long-term permeability results are brought into question by the choice of assumptions and interpretations discussed above.

4.4.9. Validity of Conclusions

To obtain the permeability-time parameter values, appropriate test data were obtained and reduced by accepted methods. However, the currently published conversion of the test data into the Form 464 pass-off values to PA are severely in question because of the reasonable alternate assumptions and interpretations that are possible (discussed above), but are not yet fully addressed by the project. In particular, the high end of the long-term (times greater than 200 years) permeability distribution range may be too low. The Panel therefore finds that the conclusions as currently drawn, based on published reports and PA handoff, with regard to long-term crushed salt permeability are not fully valid. It appears however, that presently ongoing work, including new tests and data interpretations, may resolve this validity issue in a positive sense. This ongoing work should be fully documented, understood, and reviewed in order to establish the validity of the long-term crushed salt permeability values.

In the opinion of the Panel, the crushed salt permeability data should be re-evaluated by SNL, with the inclusion of the new data and explanation of interpretations as appropriate. The Panel cannot come to a conclusion of validity of the interpretation of these data until such a re-evaluation is done.

4.4.10. Dissenting Views

None

M

4.5. Permeability of SMC

4.5.1. General Evaluation

The intrinsic permeability of SMC is a parameter needed to model the performance of the shaft sealing system.

As described in Section 4.1.1, there are three identical concrete components in the Salado shaft sealing system, each one composed of three elements: an upper concrete plug, a central asphalt waterstop and a lower concrete plug. The overall design length of each component is 15m. There is also a 6m long SMC plug in the Rustler formation. In addition, SMC is used to construct a concrete monolith at the base of the shaft; however, this is not considered to be part of the shaft sealing system (Sandia WIPP, 1996, pp. 25-29).

There are three applications of SMC for which permeability is needed:

- The concrete column in the shaft for the first 400 years (CONC_T1).
- The concrete column in the shaft from 400 to 10,000 years (CONC_T2).
- The degraded concrete monolith at the shaft base (CONC_MON).

The permeability of interest is the permeability of brines passing up and down the shaft. (Generally, gas permeabilities will be at least an order of magnitude higher, i.e., more permeable than brine permeabilities. This depends on a variety of factors, including the moisture content of the concrete).

In general, permeability values are needed in all three orthogonal directions (one vertical and two horizontal). Since SMC concrete is expected to be homogeneous and isotropic, however, its permeability is assumed to be uniform in all directions.

In BRAGFLO, SMC permeability is treated as a triangular distribution during the first 400 years of its life. It is then assumed to degrade immediately and then is treated as a constant (from 400 years to 10,000 years). Permeability is expressed in its log form. The parameters listed on Form 464 and their assigned values are given in Table 4.5.1.

Permeability of Concretes

Concretes are designed to be durable. Lack of durability may be due to internal causes within the concrete itself and/or a variety of external causes. SMC has been specially designed to be durable under the conditions to which it will be exposed in the WIPP. Its success as a seal will depend on many factors, including the quality of construction and its ability to remain relatively impervious for a long period of time, i.e., to maintain a low value of permeability.

The permeability of the paste largely determines the permeability of the concrete. Generally, concrete permeability decreases as the water/cement ratio is decreased, and as the age of the concrete increases and hydration progresses. By way of comparison, Neville (1973, p. 387) quotes typical values for the permeability of concrete used in dams in the U.S. as being in the range of 8 to 35 x 10^{-12} m/s (8 to 35 x 10^{-19} m^2, assuming water to be the permeant).

Test Results for SMC Concretes

RE/SPEC performed gas permeability tests on concrete specimens from an SMC sample batched by the WES and from two cores recovered from the SSSPT at the WIPP facility. The results are summarized in RE/SPEC (1996, p. 14). The permeability of the SMC specimens ranged from 2.1 to 7.5 x 10^{-21} m^2, with an average of 4.71 x 10^{-21} m^2. The SSSPT specimens had a range of 0.3 to 5.0 x 10^{-19} m^2 with an average of 2.18 x 10^{-19} m^2.

Knowles and Howard (1996) have published the results of field permeability tests carried out in the SSSPT boreholes using gas and brine. Overall seal system permeabilities were determined using gas and ranged from 1.0 x 10^{-20} m^2 to 1.0 x 10^{-17} m^2 for tests carried out from 1985 through 1987, and from 1.0 x 10^{-23} m^2 to 1.0 x 10^{-19} m^2 for the 1993 through 1995 tests. Testing using brine gave values of 1 x 10^{-19} m^2 for the 1985 through 1987 tests, and from 1.0 x 10^{-22} m^2 to 1.0 x 10^{-19} m^2 for the 1993 through 1995 tests.

Table 4.5.1 Assigned Values to the Permeability of SMC, as Recorded on Form 464

id	idmtrl	idpram	tblmateri	units	distyp	mean	mode	std dev	max	min
2470	CONC__T1	PRMX_LOG	Concrete column; 0 to 400 years	log (m^2)	TRIANGULAR	-18.8160	-18.7496	0.7550	-17.0000	-20.6990
2471	CONC__T1	PRMY_LOG	Concrete column; 0 to 400 years	log (m^2)	TRIANGULAR	-18.8160	-18.7496	0.7550	-17.0000	-20.6990
2472	CONC__T1	PRMZ_LOG	Concrete column; 0 to 400 years	log (m^2)	TRIANGULAR	-18.8160	-18.7496	0.7550	-17.0000	-20.6990
2486	CONC__T2	PRMX_LOG	Concrete column; 400 to 10,000 years	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01
2487	CONC__T2	PRMY_LOG	Concrete column; 400 to 10,000 years	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01
2488	CONC__T2	PRMZ_LOG	Concrete column; 400 to 10,000 years	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01
3059	CONC__MON	PRMX_LOG	Degraded concrete monolith	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01
3060	CONC__MON	PRMY_LOG	Degraded concrete monolith	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01
3061	CONC__MON	PRMZ_LOG	Degraded concrete monolith	log (m^2)	CONSTANT	-1.400E+01	-1.400E+01	0	-1.400E+01	-1.400E+01

(It appears that SMC is about an order of magnitude more permeable to gas than brine.) These permeability ranges encompass the range of permeabilities measured in the laboratory by RE/SPEC. The permeabilities of the individual seal components were not determined in the field tests. Concrete permeabilities were derived as a result of computer simulations of brine and gas flow behavior.

Derivation of the Intrinsic Permeability of SMC Up To 400 Years

The SMC laboratory data on permeability are very consistent, with an average value of 4.7×10^{-21} m^2 (RE/SPEC, 1996, p. 13). It is possible that the consistency is largely due to the fact that all tests were performed on one batch of SMC prepared in the laboratory under carefully controlled conditions. The wider range of values obtained in the SSSPT may be more representative of the range that will be found when SMC is placed in the field.

By including the SSSPT data set with the SMC data set, RE/SPEC has effectively increased the permeability of SMC to an average value (mode) of 1.78×10^{-19} m^2 (or 38 times more permeable than the laboratory average). This increase in permeability tends to account for the following uncertainties:

- Less procedural consistency (and therefore higher permeability values) when the SMC is placed under field conditions.
- The samples contained some moisture. Drying the samples typically increases gas permeability measurements by 1 to 2 orders of magnitude. This may be largely offset, however, by the Klinkenberg correction, which was not applied, and usually would reduce the gas permeability by about an order of magnitude. Under field conditions the concrete will not be dried out, so the laboratory values of permeability obtained by RE/SPEC are probably representative of the emplaced concrete.
- The tendency for concrete to degrade over time.
- The possibility of leakage at the concrete/salt interface.

RE/SPEC has used the data in RE/SPEC, 1996, p. 14, to determine the probability density function (PDF) for the SMC, defined by a log triangular distribution with a best estimate of 1.78×10^{-19} m^2 and with lower and upper limits of 2.0×10^{-21} m^2 and 1.0×10^{-17} m^2, respectively (RE/SPEC, 1996; Pfeifle, 1996). These values are reasonable and consistent with the SSSPT seal system permeabilities of SMC reported by Knowles and Howard (1996) in Table III.

Permeability of Degraded Concrete

The SMC is specially designed for use as a shaft seal in the Salado formation. Sufficient salt is added as a dry aggregate to saturate the hydration water with sodium chloride. Even without protection it is unlikely that the SMC monoliths will be exposed to large quantities of brine that could cause alteration of the cement paste and removal of mass. The concrete monoliths are protected in the shaft, however, with asphalt and clay, which are designed to almost entirely eliminate any kind of transport of the concrete constituents (Hansen, 1996).

RE/SPEC has largely discounted the function of the concrete after 400 years, assuming that the concrete has deteriorated and is comparable to a dense soil with a permeability range from 1×10^{-17} m^2 to 1×10^{-12} m^2, with a best estimate of 1×10^{-14} m^2 (Pfeifle, 1996). This is similar to the earthen fill used higher in the shaft. These assumptions are conservatively reasonable (i.e., the permeability average will probably be higher than projected, especially in the near to intermediate term of 400 to 1000 years). This value of 1×10^{-14} m^2 is applied to the shaft concrete (CONC_2) from 400 to 10,000 years, and to the degraded shaft monolith (CONC_MON). It is a constant value of permeability and applies to all three orthogonal directions (x, y, and z).

4.5.2. Adequacy of Requirements and Criteria

The performance requirements for SMC have been stated in many documents (e.g., Wakeley, Harrington, and Hansen, 1995, chapter 2; Wakeley, 1994). SNL and WES have worked together to develop a highly placeable and reproducible salt-saturated mass concrete that will bond with the Salado host rock and is designed to be stable in the Salado formation for a long period of time. It is also designed to have a very low permeability initially and for at least 400 years.

4.5.3. Assumptions

It is assumed that appropriate process and quality controls will be maintained when the concrete is mixed and placed underground, and that the SMC samples tested by RE/SPEC are representative of the concrete that will be emplaced during construction of the seals. It is also assumed that the clay and asphalt seals will be constructed as designed so as to afford additional protection to the concrete seals from brine-flow associated damage. It is assumed that there is no significant deterioration in the permeability of the SMC for the first 400 years of its life.

It is assumed that the concrete behaves as designed, so that no shrinkage cracks develop during curing; fractures would likely increase the overall permeability of the concrete mass, since porous flow is assumed rather than fracture flow.

It is assumed that the concrete will act as a rigid inclusion within the Salado formation, and that salt *creep will eliminate the DRZ around the shaft within a short time* (probably a few years) and provide a tight interface with the emplaced concrete. The interface is included in the value of permeability for the SMC, while the DRZ effect is handled in the PA model. It is assumed that the concrete remains in a compressive environment and does not fracture.

4.5.4. Alternate Interpretation

Alternate interpretations include the converse of the assumptions discussed in Section 4.5.3. For example, there may be some geologic circumstances that would place some of the SMC in tension, leading to the development of cracks within the concrete. The tendency for salt to creep, however, and the fact that the SMC is a "stiff" plug in a "soft" environment of salt, argues against significant tension developing in the concrete. This also seems unlikely, based on the experience of placing bulkheads in shafts to control mine flooding in South Africa. Based on evidence in placing mass concrete in bulkheads and gravity dams, shrinkage cracks are deemed unlikely and are avoidable through proper design and emplacement processes.

There is a possibility of minor degradation at the concrete/salt interface. This is expected to be superficial based on decades of experience with borehole plugs, and the experience of building an emergency bulkhead in a salt horse at the Rocanville Mine in Saskatchewan, that has been withstanding 8.7 MPa of hydraulic pressure for over eight years without leakage at the interface. In any case, it has been demonstrated at WIPP that there is a tendency for the salt to creep around a rigid inclusion, eliminating the DRZ and tightening the interface (Knowles et al., 1996).

There is some uncertainty concerning the long-term performance of the concrete because magnesium-rich brines cause degradation of concrete (Wakeley et al., 1994). Degradation is time-dependent, but the time scale for SMC is not known. At the WIPP, stress and strain measurements reported by Knowles and Howard (1996) showed that seal compressive stresses rose rapidly after concrete seal construction and reached steady state in 100 to 200 days. There was no visual evidence of spalling or structural degradation, and the salt-saturated concrete has maintained its integrity for more than 10 years. During extraction of concrete/host rock interface material, breakage occurred preferentially in the concrete seal material rather than along the interface (hence, leakage at the interface is unlikely). In addition, the calculated gas permeabilities showed that in the immediate vicinity of the concrete seal, a disturbed zone did not exist (implying that the DRZ had completely healed). In conclusion, the performance so far has been excellent and bodes well for long-term performance, especially within the 400-year time frame required by PA for this material.

4.5.5. Uncertainties and Consequences

The SMC is an excellent mix for its intended function as a shaft seal in salt. If it is not mixed and placed as designed (i.e., there is poor quality control during construction), it may not function as intended. This is deemed unlikely given the emphasis on quality work and quality assurance in the WIPP program.

The extreme consequences of poor quality control are loss of function of the concrete (i.e., it is not strong enough or impermeable enough to function as an effective shaft seal).

4.5.6. Appropriateness and Limitations of Methodology and Procedures

The procedures used to design the mix and test it are at current state-of-the-art, and were performed by knowledgeable and experienced personnel at WES. However, only five permeability measurements were made at RE/SPEC on a single specimen of SMC. Measurements from other batches are desireable to ensure that these low permeabilities can be reproduced in multiple batches of SMC.

4.5.7. Adequacy of Application

Even though the samples were not dried out prior to determining the gas permeability of the concrete in the laboratory, the moisture conditions in the samples are fairly representative of moisture conditions that will be encountered in the emplaced concrete. Hence, the selected best estimate value of 1.7×10^{-19} m^2 is probably fairly representative of brine permeability.

The laboratory values of permeability were effectively increased to take into account uncertainties in placing the concrete, the tendency for concrete to degrade over time, and the possibility of minor leakage at the concrete/salt interface. This is an appropriate adjustment. The resulting permeability is consistent with the SSSPT field measurements reported by Knowles and Howard (1996).

4.5.8. Accuracy of Calculations

The individual calculations of permeability appear to be accurate. They are based on laboratory tests on SMC specimens and SSSPT specimens. The inclusion of the SSSPT data in the data set increases the permeability derived for the SMC. This produces a conservative overall number for SMC, since lower permeabilities are desireable and, conversely, higher permeabilities are less desireable. This distribution function was calculated by RE/SPEC using equations derived by others. These calculations were not checked in detail; however, they appear to be reasonable and yield reasonable results.

4.5.9. Validity of Conclusions

The permeability of SMC during its first 400 years of life has been defined by a triangular distribution with a best estimate of 1.78 x 10^{-19} m^2, and with lower and upper limits of 2 x 10^{-21} m^2, and 1.0 x 10^{-17} m^2, respectively. This is adequate and reasonable.

After 400 years the concrete is assumed to degrade to the permeability of a dense soil, 1 x 10^{-14} m^2. This estimate is also applied to the concrete monolith at the bottom of the shaft. Although this appears to be a conservative estimate (i.e., the concrete probably will not degrade as quickly in practice), given the uncertainties in predicting the durability of the concrete a long time into the future, the estimate of 1 x 10^{-14} m^2 is not necessarily unreasonable, especially for time periods exceeding 1000 years.

4.5.10. Dissenting Views

None

4.6. Permeability of Compacted Clay

4.6.1. General Evaluation

A large portion of the shaft seals consists of compacted bentonite clay. The intrinsic permeability of the clay is needed to model the performance of the overall shaft sealing system.

The compacted clay columns will be constructed in three locations: the Lower Salado immediately above the shaft station monolith (one interval 28 to 33m in length depending on the shaft being sealed), the Upper Salado between the middle and upper concrete components (102 to 105m in length), and the Rustler formation (approximately 71m in length) (Sandia WIPP, 1996). The permeability of the compacted clay is required by PA for different time periods (0 - 10 years, 10 - 25 years, 25 - 50 years, 50 - 10,000 years).

Depending on the depositional climate, the permeability of natural clays is frequently different in the vertical and horizontal directions. Hence, it is common practice to determine the permeability in three orthogonal directions (one normal and two parallel to the bedding). In remolded clays the permeability is usually isotropic, as in the case of the compacted clay at WIPP.

In BRAGFLO the permeability of the compacted clay is treated as a triangular distribution and expressed in its log form. The permeability parameters for compacted clay contained in Form 464 are shown in Table 4.6.1, together with their assigned values. The best estimate value for the permeability of the compacted clay is 5×10^{-19} m^2.

Permeability of Compacted Clay

Clays are natural materials that are generally stable and have low permeability. In nature, clay layers often comprise the aquitards of natural flow systems and act as natural seals, so it is not surprising that reconstituted clay is being considered as backfill or a sealing agent at the WIPP site.

The specifications for the compacted clay seals in the Salado and Rustler formations is for a well-sealing grade of sodium bentonite (Kelley, Jones, and Ogintz, 1996). The composition is typically 80 to 90% montmorillonite, with the remaining portion dominated by quartz or feldspars. The age of candidate bentonite sources in Wyoming and Canada ranges from 10^6 to 10^8 years (Gray, 1993, pp. 167-168). The seals will be emplaced at a dry density of 1.8 g/cm^3 (112 lb/ft^3) or better.

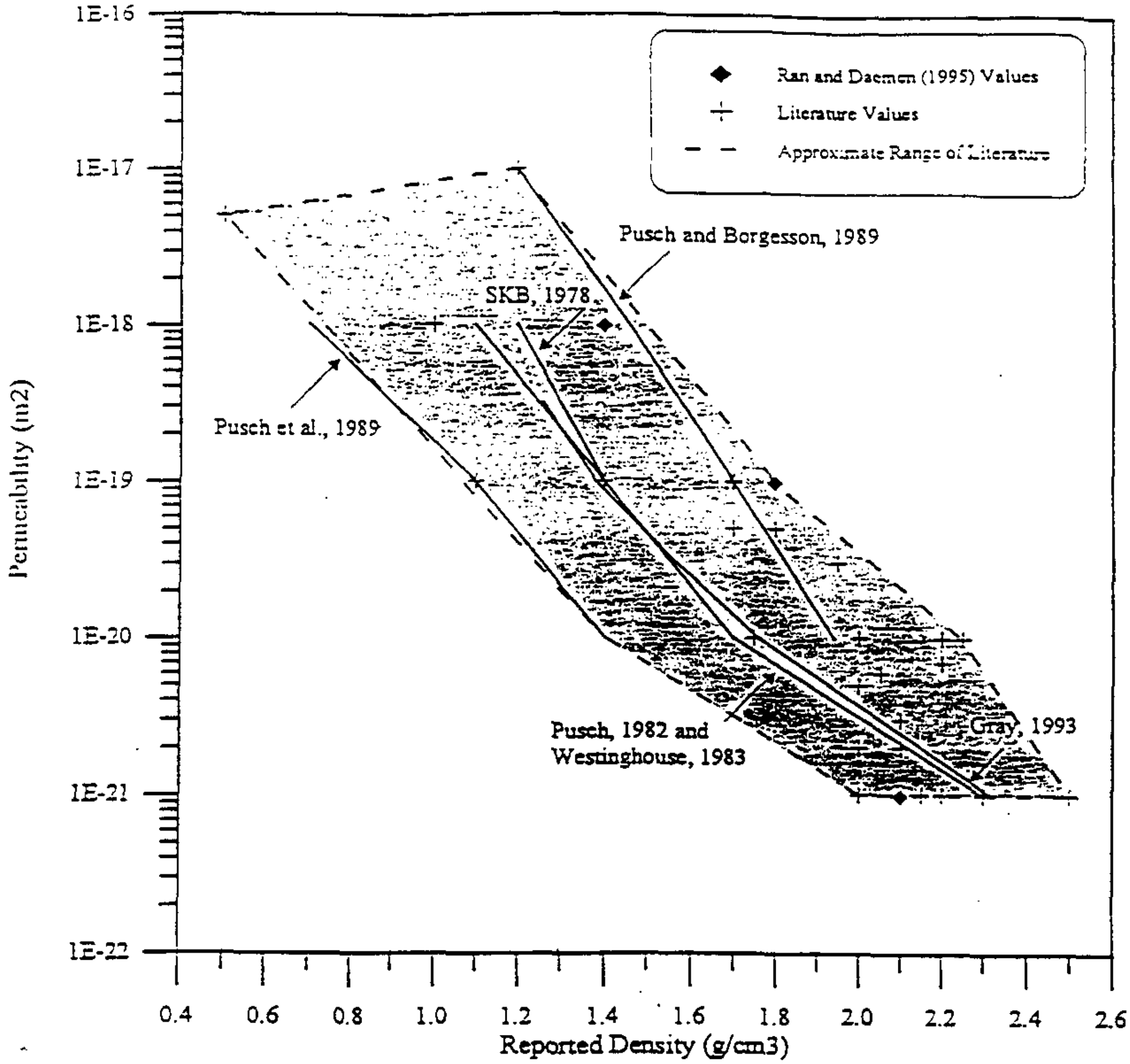
Kelly, Jones, and Ogintz, 1996, have summarized a large body of data from the literature concerning the hydraulic conductivity and permeability of compacted bentonite in Tables 2-1 and 2-2 of their report. The permeabilities are plotted in Figures 2-1, 2-2 and 2-3 of that report, generally as a function of density. Figure 2-3, reproduced here as Figure 4.6.1, shows the relationship of permeability versus density. The permeability of reported bentonites range from 1×10^{-21} to 1×10^{-15} m^2.

Experiments have shown that sand can be added to the bentonite without affecting the overall permeability of the bentonite/sand mix, provided that the clay content remains above 50% and the equivalent dry density remains the same (Cheung, Gray, and Dixon, 1987). Nevertheless, it is the opinion of the Panel that for long-term performance the seals should be as rich as possible in clay minerals and that any dilution with quartzitic materials be avoided (or minimized).

Two factors that affect the permeability of bentonite are the dry density at emplacement and the salinity of the permeant fluid. Work by Ran and Daeman, 1995, for SNL demonstrates how the permeability of bentonite is reduced from 10^{-18} m^2 at a density of 1.4 g/cm^3, to 10^{-21} m^2 at a density of 2.1 g/cm^3. Clearly, higher densities are desirable, and the achievement of low permeabilities in the field will depend largely on emplacement techniques and quality control.

Table 4.6.1. Assigned Values to the Permeability of Compacted Clay, as Recorded on Form 464

id	idmtrl	tblmateri	idpram	units	distyp	mean	mode	std dev	max	min
2385	CL_M_T1	Upper Salado clay; 0 to 10 years	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2386	CL_M_T1	Upper Salado clay; 0 to 10 years	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2387	CL_M_T1	Upper Salado clay; 0 to 10 years	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2453	CL_M_T5	Upper Salado clay; 100 to 10,000 years	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2454	CL_M_T5	Upper Salado clay; 100 to 10,000 years	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2455	CL_M_T5	Upper Salado clay; 100 to 10,000 years	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2351	CL_M_T2	Lower Salado clay; 10 to 25 years	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2352	CL_M_T2	Lower Salado clay; 10 to 25 years	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2353	CL_M_T2	Lower Salado clay; 10 to 25 years	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2368	CL_M_T3	Lower Salado clay; 25 to 50 years	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2369	CL_M_T3	Lower Salado clay; 25 to 50 years	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2370	CL_M_T3	Lower Salado clay; 25 to 50 years	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3078	CL_M_T4	Lower Salado clay; 50 to 10,000 years	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3079	CL_M_T4	Lower Salado clay; 50 to 10,000 years	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3080	CL_M_T4	Lower Salado clay; 50 to 10,000 years	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3009	CLAY_RUS	Rustler compacted clay	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3010	CLAY_RUS	Rustler compacted clay	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
3011	CLAY_RUS	Rustler compacted clay	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2317	CLAY_BOT	Shaft bottom clay	PRMX_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2318	CLAY_BOT	Shaft bottom clay	PRMY_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000
2319	CLAY_BOT	Shaft bottom clay	PRMZ_LOG	log (m^2)	TRIANGULAR	-18.8670	-18.3010	0.7811	-17.3010	-21.0000



(Kelley, Jones and Ogintz, 1996)

Figure 4.6.1. Sodium Bentonite Permeability Versus Density

In general, permeability increases as salinity increases because electrolyte concentration reduces swelling pressure in the bentonite. This effect is less noticeable at higher densities, another reason for achieving high emplacement densities in the field. Kelley, Jones, and Ogintz (1996) recommend that permeabilities measured using fresh water be increased by a factor of 5 to account for the degrading effects of water salinity on the shaft seals. The factor of 5 is based on work undertaken as part of the Swedish (SKB) borehole plugging program (Pusch et al., 1987; see Section 4.6.5); however, it appears to be a conservative number (i.e., a higher factor than expected) based on the work of Cheung et al., 1987, Table 1.

Field Tests at the WIPP

The Series D tests, carried out as part of the SSSPT, tested two 100% bentonite seals in vertical boreholes within the Salado formation at the repository horizon. Each seal was 0.91m in diameter and 0.91m in length. The initial clay densities were 1.8 and 2.0 g/cm^3. Brine pressure differentials of 0.72 and 0.32 MPa were maintained for several years, and no visible brine has been observed at the downstream end of the seals. Knowles and Howard (1996) have reported a bounding calculation of brine permeability for these seals of 1×10^{-19} m^2 (i.e., this is the highest possible value for permeability). Gas flow tests on one of the bentonite seals exhibited negligible gas flow until the test interval pressure exceeded 4 MPa.

Derivation of Intrinsic Permeability of Compacted Bentonite Clay

Kelley, Jones, and Ogintz (1996) have specified the distribution function for the permeability of the compacted clay to be used as seals at the WIPP as follows:

- It is a triangular distribution, in which the maximum and minimum permeabilities are 5×10^{-18} m^2 and 1×10^{-21} m^2, respectively.
- The best estimate is 5×10^{-19} m^2.

4.6.2. Adequacy of Requirements and Criteria

The requirement is to establish a permeability value (or distribution) representative of the emplaced seal material, so that this value can be used in PA calculations.

In the field, the requirements are to emplace the clay so that it is an effective shaft seal with a very low permeability. Natural bentonite is a stable material that generally will not change significantly over a period of 10,000 years. Consequently, it is incumbent upon WIPP not to add anything to the bentonite that will compromise its ability to provide a long-term seal, and to ensure that the bentonite is compatible with the formations (Salado, Rustler) in which it is placed. Moisture content and density must be controlled during emplacement. The specifications call for a minimum clay density of 1.8 g/cm^3 (the calculations allow 1.6 g/cm^3). This must be maintained and verified through standard field control methods for emplacement of soils.

4.6.3. Assumptions

It is assumed that densities achieved will be 1.6g/cm^3 or better; this is achievable. It is also assumed that Salado brines will not cause the permeability of the bentonite seal to increase by more than a factor of five, when compared to tests conducted using fresh water. As discussed in Sections 4.6.2 and 4.6.4, this factor appears to be a conservative number (i.e., it is at the higher end of the range based on current research). Again, it is assumed that the repository environment does not allow the bentonite to dry out and allow shrinkage cracks to develop; this is most unlikely, but if it did occur, re-wetting would immediately cause the bentonite to swell and thereby maintain the seal.

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4.6.4. Alternate Interpretation

Since the flow of brines within the DRZ is accounted for in the PA model, the interface and DRZ effects do not have to be accounted for in specifying the permeability of the clay.

Alternate interpretations include the converse of scenarios discussed in Section 4.6.3. As discussed by Gray (1993), the compacted bentonite seal could be disrupted by externally applied forces, or the internal structure of bentonite could alter to the point where it would be unable to sustain the loads to which it is subjected. Fluid flow properties, including permeability, could be affected by either or both of these mechanisms.

Three internal mechanisms could affect the sealing properties of bentonite: illitization, silification and charge change (Gray, 1993). Illitization is the transformation of the montmorillonite to illite, which involves the substitution of Al^{3+} for Si^{4+} within the montmorillonite layers. Since illite clay crystals are larger than those of montmorillonite, the clays are less active and have a higher permeability. Although there are many uncertainties in estimating the rate at which montmorillonite converts to illite, the SKB work (Gray, 1993) concluded that at 60° C (higher than the *in situ* temperature at WIPP and therefore conservative), there would be negligible transformation over a period of 100,000 years.

Silification is the deposition of silica within the clay structure, which tends to strengthen the clay but can also increase permeability. As part of the SKB work, samples of bentonite were heated and subjected to water pressure in an autoclave to try and accelerate the processes of illitization and silification. Exposing bentonite to an Na-rich solution caused virtually no increase in hydraulic conductivity (1×10^{-7} m/s) at temperatures below 100° C. Also, there was little silification below 100° C. Between 60 and 100° C, the number of water layers found between the clay crystals was reduced from 2 to 1. These tests, together with a study of natural bentonite deposits, indicated that K^+ montmorillonite clays will convert to materials rich in hydrous mica but, in the absence of significant heat, it would take millions of years for the composition of the montmorillonite to be significantly altered.

4.6.5. Uncertainties and Consequences

As part of the SSSPT program at WIPP, bentonite seals have proved effective in preventing the flow of saline solutions. These tests, however, are relatively short term (about 10 years). Extrapolation to 10,000 years is only possible by combining this experience with natural clay analogs.

Stress measurements within a 100% bentonite core seal tested as part of the SSSPT program at WIPP indicated a reduction in stress at approximately 1400 days (Knowles and Howard, 1996, Figure 11). Knowles and Howard suggest that this may be related to ion-exchange with permeant brines in the bentonite fabric. This is under investigation and the impact, if any, is unknown at this time.

Pusch et al. (1987) discuss the effect of chemical composition of the groundwater on the borehole sealing tests at Stripa, using clay rich in montmorillonite from Wyoming with sodium as a major adsorbed cation. Cations from the groundwater can diffuse into the clay plug and replace the initially adsorbed sodium. Another possibility is that salt water, still having sodium as a dominant cation, can increase the salinity of the clay porewater. Both processes cause a drop in swelling pressure and an increase in hydraulic conductivity. Pusch et al. (1987) estimate that for bulk densities in the range 1.8 to 1.9 g/cm^3 (similar to that expected at WIPP), the swelling pressure when passing from the sodium state to the calcium state may drop by 20 to 50%, while the hydraulic conductivity increases 2 to 5 times. They estimate that if the salinity of the clay porewater increases "to that of the oceans" (quite likely at WIPP, especially at the edges of the clay seal), then the hydraulic conductivity could increase 5 times. This is the basis of the factor of 5 for the degrading effects of salinity recommended by Kelley, Jones, and Ogintz (1996), discussed in Section 4.6.1. Mitigating factors at WIPP include the low permeability of the salt host rock (so that little groundwater is brought into contact with the clay seal), and the thickness of the clay seal (which means that any degradation will start at the periphery of the seal and gradually work its way inward). The low permeability of the host rock mitigates against the possibility of erosion and removal of the bentonite, which was a concern in the fractured crystalline rocks at Stripa (Pusch et al., 1987).

The main uncertainty in defining this parameter is the quality of construction at the time the seals are emplaced. Given the emphasis at WIPP on the use of standard operating procedures and quality of work, and the fact that this represents standard construction practice, it need not be a concern.

4.6.6. Appropriateness and Limitations of Methodology and Procedures

The procedures used for determining the permeability of the compacted clay are standard in the industry. There is also a wide body of published results in the literature to back up the value chosen.

4.6.7. Adequacy of Application

Bentonite is a stable, geologic material containing mainly montmorillonite clay, which has remained unchanged in nature for millions of years. When adopted by man for engineering uses it has proved to be an effective seal in the long term.

4.6.8. Accuracy of Calculations

The calculations of permeability are standard in hydrology. They are straightforward, uncomplicated, and appear to be accurate. The fact that there is much data contributed by many different researchers, and that these data are generally consistent, increases the Panel's confidence in the overall result.

4.6.9. Validity of Conclusions

The use of bentonite as a shaft seal is proven technology. For a bentonite seal placed according to standard construction techniques with a density above 1.6 g/cm^3 (the value used in the design calculation, although the construction specifications call for a density above 1.8 g/cm^3), the chosen distribution for clay permeability is appropriate and valid (the best estimate value is 5×10^{-19} m^2). Since properly placed bentonite is not expected to deteriorate with time, this triangular distribution of permeability is isotropic, and applies to all the time-dependent parameters listed in Table 4.6.1.

4.6.10. Dissenting Views

None

5.0 EVALUATION OF DISPOSAL ROOM/ROCK MECHANICS PARAMETERS

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5.1. Initial Density of Waste

5.1.1. General Evaluation

The initial density of the waste (prior to consolidation due to overburden pressure) is needed for the PA. Butcher and Holmes (1995) have derived an overall average value for all waste components of 559.5 kg/m^3, which is currently being used in PA calculations.

The disposal room is treated in the WIPP PA as an area with time-varying porosity driven by creep closure, waste compaction, brine or gas inflow/outflow, gas pressure generation and possible outflow (see Section 5.6). The pore space thus defined can contain both gas and liquid. The room also has certain internal fluid-flow properties (Sandia WIPP, 1992). Waste densities are one group of parameters ultimately needed to determine initial disposal room porosity and changes of room porosity with time. The objective of determining waste densities is therefore clear. For the purposes of this review, waste densities are here defined as "initial" waste densities. That is, they are the densities of waste components as delivered to the WIPP. Although the units are those of a conventional density (kg/m^3) the actual meaning is "mass of solid waste per unit volume of container." Furthermore, these densities are summed into a single total "density" for subsequent calculations. Changes of waste density (if any) during the life of the WIPP are discussed in Sections 5.2 and 5.6. "Waste" is usually defined as the total of waste containers (such as drums) and their contents, although the exact use of the term waste is not entirely consistent throughout the WIPP project literature. (In some cases, waste has been used to describe the solid contents of containers. In the case reviewed here, waste volume includes the solid contents of the containers and the void space in the containers, but does not include the mass of the containers.) Waste densities are listed by Butcher, 1996A, B, and C and derived largely from the current baseline inventory, WTAC, 1995A. They are shown in Table 5.1.1. The solid densities used to derive these densities (by using the individual weight fractions) are provided in Table 5.1.2.

As shown, the waste components are metallics, sorbents, cellulose, rubber and plastics (grouped together), and sludges. The total inventory estimates are not necessarily accurate, because waste has not been characterized and assayed in detail. Instead, some assumptions are made by WIPP in determining waste content and character. With the assumed component solid densities and fractions, as listed in the references, the initial total waste density used for current calculations, as stated above, is 559.5 kg/m^3.

Table 5.1.1. Mass Quantities of Solid Waste Per m^3

Name	Value
Metallic	122 kg
Sorbents	40 kg
Cellulose	170 kg
Rubber and Plastic	84 kg
Sludges	143.5 kg
Total: Initial Waste Density	559.5 kg/m^3

Table 5.1.2. Waste Solid Densities

Name	Value
Metallic	7830 kg/m^3
Sorbents	3000 kg/m^3
Cellulose	1100 kg/m^3
Rubber and Plastic	1200 kg/m^3
Sludges	2200 kg/m^3
Waste Solid Density	1757 kg/m^3

That is, there are 559.5 kg of "solid" waste in 1 m^3 of drum volume. The term solid is here placed in quotation marks because some of the solid waste, such as rags and sludge, contains internal liquid-filled porosity that is considered part of the solid, but in actuality might later become free liquid. From the initial waste densities and component fractions, an initial waste porosity of 0.681 is calculated and used in subsequent calculations of room porosity for input to PA.

5.1.2. Adequacy of Requirements and Criteria

Clearly, a solid density is required as a starting point for any room porosity calculation. This waste density (and its contributing component densities) parameter serves that purpose.

5.1.3. Assumptions

Other than assuming the validity of standard concepts of density and porosity, the main assumptions appear to be: (a) the waste solids do not themselves contain liquids, (b) only contact-handled transuranic (CH-TRU) waste (including drums but no boxes) need be considered, and (c) the volume of steel in the drums and plastic in the liners can be ignored. Assumption (a) will lead to no error in initial density but possibly to a small error in subsequent compaction calculations. Assumptions (b) and (c) could result in some dense material being ignored, thereby leading to a slightly lower initial waste density than may actually exist in the repository. However, in view of other uncertainties in waste content, room geometry, and the ongoing determination of whether or not backfill will be used, these assumptions and subsequent minor inaccuracies do not appear to have any critical effects (see Section 5.1.5).

5.1.4. Alternate Interpretation

A second revision of the baseline inventory report (WTAC, 1995B) is discussed by Butcher, 1996B. Here, the presence of some vitrified waste is assumed, where before it was not. This change increases the proportion of metal-based waste, and therefore probably increases the initial component waste density, but may either increase or decrease waste porosity, depending on the packing density. Because of the uncertainties in composition and packing, and the fact that calculations were already underway, the waste density changes that would be caused by the second revised baseline inventory were not made (Butcher, 1996B.) This omission does not appear to have a major effect on subsequent porosity calculations, in view of the overall uncertainties involved.

5.1.5. Uncertainties and Consequences

From the documentation, it is apparent that the exact composition and proportions of the waste packages to be delivered to WIPP are somewhat uncertain. The present waste density estimates reflect this. However, the present waste density uncertainties are not excessive and do not have any adverse consequences on PA calculations.

5.1.6. Appropriateness and Limitations of Methodologies and Procedures

The basic methodologies for calculating waste densities (and waste porosity) are documented in Butcher, 1996C. These are standard definitions and equations and the methodologies and procedures are appropriate.

5.1.7. Adequacy of Application

The method of incorporating waste densities by adding fractional mass is appropriate and adequate for use in room porosity calculations, which is its use within PA.

5.1.8. Accuracy of Calculations

The present calculations of initial waste density are sufficiently accurate. However, additional accuracy could be achieved by accounting for components according to the current best inventory estimates based on improved waste characterization analysis for waste containers such as drums and boxes. If new PA calculations are required in the future, minor adjustments should be made to account for any new information concerning these factors.

5.1.9. Validity of Conclusions

Conclusions with regard to waste densities are reasonable and valid, as based on current data and assumptions. This validity applies specifically to the initial waste density value of 559.5 kg/m^3 currently used as input to room porosity calculations.

5.1.10. Dissenting Views

None

5.2. Mechanical Properties of Waste

5.2.1. General Evaluation

Closure of the waste disposal room to encapsulate the waste will be resisted by the physical strength, or crush resistance, of the waste containers and waste components within the containers (and also any gas/liquid pressure and backfill in the room). Thus, the mechanical properties of the waste are key to determining the ultimate closure magnitude and closure rate of the room/panel system. These properties are part of the disposal room porosity surface generated by the SANTOS code and used in PA calculations (defined in Section 5.6). In this section, only the waste mechanical properties are discussed.

To allow for systematic and predictable waste compaction, a model is required and the parameters of that model must be determined. If feasible, these parameters should be determined by experiments, since little or no information exists on compaction measurements of these material types or configurations. Such experiments have been conducted by WIPP on simulated waste and are described by Butcher et al., 1991 and Thompson and Luker, 1990. Furthermore, the development and use of an elastic-plastic waste compaction model are described in Weatherby et al., 1991; Sandia WIPP, 1992; Butcher and Mendenhall, 1993; Stone, 1996; and Butcher, 1996A. Following the approach used in these references for the WIPP PA, waste mechanical properties are expressed as five elastic-plastic parameters and a pressure-relative density table (Tables 5.2.1 and 5.2.2).

Table 5.2.1. Waste Elastic-Plastic Constants

Name, Unit	Value
Shear modulus (G), MPa	333
Bulk Modulus (K), MPa	222
Yield Parameter a_0, MPa	1.0
Yield Parameter, a_1	3.0
Yield Parameter, a_2	0.0

Table 5.2.2. Pressure-Relative Density Relationship for Waste (Drums)

Pressure, MPa	$\ln(\rho/\rho_o)$
1.53	0.510
2.03	0.631
2.53	0.719
3.03	0.786
3.53	0.838
4.03	0.881
4.93	0.942
12.0	1.140

The elastic parameters and yield parameters (Table 5.2.1) are assumptions only. Only the pressure-relative density (ρ/ρ_o) values are based on the experimental data, as summarized in Butcher et al., 1991. The parameter values in Table 5.2.1 assure that plastic flow and the onset of compaction occur very early in the loading process and dominate the behavior. Thus, the exact values of the Table 5.2.1 parameters are relatively unimportant, and the Table 5.2.2 parameters dominate the waste mechanical behavior. This method (of assuming the values of elastic and yield parameters and measuring the values of volume compaction parameters) is justified by the fact that the phenomenon of inelastic volume compaction is shown by the data to completely dominate the behavioral regime of relevance.

At first, it may seem that the last value of pressure (12 MPa) in Table 5.2.2 is not high enough to cover the expected range of behavior at the repository depth (where overburden stress is about 14 MPa). However, for SANTOS, the pressure values in Table 5.2.2 are assumed to be mean stress values in the case of axial drum compaction, with no net lateral stress. That is, $P = (\sigma_{axial} + 2\sigma_{lateral})/3$. Therefore, the pressure value of 12 MPa corresponds to a maximum axial stress on the drums of 36 MPa, which is more than sufficient to cover the applicable range of behavior.

5.2.2. Adequacy of Requirements and Criteria

Waste compaction is an important element of room closure and room total porosity determination. Requiring that laboratory measurements be made of the most important aspect of this behavior (the non-elastic compaction) and that the results be evaluated in the form of a model, even given the uncertainties in waste content, is an essential and adequate requirement for this aspect of WIPP modeling.

5.2.3. Assumptions

The main assumptions leading to the identification of waste mechanical properties appear to be: (a) the simulated waste tested is representative (in both type and geometry) of the actual waste, (b) waste compaction is independent of other events or processes, (c) waste compaction is rapid (in comparison to the time required for room closure), (d) the elastic-plastic compaction model chosen to represent behavior is representative, and (e) for purposes of parameter determination, the waste compacts primarily in the axial direction. Certain subsidiary assumptions made during the course of test analysis and modeling are discussed later.

For assumption (a) that the simulated waste tested is representative, the WIPP principal investigators started with the published baseline inventory, and then selected sample types and amounts consistent with this inventory, using local sources of similar materials. Of course, the actual waste will have more variability than the simulated waste tested, and may even be different on average. With regard to assumption (b) the independence of behavior, there may be several ways that this may be violated. The most likely is that corrosion and decay of the waste can cause it to abruptly lose its mechanical strength. Assumptions (c) and (d) are appropriate and require no discussion. With regard to assumption (e) of axial compaction, most of the actual data exist for axial compaction, and room closure will be primarily axial, as is shown by subsequent calculations of the porosity surface (Section 5.6).

Although some of the above assumptions may not be completely valid, none of them change the essential behavior of starting from a set density/porosity, and compacting smoothly to a reasonable end state, which are the important aspects of this behavior. The Panel therefore finds that none of the assumptions are likely to lead to any critical oversight.

5.2.4. Alternate Interpretation

Changes in the assumptions or changes in data reduction procedures (Section 5.2.8) can lead to alternate interpretations. However, clearly, the waste must compact, and the end state of the compaction is to an equivalent of its initial solid volume or slightly less, if internal porosity is accounted for. With room expansion, the waste should rebound within an elastic limit, but for other porous materials, this phenomenon will occur with an equivalent stiffness much greater than its stiffness for compression. Within these bounds of behavior, there is room for other interpretations of the data based on other models. However, all of these interpretations will have similar end points and will likely proceed smoothly between the two end points. This means that alternate interpretations are not likely to cause critical differences in results. For the waste mechanical compaction parameters, it is only necessary to use a data interpretation that provides results in a reasonable, physically realistic range, which the current experiments and interpretations do. Only if PA requires more detailed sampling of the waste mechanical properties (which it currently does not) should alternate interpretations be considered seriously. In the current situation, the interpretation used is adequate.

5.2.5. Uncertainties and Consequences

The waste composition and geometries are uncertain, the effect of packing and compositional variability are uncertain, and the stress state on the waste is uncertain. These uncertainties generally apply to the interpretation of laboratory data for waste mechanical properties as well as to the WIPP itself (except that the simulated waste composition is known in the laboratory). All of these uncertainties could contribute to changes in the resulting data interpretation and model behavior. However, the consequences will be to somewhat alter the shape of the final porosity surface (Section 5.6) but not to significantly alter closure behavior with regard to the performance of the repository. The assumed elastic-plastic parameters are in a reasonable range for a weak porous material and appear to be of little consequence except possibly in the case of room expansion and the associated unloading of waste. Then they would have some effect on the expansion rate. It does not seem, however, from the subsequent calculation of the porosity surface (Section 5.6) that the waste expansion plays a significant role as compared to the elastic and reverse creep properties of the halite. Therefore, no severe consequences result from uncertainties.

5.2.6. Appropriateness and Limitations of Methodologies and Procedures

Two types of waste compaction laboratory data were acquired and described in Butcher et al., 1991, Thompson and Luker, 1990, and associated data packages (WIPP Records Package, WPO26468). These data consist of a fairly large number of small-scale tests on specific materials in a relatively small 4-inch diameter oedometer (a rigid-walled axial compaction device), and four full-scale tests on drums with simulated waste mixtures. (Only two drum tests were used to assist in eventual parameter determination.) The major advantage of using the small oedometer is that a fairly large number of tests could be done to characterize individual waste types and estimate some short-term creep compaction end-points. The major disadvantages of the oedometer are that unknown effects exist related to size scaling, wall friction, and lateral stresses. The major advantage of full-scale drum tests is that they are at full size with realistic waste contents. The major disadvantages of the full-scale drum test are that only a few could be run and no lateral confining stress could be applied. Both test types suffer from unknown effects of packing, sampling, and scale.

The oedometer tests on specific waste components allow the response of a variety of waste mixes to be calculated later, if required, by use of a volumetric mixing law. The major purpose of the small number of drum tests on mixed wastes was to substantiate the use of the oedometer tests to predict drum results.

Considering the limitations mentioned, the test methodology and procedures are adequate to determine simulated waste compaction curves and are certainly much better than pure estimates made without the benefit of laboratory testing. It is highly unlikely that the true compaction curves will lie completely outside the range measured in the laboratory, or far enough from the derived recommended curves to adversely affect appropriateness.

5.2.7. Adequacy of Application

The data and interpretations presently obtained for waste mechanical properties are adequate for use in disposal room porosity surface calculations and as input to PA. If the results of more precise waste characterization become available, waste compaction properties can be re-calculated as required.

5.2.8. Accuracy of Calculations

To establish recommended drum compaction curves, an assumption concerning data interpretation had to be made so that oedometer test results could be re-calculated to become equivalent drum compaction curves. Three methods were attempted: (a) treat the drums as metallic waste in a mixture, (b) use the observed "ring-compaction" geometry to estimate a conversion, and (c) ignore the drums. Method (c) gave the best agreement with data, and was therefore used. That method (a) should produce results that are too stiff, which it did, was anticipated because the thin-walled drums are not as mechanically strong as smaller metallic waste parts. However, why method (c) worked best is not well-explained in the documentation. It is possible that the oedometer tests could be expected to be systematically too stiff, due to size scaling and wall friction effects. If so, a systematic correction in the softening sense would be required to make the drum results agree with the oedometer results. Ignoring the drum itself would fortuitously apply such a correction. This makes the choice of data interpretation model also somewhat fortuitous, but the results still make sense and unreasonable errors are avoided.

Another aspect of the results possibly affecting accuracy is that compaction curves are derived in terms of axial stress on the drums only. In the repository, some lateral stress will certainly exist. Therefore, the issue is to ascertain the importance of shear stresses (proportional to the difference between axial and lateral stresses) on compaction. Butcher et al., 1991, show that assuming the presence or absence of shear stresses may make little difference. However, to reasonably allow for some shear stresses, and yet maintain simplicity, the assumption that lateral stress is zero is made to calculate a final compaction curve. As shown in the Butcher report, this convenient simplification has only a small effect as compared to the variation in results caused by waste composition.

5.2.9. Validity of Conclusions

Many uncertainties exist in measuring and modeling the waste mechanical properties to obtain model parameters. However, some data and/or model relationship is needed to allow the starting waste porosity to translate into the compacted porosity, and to reflect the role the waste plays in resisting closure of disposal rooms. A combination of experimental procedures, assumptions and calculations are used to arrive at the five elastic-plastic parameters given in Table 5.2.1 and the pressure-relative density given in Table 5.2.2. The conclusions and values derived for these waste mechanical properties are substantially reasonable, valid, and useful for the purpose of disposal room closure calculations.

5.2.10. Dissenting Views

None

5.3. Initial Water Content of Waste

5.3.1. General Evaluation

The initial waste water content is a parameter used to quantify the initial source of water in the BRAGFLO calculations for gas generation and transport of radionuclides. It is identified as SAT.IBRN. The value assigned to SAT.IBRN is .015, which represents 1.5% waste container saturation by volume (Form 464, Parameter #669).

Many of the models in the WIPP PA fundamentally require that the waste be characterized for contents of the stored drums, including water content. This need ranges from physical properties including waste strength, density and porosity to inventory such as rags, paper, metals, and woods. The conceptual models dependent on these parameters range from gas generation, nuclear actinide loading, and resistance to room creep closure, to accidental release. Water from the waste drums is added to water from other sources as part of the disposal system (such as brine inflow following repository closure) mostly in order to accurately calculate the time history of gas production that leads to other modeling considerations. Because it is difficult to get an accurate profile of free water in the radioactive waste, this parameter is derived by calculations made from assumed values based on bounding conditions. The lower bound is determined by assuming no water to be present. The upper bound can be assumed to coincide with the limit of free water permitted by the Waste Acceptance Criteria (WAC) for transportation of the waste. This maximum value for free liquids is 1.0% by volume of pure water. A mid value can be computed between these bounds from data acquired by the Idaho National Energy Laboratory (INEL) on Rocky Flats waste.

5.3.2. Adequacy of Requirements and Criteria

The objective was to provide an estimate of the total initial water content of waste for PA calculations. This was done by using assumed water content values per drum, which w[illegible] converted to a percent saturation of available void space in the waste container. Restraints were placed on the actual water content per drum by limiting it to free water, not to include any sorbed waters. This is believed to be due to difficulties in characterizing the waste and determining the amount of moisture it might contain when it is placed in the repository.

5.3.3. Assumptions

The assumption is that the unknown characterized state of the waste inventory requires a designated value. In this case, it is assumed that the waste compacted within the containers is are totally dry, with no adsorbed or absorbed water. The only water to be considered is free water, which is limited by the bounds of 0 to the 1.0% limit for shipping. This water is further assumed to be pure.

5.3.4. Alternate Interpretation

No alternate interpretation of the parameter was found except in regard to the average actual water content as determined by INEL to be approximately 0.181 pints per drum. Calculations showed this average value to be well within the range calculated by the bounding limits.

5.3.5. Uncertainties and Consequences

The uncertainties discussed in sections 5.3.2 and 5.3.3 are important to the parameter value; however, the consequences appear to be insignificant (less than 2.5% of potential brine inflow) when viewed in reference to a brine inflow scenario in which up to 30,000 m^3 of brine flow into the repository during the storage period (a PA assumption).

5.3.6. Appropriateness and Limitations of Methodology and Procedures

Nothing was found to indicate the data input as defined and converted is inappropriate, but it can be constrained by limitations due to problems the U.S. Department of Energy (DOE) has in characterizing the waste.

5.3.7. Adequacy of Application

It is inherent that the presence of water in the drums contributes to the chemistry and gases produced during the repository life. The methodology used to arrive at the actual liquid content of a "typical" drum might be more exacting and definitive if justified by scientific requirements. However, within the context of its overall impact on chemical and gas calculations, the assigned parameter value is believed to be adequate.

5.3.8. Accuracy of Calculations

The calculations that convert the assumed volumes of water in the waste drums were checked and found to be accurate. (The use of six significant digits in some of the numbers below is probably unwarranted.)

Elliott (1993) suggests that because of the availability of INEL database of Rocky Flats Plant (RFP) waste, it would be "more realistic" to use these data than to use bounding water values as previously used. The INEL data base shows values ranging from zero to 0.39208 pints, with an average of 0.18109 pints water per drum (Elliott, 1993). This average is much less than the upper bound established by the WAC of one percent or 4.4 pints per 55-gallon container.

In summary, the SNL calculations show the waste water saturation in the container to be 0% minimum, .060% average, and 1.468% maximum, with the average computed from the INEL data and the maximum resulting from WAC input. For additional conservatism, when additional water from a 5% probability of a one-gallon sealed container of water per drum is included the maximum saturation increases to 1.57%. The parameter value established for WIPP PA use is 1.5% by volume, a compromise between the two maximum computed values. The computations were checked and found to be accurate. It should be noted that the calculation sheet implies a room saturation basis, but true to the parameter need, the value as calculated is actually in terms of percent of available void volume within the waste containers.

5.3.9. Validity of Conclusions

There appears to be no reason for concern that the conclusion of the stated parameter is invalid. However, it should be clear from the comments above that because of the difficulty in obtaining accurate waste characterization data, the waste water content is somewhat subjective. The bounds, as limited by regulation, bracket quite well the available values of water content in waste drums in storage at INEL (Elliott, 1993). Therefore, since the parameter constant, listed as SAT. IBRN (Id 669) and discussed in Section 5.3.8, represents the upper end of the regulatory range (.015), this value should be considered valid, meaningful, and conservative.

5.3.10. Dissenting Views

None

5.4. Permeability of Consolidated Waste

5.4.1. General Evaluation

The permeability of compacted drums of TRU radioactive waste is used in modeling contaminated brine flow in the WIPP repository.

The value currently assigned to the overall permeability of the waste is 1.7×10^{-13} m^2. It applies to all three orthogonal directions (one vertical and two horizontal). In BRAGFLO, waste permeability is treated as a constant and expressed in its log form. Hence, there are three Form 464 parameters: Parameter 663 (PRMX__LOG), Parameter 664 (PRMY__LOG), and Parameter 665 (PRMZ__LOG), each with the same assigned value of -12.769 log m^2.

Laboratory Testing Program

The CH TRU waste to be stored at WIPP consists of a variety of materials that can be broadly categorized into metals, combustibles (plastics and fibers), and sludge. These will be mostly contained in 55-gallon drums and stored in backfilled rooms in the WIPP. Creep closure of the rooms is expected eventually to collapse the drums and compact the waste, leading to a reduction in its overall porosity and permeability.

Butcher's (1989) analysis of the likely composition of the waste delivered to WIPP from various sources was used as the basis for selecting eight different mixtures of materials (Luker et al., 1991, p. 694). Two laboratory tests were performed on each simulated waste mixture. Each mixture was placed in the oedometer (4" ID), the sample holder was filled with brine (which was allowed to drain as necessary), and the sample was compacted under a maximum axial stress of 14 MPa (2000 psi), equivalent to the overburden stress. After compaction (which took from 24 to 1414 hours depending on the material mixture), brine permeabilities of the waste were determined by establishing a constant flow rate through the sample and then measuring flow rate and pressure drop. Multiple flow rates were used in several tests. A backup flowmeter system also was used to measure flow rate, which generally gave good agreement with the primary electronic system. Details of the test set-up and procedures are given in Thompson and Luker (1990).

The test results are summarized in Luker et al. (1991, p. 700). Permeabilities varied with materials, and sometimes varied considerably between different samples of the same material. Most waste materials had permeabilities of the order of 10 to 100 mD (1 to 10 x 10^{-14} m^2). Granular magnetite and limonite had values on the order of 100 - 1000 mD (10 to 100 x 10^{-14} m^2), while values for crushed salt and metals varied from less than 100 mD to over 1000 mD (<10 to >100 x 10^{-14} m^2).

Waste Permeabilities for Different Material Groups

Permeabilities for the three material groups are summarized in Sandia WIPP, 1991, pp. 3-130 and 3-131. These data have been transferred into the first three columns of Table 5.4.1. All permeability data in this table are expressed in 10^{-14} m^2. The last two columns in Table 5.4.1 compare the median value (in column 3) with the experimental results from Butcher (1990) in column 4, and Luker et al. (1991) in column 5.

Line A considers combustibles. The value of 1.7 is the mean of the tests on material #4 in Butcher, 1990. It is also the value obtained by one of the tests in Luker et al., 1991; the mean of all four tests on combustibles in the latter program is 4.6 x 10^{14} cm^2. This is only a factor of 2.7 higher than the "median" quoted in column 3. In practical terms, this agreement is acceptable considering the variability in the combustibles tested and the expected variability in the waste material that will be delivered to WIPP.

Table 5.4.1. Comparison of Waste Permeabilities, Averaged for the Principal Material Groups, in Various Documents (All Units are 10^{-14} m^2)

Materials	Waste Permeability (10^{-14} m^2) SAND91-0893/3 pp. 3-131 to 3-132		Median compared to Butcher, 1990, p. 6	Median compared to Luker, Thompson & Butcher, 1991, p. 700
	Range	Median		
A. Combustibles	0.2 to 20	1.7	Yes, material #4	Same as Test 1-2. Average of 4 tests = 4.6 x 10^{-14} cm^{-2}
B. Metals/Glass	0.4 to 120	50	No; 50 represents the highest value measured	Average of 10 relevant mixtures (excluding Test 15-8) = 27.4 x 10^{-14} m^2
C. Sludge*	0.0011 to 0.017	0.012	No data	No data

* Permeabilities of sludges are based on cement data from the literature

Line B considers metals and glass. [Note the typing error on page 3-130 of Sandia WIPP, 1991 (SAND91-0893/3), in which the lower end of the range for metals/glass should be 4 x 10^{-15} instead of 4 x 10^{-14}]. The median value of 50 represents the highest value obtained from the tests discussed in Butcher, 1990. There are 10 tests in Luker et al. (1991) which involve mixtures containing metals and/or glass that have reasonably well-defined permeabilities. The average of these 10 tests is 27.4 x 10^{-14} m^2. Again, in view of the variability of the mixtures, this is reasonably close to the chosen "median" value of 50 x 10^{-14} m^2 in column 3 of Table 5.4.1.

Line C considers sludges. In the absence of any test data, Butcher (1990) based the range of values on that of ordinary Portland cement (minimum value) and high-alumina cement mixed with flyash for the maximum value (values were selected from Coons et al., 1987). Butcher chose a "median" value of 0.012 x 10^{-14} m^2 towards the high end of that range.

Derivation of an Overall Permeability Value for the Waste

In Lappin et al. (1989) p. 4-56, there is a discussion on how the average permeability depends on whether the flow paths through the different materials are parallel or in series; the cemented-sludge permeability of 4 x 10^{-16} m^2 dominates the series path, and the metal waste permeability of 4 x 10^{-13} m^2 dominates the parallel path. In that report, flow in parallel was conservatively assumed by assigning a permeability of 1 x 10^{-13} m^2 to the room contents. The assignment of this value also assumes that any compacted backfill does not form a continuous zone within the room, so that the controlling permeability is that of the metallic waste.

In the 1992 PA calculations the same average permeability of 1×10^{-13} m^2 was used for the permeability of the waste (Sandia WIPP, 1992, p. 3-57).

In Sandia WIPP, 1991 (pp. 3-130 to 3-134) it is argued that the effective distribution of a collapsed drum is the weighted sum of uniform distributions (from the minimum to the maximum values for each waste component), the weights being percent by volume of each component. Based on 40% combustibles, 40% metals/glass, and 20% sludge, the expected permeability is actually calculated as 2.1×10^{-13} m^2. This is different from the value of 1.7×10^{-13} m^2 recorded on Form 464.

This discrepancy was discussed with Martin Tierney of SNL, who pointed out another discrepancy on page 3-131 (Sandia WIPP, 1991). The permeability components are cumulative distributions rather than uniform distributions. The distribution is best represented by a piecewise-linear cumulative distribution function (CDF) similar to that shown in Figure 5.4.1. The expected value of the mean can be derived from the range and an estimate of the median using the general equations for cumulative distribution given in Tierney (1990), p. II-6, and the specific equations supplied by Tierney, which are included in Figure 5.4.2.

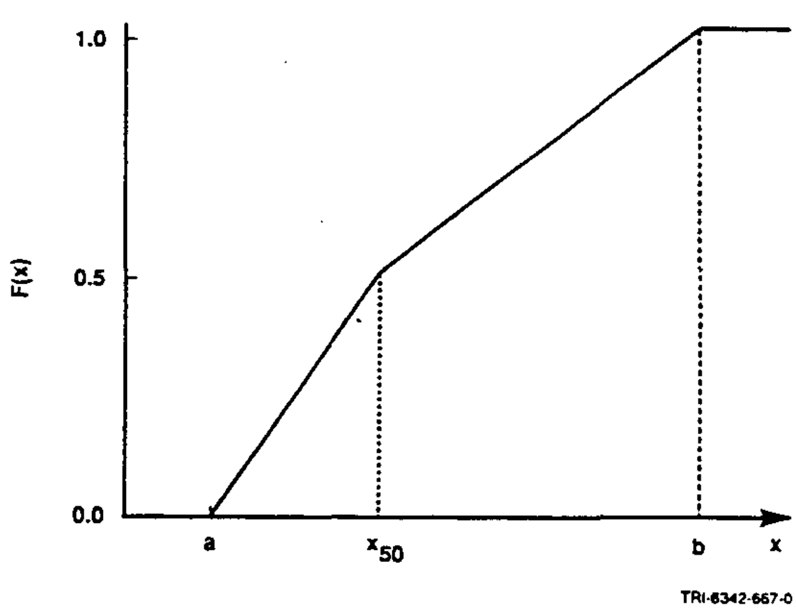

Figure 5.4.1. Piecewise-Linear CDF Based on Range and Median Value (Tierney, 1990)

Cumulative Distribution

A Cumulative Distribution (also called a *Constructed Distribution)* is described by a set of N ordered pairs:

$$(x_1,0),(x_2,P_2),(x_3,P_3),\cdots,(x_N,1) \quad \{i.e.\ \ P_1=0 \ \ and \ \ P_N=1 \ \ always\}$$

where $x_1 < x_2 < x_3 < \cdots < x_N \quad and \quad 0 < P_2 < P_3 < \cdots < P_{N-1} < 1$

Due to the nature of the data, the probability density function (pdf) for this distribution takes the form :

$$P(\xi)=\begin{cases} 0 & if\ \xi < x_1 \\ \dfrac{P_n - P_{n-1}}{x_n - x_{n-1}} & if\ x_{n-1} \le \xi \le x_n, \quad n=2,3,\cdots,N \\ 0 & if\ \xi \ge x_N \end{cases} \tag{1}$$

and so the cumulative distribution function (CDF) takes the form:

$$P_r\{X \le \xi\} \approx \Pi(\xi)=\begin{cases} 0 & if\ \xi < x_1 \\ P_{n-1} + \dfrac{(P_n - P_{n-1})(\xi - x_{n-1})}{(x_n - x_{n-1})} & if\ \dfrac{x_{n-1} \le \xi \le x_x}{n=2,3,\cdots,N} \\ 1 & if\ \xi > x_N \end{cases} \tag{2}$$

Expected Value: $$E(X)=\sum_{n=2}^{N}(P_n - P_{n-1})\frac{(x_n + x_{n-1})}{2} \tag{3}$$

Variance: $$V(X)=\sum_{n=2}^{N}(P_n - P_{n-1})\frac{(x_n^2 + x_n x_{n-1} + x_{n-1}^2)}{3} - \{E(X)\}^2 \tag{4}$$

Median: $$X_{0.50} = x_{m-1} + (x_m - x_{m-1})\frac{(0.50 - P_{m-1})}{(P_m - P_{m-1})} \quad \text{where } P_{m-1} \le 0.50 < P_m. \tag{5}$$

When use of the cumulative distribution is appropriate:

The cumulative distribution takes its name from the fact that it closely resembles the empirical cumulative distribution function(Blom 1989; pg. 216) obtained by plotting the empirical percentiles of the data set ($x_1,x_2,x_3,\dots,x_N$). Usually, the cumulative distribution (in the sense used here) is the result of plotting the *subjectively determined* percentile points (x_1,P_1), (x_2,P_2), (x_3,P_3) ... , that arise in a formal elicitation of expert opinion concerning the form of the distribution of the parameter in question. Also, a simple form of the cumulative distribution is appropriately used when the range [a,c] of the parameter is known and the analyst believes that his or her "best estimate" value, b, is also the median (or 50th percentile) of the unknown distribution. In this case, the subjectively determined percentile points take the form: (a, 0.0), (b, 0.5), (c, 1.0).

The cumulative distribution is the *Maximum Entropy* distribution associated with a set of percentile points (x_1,P_1), (x_2,P_2), ..., (x_N, P_N), no matter how that set of percentile points is obtained (i.e. independent of whether the points are empirically or subjectively derived).

Figure 5.4.2. Equations Describing a Cumulative Distribution (Supplied by M. Tierney, Sandia)

Applying equation (3) in Figure 5.4.2, the expected mean values for combustibles, metals/glass, and sludge are 5.9×10^{-14} m^2, 5.5×10^{-13} m^2, and 1.05×10^{-16} m^2, respectively. When these are combined based on respective volume percents of 40, 40, and 20, the overall permeability of the waste was calculated by Tierney to be 2.4×10^{-13} m^2.

5.4.2. Adequacy of Requirements and Criteria

The requirement is to provide an estimate of the overall permeability of the compacted waste (i.e., after the rooms have collapsed and the waste has compacted to a "final" density under full overburden loading). This is needed for modeling the WIPP hydrologic system in BRAGFLO. It also indirectly impacts some of the borehole intrusion scenarios, such as "blowout."

5.4.3. Assumptions

It is assumed that the composition of the waste to be emplaced at WIPP is already known, that it is reasonable to divide the waste into just three components (combustibles, metals/glass, and sludge), that the laboratory mixtures tested were representative of the individual components, that scale effects (between the large drums of actual waste and the small laboratory samples) were appropriately accounted for, that the CDF's for the different components were appropriately derived, and that the components were combined appropriately (using realistic volume percents) to produce a realistic overall permeability for the compacted waste.

M

5.4.4. Alternate Interpretation

Alternate interpretations include the converse situations listed under assumptions. All of these situations have been taken into account to the extent possible, during SNL's assessment of waste permeability.

5.4.5. Uncertainties and Consequences

The largest uncertainty is the make-up of the transuranic waste delivered to WIPP. Will this be placed in a uniform manner, so that it is reasonable to assign a constant value of permeability to the waste in the repository? This might not be reasonable if, for instance, all the combustibles are placed together in one section of the repository, with the other components in their own separate sections.

There is some uncertainty over the role of the drums and how long it will take them to collapse and/or disintegrate. This, in turn, will change with the use or non-use of backfill around the drums (the use of backfill should speed up the consolidation process).

In the opinion of the Panel, these uncertainties could cause the waste permeability to vary by up to an order of magnitude. Since the waste permeability is about four orders of magnitude higher than any other geologic or seal component, any fluid flow will occur within the waste relatively quickly. Overall travel times to the accessible environment are expected to be fairly insensitive to waste permeability changes within an order of magnitude, but a detailed assessment of this effect is beyond the scope of this review.

5.4.6. Appropriateness and Limitations of Methodology and Procedures

The methodology used in deriving the overall permeability of the waste appears to be appropriate. The laboratory testing that was carried out on different material mixtures is valuable, since it provides a scientific basis for deriving the permeability distributions of the different waste components.

5.4.7. Adequacy of Application

Approximate scale effects were taken into account in selecting the composition and size of the individual waste elements for each laboratory sample prior to testing. The application of these data to the field scale appears adequate and reasonable. However, if the nature and composition of the waste changes significantly from that assumed by Butcher (1989), on which the current waste permeability value is based, this issue will need to be re-examined.

5.4.8. Accuracy of Calculations

Typing errors in the documents caused some initial confusion, but they were easily resolved from information within the documents, without the need to consult the authors.

At some point it appears that there was miscommunication between the different disciplines at SNL in specifying the nature of the probability distribution functions (PDF) for the three waste components. Some thought they were uniform distributions, while the statistician considered them to be piece-wise cumulative distributions. This led to an error in the final calculation of the overall permeability.

The Panel resolved these discrepancies with Dr. Tierney of SNL, and checked his new calculated value of 2.4×10^{-13} m^2.

5.4.9. Validity of Conclusions

It is useful to compare the waste permeability results with those for municipal landfills. Based on a pumping test and a search of the literature, Oweis et al. (1990) concluded that "a saturated conductivity of 10^{-3} cm/sec (10^{-12} m^2 using water as the permeant) is a reasonable first estimate for typical municipal waste that has good compaction." A falling head field test on compact waste (density of 50 to 90 lb/ft^3) produced a hydraulic conductivity of 1.5×10^{-4} cm/sec (1.55×10^{-13} m^2). The average overburden thickness was about 75 ft (0.27 MPa) at these landfills, compared to the 14 MPa of overburden at the WIPP site. Once allowance is made for the greater densities and overburden pressures at the WIPP site, permeabilities of about 2.4×10^{-13} m^2 for the waste do not appear to be unreasonable.

As calculated by Tierney, a more realistic value for parameters 663, 664 and 665 recorded on Form 464 is 2.4×10^{-13} m^2 (instead of 1.7×10^{-13} m^2).

5.4.10. Dissenting Views

None

5.5. Strength of Waste for Blowout

5.5.1. General Evaluation

In this section the Panel evaluates the strength of the disposed waste as a property relating to its ability to resist particulate separation from the waste's mass due to forces created by gas movement. This property is called "cement" on the parameter list. The value assigned (Form 464, Parameter #3245) is 6895.0 Pa (1.0 psi).

During the controlled years, a possible pathway for release might be created by a borehole that penetrates a waste storage room. Three concepts are used to describe the possible mechanisms of this intrusion: 1) those resulting from the cutting actions of the drill bit itself and mechanical friction (cuttings); 2) those associated with erosion by fluids in the borehole (cavings); and 3) those related to processes that produce debris as a result of pressure change or turbulence in the gases and fluids (spalling). The cuttings mechanism is the easiest to address because the volume of waste cuttings is a simple calculation of the borehole cross-section across the room height. The cavings mechanism is somewhat more complicated as it must incorporate the erosional effects on the borehole wall as a result of abrasive laden fluids and drill pipe friction.

Spallings are defined as waste introduced into the drilling fluid caused by the release of waste-generated gas escaping to the lower-pressure borehole. This requires a repository gas pressure that exceeds the hydrostatic pressure of the drilling mud. Spallings can be further subdivided into three regimes: blowout, gas erosion and stuck pipe. These are dependent upon the state of waste permeability and gas pore pressure at the time of intrusion. Blowout is the direct release to the surface of waste entrained in waste decomposition gas that ejects the borehole annulus of drilling mud and flows freely to the surface.

Gas erosion occurs when low permeability waste is pressed against the drillstring due to stresses from escaping decomposition gas and is subsequently eroded by the flowing drilling mud. Stuck pipe is low permeability waste that is pressed against the drillstring sufficiently hard to prevent normal drilling. This occurs at high gas pressures. Brine flow and brine slurry, two additional contributors to spallings, occur when solid wastes are transported via brine movement to the borehole and then to the surface.

Numerous parameters are associated with the intrusion release processes. Many of these have been previously qualified or are obtained under controls of a qualified QA program. This report covers only one specific parameter relating to those processes that need to have a property depicting the ability of pieces of waste to separate from the compressed, stored mass. This is the tensile strength of the waste, herein called waste strength for blowout.

5.5.2. Adequacy of Requirements and Criteria

The need to establish a limiting process to determine the amount of waste ejected by a gas blowout required the development of a process description. In the process, the high pressure gases begin to exit via the drill hole annulus of the drill pipe in the borehole. Particulates become entrained in the gas and are swept away. This process would eventually erode channels from initial weaknesses (e.g., cracks) in the compacted waste. At some point of pressurization and distance from the exit port, the particles will no longer be able to separate from the waste mass and/or be lofted into the gas stream, at which time the waste release will cease. The state at which this process ceases is believed to be a function of the velocity of gas passing the waste surface (lofting and entrainment), and the cohesive strength or other strength property to resist movement. Until recently, in the spall blowout model the ability of the waste to resist flaking or breaking away from its compressed mass was assumed to be due to capillary tension. Experimental results showed that this type of strength was not enough to influence the releases to be simulated. Typical values for capillary tension are on the order of less than 0.5 psi. It was realized that this level of tensile strength is most applicable in the realm of small diameter particles, which experience large capillary forces (Butcher, 1996E). Other mechanisms of cohesive or adhesive forces also contribute to the tensile strength, including particle cementation. Testing scenarios mentioned by Butcher (1996E) resulted in a plausible tensile strength value of 1.0 psi, based on cementation and other factors.

The requirements and criteria for the waste strength parameter are that it be representative of a material that will enable calculation of waste movement by a natural process, but also one that recognizes conditions controlling and bounding the process. There are few analogues for this process to assist with the phenomenology involved. The SNL approach also will be discussed in Section 5.5.3.

The establishment of this parameter, and its value, is a process that includes both reasonable assumptions and scientific conjuring. Even the mechanisms of the waste strength appear still to be speculative, but the reasonings for its applicability appear to be appropriate. The question is whether the mechanism is, for example, cementation, cohesion, capillary, tension, or a combination of these. Once defined, however, the strength must be quantified for specified conditions and a plausible value must be found.

Physically, 1.0 psi hypothetically represents the strength at which a suspended lengthening column of cohesive sand-like material will break at 12 inches. This analogy helps the Panel to envision that the waste has strength to resist breaking, but can easily be eroded. While the parameter value for waste strength seems highly speculative, it is important to recognize that the condition and properties of the waste at any given time of intrusion is highly uncertain and a definitive strength concept and value are not easily derived. It is believed that the requirements of and criteria for this parameter have been well thought through, and the value assigned is plausible.

5.5.3. Assumptions

For the technology current at the time of this writing, it appears that the waste strength is assumed to be derived from cementation forces. It also appears that this cementation is assumed to be attributed to crystallized salt precipitated from supersaturated brines that have wicked into the wastes or their residual decay products. Both assumptions appear realistic, although they are not necessarily all inclusive of the process. For purposes of this parameter, however, no tests were found to be performed on these assumptions, probably due to the infancy of this concept. No assumption is made concerning moisture in the waste and its effect on the waste strength. Also the particle size is not prescribed. To date, mechanistic testing has centered on sparging high-pressure air radially through a compressed bed of uniform fine Ottowa silica sand (Lenke, Berglund, and Cole, 1996) as an evaluation of the capillary bonding theory, but not the cementation theory. Scoping tests described by Butcher (1996E) reveal that the value of 1.0 psi is realistic for purposes of their calculations. If any parameter correction is required, it would probably be because an unrealistically high volume of waste release is produced by the blowout spall resulting from an inappropriate bounding characteristic that is a function of the waste strength.

5.5.4. Alternate Interpretation

In order to be able to model the removal of solid waste, alternative interpretations would require a change in the phenomenology involved. One such alternative could be to assume all waste is in a granular or powdered state subject to movement by only modestly turbulent gas movement to loft the waste into the gas stream. In this case, waste strength or capillary forces are not important. This does not seem plausible, however, and would require even further wide-ranging assumptions than does the subject parameter. Another alternative is that the dominant size of the decayed waste is sufficiently coarse to resist movement by any flowing gases. This consideration may have merit on a selective basis, but it probably would be eliminated because it is not conservative. No alternate interpretations were found in the records, other than the spallings concept caused by a high-pressure steep gradient at a surface, which is another part of this model.

5.5.5. Uncertainties and Consequences

Uncertainties are numerous and the consequences are high. The condition or physical state of the waste at any time in the project cycle is unknown. The mechanism causing separation of the particulates is uncertain. Conditions of the waste room atmosphere, such as state of room closure or open channels for gas movement, are speculative. Finally, any serious misrepresentation of this parameter could result in erroneous or unrealistic calculation of radioactive releases, which would negate the purpose for modeling this specific event instead of using an assumed release value. A convincing argument can be made for assuming an unresolved process that would provide a prescribed volume of waste from a defined distance at the opening of the borehole in the repository. Such an assumption would make the calculations more certain and straightforward, and could be sampled in the PA calculations.

5.5.6. Appropriateness and Limitations of Methodology and Procedures

Although speculative, the thought processes, scientific reasoning, and methodology used in establishing the waste tensile strength appear to be appropriate and fundamentally sound. The assigned value may be subject to change based on development of further phenomenology, or PA results that show unreasonable values for a calculation that requires a self-limiting release (see Section 5.5.2).

5.5.7. Adequacy of Application

Technically, SNL appears to have concluded that the parameter value of "cement" at 1.0 psi is sufficiently representative for realistic calculated release values based on the current model. There is no established scientific school of experience nor any data base available for determining the mechanisms that this parameter supports. Furthermore, because of the uncertainty of waste conditions at the time of intrusion, it requires an assumption that the standard waste composition and condition will be a granular material of a density approximating unconsolidated lightly cemented sand of unknown porosity and low moisture. The only data (and it is sparse) in the literature is for clays, which approximates these conditions for strength properties (Lenke et al., 1996). Therefore, at this stage of process development, and considering the absence of defining conditions, it is not possible to ascertain if the value of 1.0 psi tensile strength is adequate. For the phenomenal concept being modeled, however, the parameter value is probably adequate to carry forward the study for the current stage of development and present purpose. If the concept is to survive, more research and development will be required to establish a definitive value of waste strength for a set of prescribed conditions and definitions.

5.5.8. Accuracy of Calculations

This parameter is not the product of any calculation or result. It is an assumed constant used in a calculation that produces a result basic to a conceptual model. This result will be evaluated by another Panel reviewing the conceptual models and discussed in the report of that Panel.

5.5.9. Validity of Conclusions

In the event intrusion were to occur, it appears highly probable that the process supported by the waste strength parameter will contribute significantly to the release calculation in the PA. Definitions of such an important parameter should not be based on science that is yet in its infancy. If this model and parameter become critical to the PA calculations, more data and back-up scientific evidence are required. As of this writing, the validity of the concept of the parameter "cement" appears to be appropriate within the confines of the model described, but there is not adequate information for the Panel to determine the qualification of a definite value.

5.5.10. Dissenting Views

None

5.6. Properties of Halite and Anhydrite

5.6.1. General Evaluation

Because of assigned limitations of scope, the Panel has provided just an overview of these properties, and the individual parameters listed below are not considered at the same level of detail as those reviewed in other sections of this report.

Massive halite (both clean and argillaceous) and relatively thin beds of anhydrite (and some clay layers) surround the repository rooms. The anhydrite volume is small compared to the halite volume, but anhydrite occurs in several very important beds that can affect both disposal room mechanical response and hydrologic behavior. The properties to be reviewed here are discussed in the memo by Munson, 1995. This memo provides the current status of mechanical, thermal and stratigraphic properties (including overburden stress). This review will concentrate on mechanical properties of halite and anhydrite, which are primarily used in the porosity surface calculations (Section 5.7). Thermal properties will not be discussed at all, since previous studies have shown few, if any, thermal effects in the repository environment, and no thermal properties appear to be used in the current WIPP calculations. Polyhalite properties, although they are listed in the memo, will not be discussed since they do not appear in calculations. Hydrologic properties, such as permeabilities, are also important to repository design and PA, and do appear in other WIPP PA calculations. However, they are not included in the parameter package to be reviewed here and are discussed elsewhere. The review in this section encompasses many individual parameters.

The current halite/anhydrite parameters (Munson, 1995) consist of the values given in Tables 5.6.1 through 5.6.10, and Figure 5.6.1.

Table 5.6.1. Three Elastic Constants for Both Halite and Argillaceous Halite

#	Name	Value
1	G (shear modulus)	12,400 MPa
2	E (Young's modulus)	31,000 MPa
3	ν (Poisson's ratio)	0.25

Table 5.6.2. Eighteen Creep Constants for the MDCF Model for Halite

#	Name	Value
1	A_1	8.386 E22 /s
2	Q_1	25 Kcal/mol
3	n_1	5.5
4	B_1	6.086 E06 /s
5	A_2	9.672 E12 /s
6	Q_2	10 Kcal/mol
7	n_2	5.0
8	B_2	3.034 E-02 /s
9	σ_o	20.57 MPa
10	q	5.335 E03
11	m	3.0
12	K_o	6.275 E05
13	c	9.198 E-03
14	α	-17.37
15	β	-7.738
16	α	-2.69
17	β	-1.00
18	R	1.987 cal/mol-deg

Table 5.6.3. Eighteen Creep Constants for the MDCF Model for Argillaceous Halite

#	Name	Value
1	A_1	1.407 E23 /s
2	Q_1	25 Kcal/mol
3	n_1	5.5
4	B_1	8.998 E06 /s
5	A_2	1.314 E13 /s
6	Q_2	10 Kcal/mol
7	n_2	5.0
8	B_2	4.289 E-02 /s
9	σ_o	20.57 MPa
10	q	5.335 E03
11	m	3.0
12	K_o	2.470 E06
13	c	9.198 E-03
14	α	-14.96
15	β	-7.738
16	α	-2.69
17	β	-1.00
18	R	1.987 cal/mol-deg

Table 5.6.4. Nineteen Fracture Constants for the MDCF Model for Halite

#	Name	Value
1	x_1	6
2	x_2	9
3	x_{3s}	5.5
4	x_{3t}	40
5	x_4	3
6	χ_s ($\sigma > \sigma_0$)	231.0 MPa
7	χ_s ($\sigma <= \sigma_0$)	351.1 MPa
8	χ_t	15.15 MPa
9	x_6	0.75
10	x_7	1.0 MPa
11	x_8	0.1
12	c_o	5 E04
13	c_2	850
14	c_3	10
15	c_4	6
16	c_5	25 MPa
17	t_0	1 s
18	n_3	3
19	ω_0	>=1 E-4

Table 5.6.5. Twenty Fracture Constants for the MDCF Model for Argillaceous Halite

#	Name	Value
1	x_1	6
2	x_2	9
3	x_{3s}	5.5
4	x_{3t}	40
5	x_4	3
6	χ_s ($\sigma > \sigma_0$)	231.0 MPa
7	χ_s ($\sigma <= \sigma_0$)	351.1 MPa
8	χ_t	15.15 MPa
9	x_6	0.75
10	x_7	1.0 MPa
11	x_8	0.1
12	c_o	5 E4
13	c_2	850
14	c_3	10
15	c_4	6
16	c_5	25 MPa
17	t_0	1 s
18	n_3	3
19	ω_0	>=1 E-4
20	p_1 (ρ_a>0.0)	20.6

Table 5.6.6. Four Elastic Constants for the RM Model for Both Halite and Argillaceous Halite

#	Name	Value
1	μ (shear modulus)	0.992 GPa
2	E (Young's modulus)	2.480 GPa
3	K (bulk modulus)	1.656 GPa
4	ν *(Poisson's ratio)*	0.25

Table 5.6.7. Three Creep Constants for the RM Model for Halite

#	Name	Value
1	A	1.66 E14 /s
2	Q	12 Kcal/mol
3	n	4.9

Table 5.6.8. Three Creep Constants for the RM Model for Argillaceous Halite

#	Name	Value
1	A	4.99 E14 /s
2	Q	12 Kcal/mol
3	n	4.9

Table 5.6.9. Four Elastic Constants for Anhydrite

#	Name	Value
1	μ (shear modulus)	27.8 GPa
2	E (Young's modulus)	75.1 GPa
3	K (bulk modulus)	83.4 GPa
4	ν (Poisson's ratio)	0.35

M

Table 5.6.10. Two Drucker-Prager Plasticity Parameters for Anhydrite

#	Name	Value
1	a	0.45
2	C	1.35 MPa

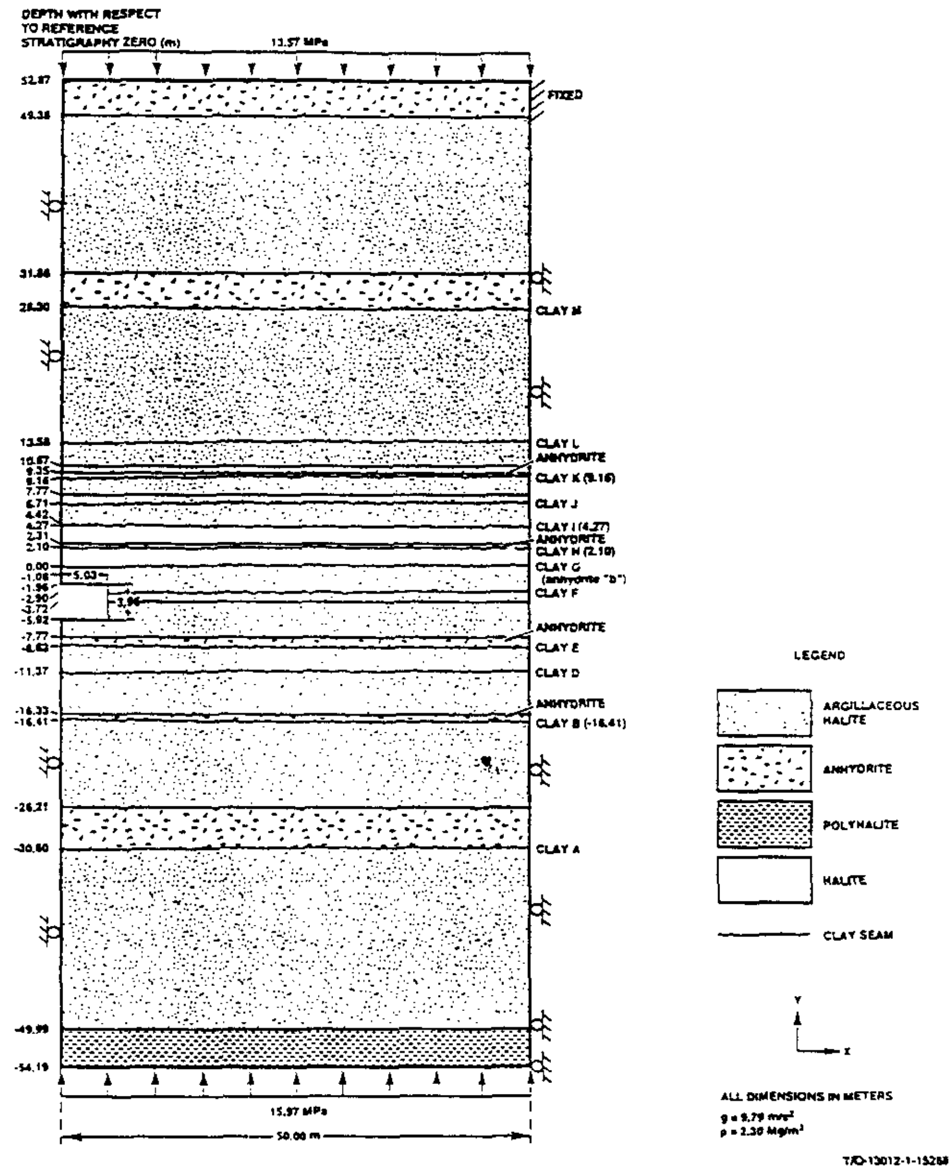

Figure 5.6.1. WIPP Stratigraphic Boundaries

Of the listed parameters, the creep parameters for halite (both types) would appear to be the most important in long-term calculations of disposal room response. The Multimechanism Deformation Coupled Fracture (MDCF) model is an extension of the original Multimechanism Deformation (MD) creep model for halite intended for use in the DRZ. Without the fracture components, the model reduces to the original MD model. In the porosity surface calculations (Section 5.7), currently the major user of these halite/anhydrite parameters, only the MD model for halite (both clean and argillaceous) is used.

The reduced modulus (RM) model is a creep model used in some earlier and current approximation calculations.

The following introductory discussion is broken down by the parameter categories in the tables above.

a) ***Three elastic constants for both halite and argillaceous halite (Table 5.6.1)*** - These constants are obtained from literature-referenced measurements on rock salt and discussed by Munson et al., 1989. They are also summarized by Butcher, 1996A.

b) ***Eighteen creep constants for the MDCF model for halite (Table 5.6.2)*** - A good initial reference for the work on halite creep is Munson and Dawson, 1979. Early tests and modeling are summarized. Most of the parameter values and concepts established here changed very little as the WIPP evolved. The early data used for parameter development is primarily from Wawersik and Hannum, 1979. More data are contributed by Senseny, 1986 and discussed by Munson et al., 1989. The raw creep data contributing to the creep models have been qualified elsewhere and are not a subject of this review. Derived parameter values, which are a subject of this review, have not apparently changed from the point of the last report mentioned above (except for the addition of the fracture parameters as discussed below).

c) ***Eighteen creep constants for the MDCF model for argillaceous halite (Table 5.6.3)*** - See discussion for b) above.

d) ***Nineteen fracture constants for the MDCF model for halite (Table 5.6.4)*** - A damage model, including fracture (in a continuum sense) has been added to the MD model for use primarily in the DRZ. It is supported by some new data. This model is presented in Chan et al., 1995. Since this model is not currently in use for PA-related calculations, it is not reviewed further here.

e) ***Twenty fracture constants for the MDCF model for argillaceous halite (Table 5.6.5)*** - See discussion for d) above.

f) ***Four elastic constants for the RM model for both halite and argillaceous halite (Table 5.6.6)*** - For calculational efficiency, earlier room calculations used a much simpler model for salt creep and elastic response. This model is still based on an activation energy creep law. Because of its simplicity, elastic modulus reduction (by a factor of 12.5) was required to simulate early-time behavior. This model is discussed in Mendenhall et al., 1991. Current room closure calculations use the MD model only.

g) ***Three creep constants for the RM model for halite (Table 5.6.7)*** - See discussion for f) above.

h) ***Three creep constants for the RM model for argillaceous halite (Table 5.6.8)*** - See discussion for f) above.

i) ***Four elastic constants for anhydrite (Table 5.6.9)*** - Anhydrite properties are discussed in Krieg, 1984, and Munson and Morgan, 1986. The anhydrite elastic properties were determined in earlier laboratory tests.

j) ***Two Drucker-Prager plasticity parameters for anhydrite (Table 5.6.10)*** - Anhydrite properties are also discussed in Krieg, 1984 and Munson and Morgan, 1986. The anhydrite Drucker-Prager plasticity parameters are estimated from the same earlier laboratory tests as mentioned in h) above.

k) ***Stratigraphic boundaries (Figure 5.6.1)*** - Stratigraphic boundaries for the halite and anhydrite units are discussed by Munson et al., 1989 (as modified from Krieg, 1984.)

5.6.2. Adequacy of Requirements and Criteria

Halite (both clean and argillaceous), and anhydrite properties are important to the behavior of the repository over time. All of the documents and test data reports leading up to the current values of the mechanical parameters for these materials appropriately recognize that role and are evaluated in accordance with adequate requirements and test and evaluation criteria.

5.6.3. Assumptions

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

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

b) Within halite and anhydrite layers, these materials can be treated as continua. This assumption is probably necessary in view of current computer modeling methods. It is also reasonable in view of program requirements and data accuracy. However, discontinuous surfaces certainly exist within the assumed continuous layers. A good example is given by the few "anomalous" creep results reported by Senseny, 1986, which were not included in the final creep parameter determination. Some of these occurred in samples that contained distinct linear clay seams. The effect of ignoring such data and other similar effects by assumption is not severe with regard to the final results, but should not be forgotten. The effect of this will be discussed in Section 5.6.4.

c) Size scale effects can be ignored. Most geologic media exhibit a size scale effect. More often than not, this takes the form (in mechanical properties) of moduli reduction with size. In the case of WIPP, one might also expect an increase of creep rate with size. Size effect is briefly noted by Munson et al. 1989, but no model changes are proposed. Such effects are frequently attributed to discontinuities, which have differing properties as functions of scale. The assumption of no size scale effects therefore ties in with the continuum assumption discussed previously, and will also be mentioned in Section 5.4.4. Despite these cautions, ignoring scale effects seems reasonable within the realm of available data and accuracy of prediction required for these massive formations.

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

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

5.6.4. *Alternate Interpretation*

Given the general acceptance of the models used and reasonableness of the assumptions made, we find no critically different alternate interpretations of mechanical data. The data are therefore well-interpreted in that sense. However, with the number of parameters used here, the number of small model variations that might be possible, and the fact that creep data are interpreted by the use of an assumption regarding unloading effects during mining and coring, alternate interpretations are certainly possible. Most of the alternate data interpretations that can be envisioned seem to speed the long-term creep or increase the deformation. These include the now-ignored effects of discontinuities, water, and small clay seams. Therefore, current closure calculations may be viewed as conservative, and are quite acceptable in that sense.

M

5.6.5. *Uncertainties and Consequences*

The major uncertainty arises from interpreting a large number of material parameters from a relatively small number of tests on small-sized specimens that probably are pre-selected for their continuous nature. A very positive and encouraging result in this regard is that the two primary sets of laboratory creep data obtained are quite similar. However, this remains as a classical problem in geotechnical testing. For example, if some of the "anomalous" results reported by Senseny (1986) were retained in the data set, a different set of creep parameters would result. To some extent, Fossum et al., 1994, attempt to account for this by statistical sampling for creep parameters; however, this approach is presently not used by the project, nor does it seem to be needed. In the future, if some sensitivity to creep proves high, the creep parameters should be sampled for the PA results. This also implies that the porosity surface (Section 5.7) need not be developed from sampled creep parameters. Thus, the present uncertainties are acceptable and no severe consequences seem to arise.

With regard to elastic properties, the moduli of halite are developed from literature-referenced test results only, and these are not on WIPP salt. Munson et al., 1989 refers to the use of "ultrasonic wave velocity" measurements as reported in Hume and Shakoor, 1981, as the source. This reference is a review paper of many earlier original sources of measurements, including ultrasonic, hydrostatic, and uniaxial tests on a broad variety of rock salt types. Studying the reference, it is unclear which of the reported data were used to obtain the WIPP halite properties. None of the reported data (either static or ultrasonic) correspond exactly to the reported WIPP values. The WIPP value of 0.25 for Poisson's ratio appears reasonable, although a "bedded salt" from the GNOME drift in New Mexico, which might be similar to WIPP salt, was reported to have a Poisson's ratio value of 0.31. The WIPP value of 31 GPa for Young's modulus is near the high end of the range of reported values of about 16 to 38 GPa, clustering near 25 GPa. It is probably possible to pick a subset of the reported values that, when averaged, would correspond to the WIPP values. Assuming that these actually were ultrasonic test results, it is likely that the Young's modulus, and subsequently calculated bulk modulus, are somewhat too large for predicting the static elastic response of large samples, as has been found for many other geologic materials. To be sure, this effect may be minimized in the relatively continuous and homogenous WIPP halite, but it is unlikely to be non-existent. Therefore, some of the "moduli reduction" recognized in the earlier MD model may actually be real. However, since elastic response is seen as an early-time phenomenon or one of lesser magnitude, little adverse effect is anticipated from this in WIPP PA except perhaps for the case of gas over-pressurization and subsequent elastic rebound of the room. Again, the adverse effects of such a miscalculation of elastic parameters would seem to be relatively small. The possible overestimation of intact halite static bulk modulus may have an observable effect on crushed salt bulk modulus predictions, as discussed in Section 4.2.

5.6.6. Appropriateness and Limitations of Methodologies and Procedures

Considering the data available and the state of the modeling science, the methodologies and procedures leading to halite and anhydrite properties are appropriate. If anything, the model used for salt creep, leading to a large number of parameters to be determined, is too complex to be fully justified for engineering use. We see, however, no technically adverse consequences or limitations arising from this, aside from the need for additional computation time.

5.6.7. Adequacy of Application

The parameters discussed here are primarily applied to the porosity surface calculations to be described and discussed in Section 5.7. They appear to be quite sufficient and adequate to calculate that surface.

5.6.8. Accuracy of Calculations

The documentation shows that halite and anhydrite parameter calculations were repeated, checked, and discussed at length. The Panel has made approximate spot checks of calculational accuracy, but because of the limited scope of this review, the Panel has not thoroughly re-checked these calculations.

5.6.9. Validity of Conclusions

Based on this overview evaluation, the halite and anhydrite parameter values derived for WIPP appear to be valid, suitable and sufficiently accurate with regard to use in the mechanical response models used for room closure predictions. Because of the limited scope of this review and the large number of these parameters, the values have not been checked at the same level of detail used in some other sections of this report; the parameters have only been broadly reviewed and spot-checked. The Panel has not seen anything, however, to suggest that any severe problems of validity exist.

5.6.10. Dissenting Views

None

5.7. Data on Final Porosity Surface

5.7.1. General Evaluation

Since the porosity surface as defined below is treated as a tabular parameter by PA, even though it is actually a submodel with many input parameters of its own, the Panel has chosen (because of scope limitations) to approach this review as an overview of the porosity surface concept and results. This means that the individual parameters contributing to the porosity surface will not be treated at the same level of detail as those direct PA parameters discussed in other sections of this report.

In the present WIPP project performance assessment calculations (using BRAGFLO) the details of the mechanics of disposal room closure and/or eventual expansion are not explicitly calculated. Instead, the room-rock system behavior is obtained from a three-dimensional lookup table entitled the "porosity surface." In this table, the three dimensions are time, total room porosity, and mass of gas in the room. Current calculations are described by Stone, 1996, and Butcher, 1996D. The porosity surface record package is labeled WPO#35697. A graphical example of a porosity surface from Butcher and Mendenhall, 1993, is shown in Figure 5.7.1.

The porosity surface is itself calculated prior to the BRAGFLO runs using the SANTOS code. This procedure is followed to avoid the massive computational effort that would be required to fully calculate (in an iterative sense) the mechanics of room closure for each PA instance. At first, this may seem to be an invalid decoupling of the external environment and the disposal room. However, if the room porosity can be shown to be described with sufficient accuracy as a variable dependent only on time and gas mass

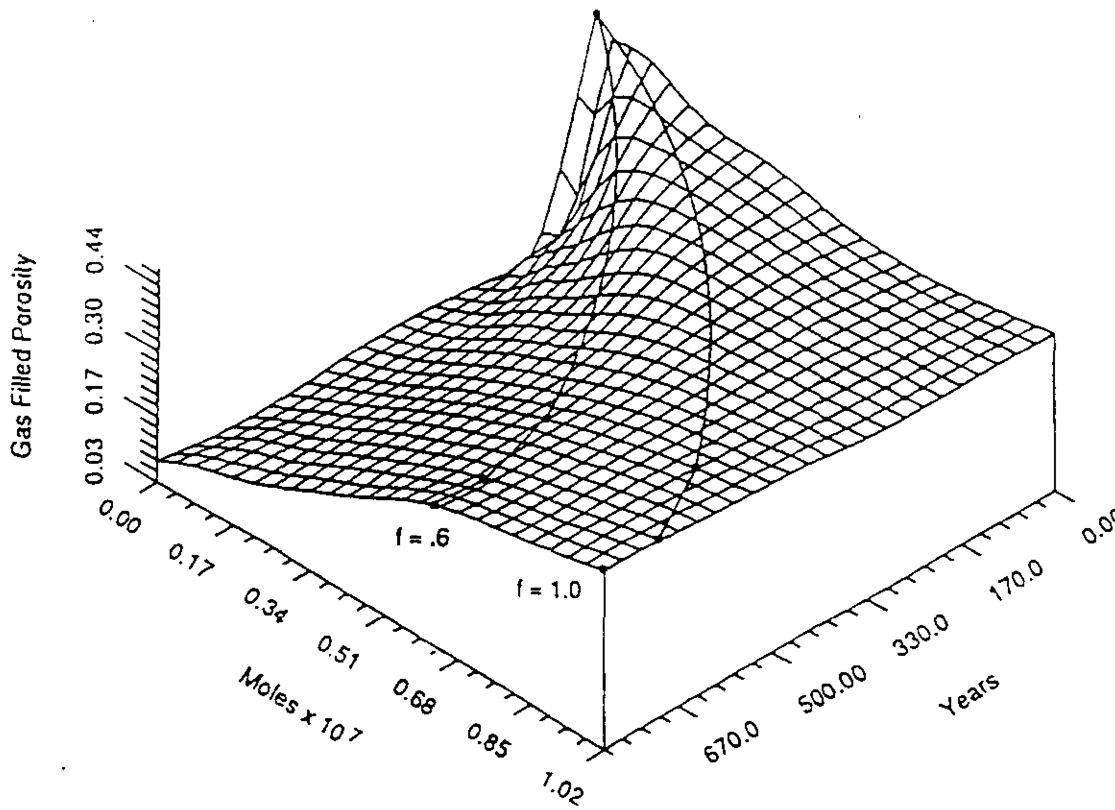

Figure 5.7.1. Example of Porosity Surface (from Butcher and Mendenhall, 1993)

(which is itself dependent only on time in the current model) then this approach is quite justified in view of its simplicity and calculational efficiency. Note that brine content of the room is not mentioned at this point, nor are there any brine parameters on the list. This is a consequence of the calculational method and interaction with BRAGFLO, and will be discussed below. Actually, 13 porosity surfaces are submitted to PA, corresponding to the assumption of 13 possible multiples of the gas generation rate vs. time in the room as compared to the nominal rate. These multipliers, expressed as the SANTOS parameter "f," are 0.0, 0.025, 0.05, 0.10, 0.2, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.6, and 2.0 (see Table 5.7.13). Inputs to the porosity surface calculations are most of the parameters considered in Sections 5.1, 5.2, and 5.6 plus such additional parameters as geometry and gas production. All of the parameters contributing to the porosity surface are listed in the following tables. These tables have been adapted from Butcher, 1996A, but are re-grouped (with comments) for the purposes of this review.

Table 5.7.1. Room Initial Dimensions

#	Name	Value	Reference(s)	Comments
1	Room height	3.96 m	Sandia WIPP Project, 1992, p. 3-5.	This is a design dimension
2	Room width	10.06 m	Sandia WIPP Project, 1992, p. 3-5.	This is a design dimension
3	Room length	91.44 m	Sandia WIPP Project, 1992, p. 3-5.	This is a design dimension
4	Initial room volume	3644 m^3	Butcher, 1996, p 4.	Calculated directly from Items 1, 2, and 3 in this table. However, the repository volume will be greater than simply room volume due to the presence of access drifts, etc. This will cause a 10-20% difference in results if these other volumes are connected to the rooms and not backfilled. This will have an corresponding effect on the porosity surface, mainly in that initial porosity will be slightly greater.

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Table 5.7.2. Waste Initial Dimensions

#	Name	Value	Reference(s)	Comments
1	Number of drums per room	6804	Sandia WIPP Project, 1992, p. 3-11.	This is a design number.
2	Number of 7-packs per room	972	Butcher, 1996, p. 4.	Calculated from Item 2 in this table.
3	Drum external volume	0.2539 m^3	Sandia WIPP Project, 1992, p. 3-10.	This is a design number.
4	Waste volume	1728 m^3	Butcher, 1996, p.4.	Calculated from Table 5.7.1 and Item 3 in this table. "Waste volume" is here defined as the total volume of the drums.
5	Waste height	2.676 m	Sandia WIPP Project, 1992, p. 3-12.	This is the height of 3 drums stacked, including the plastic pallets.
6	Nominal waste width with voids between drums	8.6 m	Stone, 1996, p. 9.	Apparently calculated from Sandia WIPP Project, 1992, p. 3-12, with an adjustment made to average the width.
7	Nominal waste length with voids between drums	89.1 m	Stone, 1996, p. 9.	Taken from Sandia WIPP Project, 1992, p. 3-12.
8	Width of waste continuum	7.35 m	Stone, 1996, p. 9.	Calculated from an equation that removes the void space between the drums by assuming lateral (but not vertical) instantaneous change at time = 0. This has the effect of slightly stiffening the waste at early times.
9	Height of waste continuum	2.676 m	Stone, 1996, p. 9.	Initial height is as emplaced, with no changes. See Item 8 in this table.
10	Length of waste continuum	87.85 m	Stone, 1996, p. 9.	Same as Item 8 in this table.

Table 5.7.3. Computational Configuration (for SANTOS)

#	Name	Value	Reference(s)	Comments
1	Pillar thickness	30.5 m	Sandia WIPP Project, 1992, p. 3-5.	See Item 4 in Table 5.7.1.
2	Half room width	5.03 m	Butcher, 1996, p 5.	Calculated from Table 5.7.1 above.
3	Distance from center of room to center of pillar	20.27 m	Butcher, 1996, p 5.	Calculated from Table 5.7.1 above.
4	Clay G (Anhydrite B)	0.0 m	Munson, 1995, p. 24/24.	Current reference stratigraphy.
5	Top boundary of calculation	52.87 m	Munson, 1995, p. 24.	Current reference stratigraphy.
6	Bottom boundary of calculation	-54.19 m	Munson, 1995, p. 24.	Current reference stratigraphy.
7	Disposal room floor	-6.39 m	Stone, 1996, p. 1.	This is treated as a slip surface with regard to the waste. This appears to be the current best estimate using MB 139 as a reference. There might be an 0.2 m or so variation here.
8	Disposal room ceiling	-2.43 m	Stone, 1996, p. 1.	See comment for Item 7 in this table.
9	Argillaceous salt boundaries, first bed	-54.19 m to -8.63 m	Munson, 1995, p. 24.	Current reference stratigraphy.
10	Anhydrite MB 139 boundaries	-8.63 m to -7.77 m	Munson, 1995, p. 24.	Current reference stratigraphy.
11	Argillaceous salt boundaries, second bed	-7.77 m to 0.0 m	Munson, 1995, p. 24.	Current reference stratigraphy.
12	Clean salt boundaries	0.0 m to 4.27 m	Munson, 1995, p. 24.	Current reference stratigraphy.
13	Clay I	4.27 m	Munson, 1995, p. 24.	Current reference stratigraphy.
14	Argillaceous salt boundaries, third bed	4.27 m to 52.87 m	Munson, 1995, p. 24.	Current reference stratigraphy.
15	Traction on upper boundary of calculation	13.57 MPa	Munson, 1995, p. 24.	See Section 5.5. This is treated as a vertical confining stress. It is calculated from a log-based overburden.
16	Traction on lower boundary of calculation	15.97 MPa	Munson, 1995, p. 24.	This is treated as a vertical confining stress. It is calculated from a log-based overburden.
17	Mesh configuration	table	Butcher, 1996, App. D.	Ties in with SANTOS verification.

Table 5.7.4. Halite Elastic Properties

#	Name	Value	Reference(s)	Comments
1	G (shear modulus)	12,400 MPa	Munson, 1995, p. 1.	Butcher, 1996, gives these units as GPa. This is a typographical error in the draft and will be corrected. The units are actually MPa, as shown here, from the original Munson reference.
2	E (Young's modulus)	31,000 MPa	Munson, 1995, p. 1.	See Section 5.5. See Item 1 in this table.
3	ν (Poisson's ratio)	0.25	Munson, 1995, p. 1.	See Section 5.5.

Table 5.7.5. Clean Halite Creep Properties

#	Name	Value	Reference(s)	Comments
1	A_1	8.386 E22 /s	Munson, 1995, p. 1-2.	See Section 5.5.
2	Q_1	25 Kcal/mol	Munson, 1995, p. 1-2.	See Item 1 above.
3	n_1	5.5	Munson, 1995, p. 1-2.	See Item 1 above.
4	B_1	6.086 E06 /s	Munson, 1995, p. 1-2.	See Item 1 above.
5	A_2	9.672 E12 /s	Munson, 1995, p. 1-2.	See Item 1 above.
6	Q_2	10 Kcal/mol	Munson, 1995, p. 1-2.	See Item 1 above.
7	n_2	5.0	Munson, 1995, p. 1-2.	See Item 1 above.
8	B_2	3.034 E-02 /s	Munson, 1995, p. 1-2.	See Item 1 above.
9	σ_o	20.57 MPa	Munson, 1995, p. 1-2.	See Item 1 above.
10	q	5.335 E03	Munson, 1995, p. 1-2.	See Item 1 above.
11	m	3.0	Munson, 1995, p. 1-2.	See Item 1 above.
12	K_o	6.275 E05	Munson, 1995, p. 1-2.	See Item 1 above.
13	c	9.198 E-03	Munson, 1995, p. 1-2.	See Item 1 above.
14	α	-17.37	Munson, 1995, p. 1-2.	See Item 1 above.
15	β	-7.738	Munson, 1995, p. 1-2.	See Item 1 above.
16	δ	0.58	Munson, 1995, p. 1-2.	See Item 1 above. Also, this parameter does not appear in the Munson reference (but only in the Butcher reference). However, 3 additional parameters do appear in the Munson reference. The difference is caused by the MD to MDCF (fracture) model change.

Table 5.7.6. Argillaceous Halite Creep Properties

#	Name	Value	Reference(s)	Comments
1	A_1	1.407 E23 /s	Munson, 1995, p. 3-4.	See Section 5.5.
2	Q_1	25 Kcal/mol	Munson, 1995, p. 3-4.	See Item 1 above.
3	n_1	5.5	Munson, 1995, p. 3-4.	See Item 1 above.
4	B_1	8.998 E06 /s	Munson, 1995, p. 3-4.	See Item 1 above.
5	A_2	1.314 E13 /s	Munson, 1995, p. 3-4.	See Item 1 above.
6	Q_2	10 Kcal/mol	Munson, 1995, p. 3-4.	See Item 1 above.
7	n_2	5.0	Munson, 1995, p. 3-4.	See Item 1 above.
8	B_2	4.289 E-02 /s	Munson, 1995, p. 3-4.	See Item 1 above.
9	σ_o	20.57 MPa	Munson, 1995, p. 3-4.	See Item 1 above.
10	q	5.335 E03	Munson, 1995, p. 3-4.	See Item 1 above.
11	m	3.0	Munson, 1995, p. 3-4.	See Item 1 above.
12	K_o	2.470 E06	Munson, 1995, p. 3-4.	See Item 1 above.
13	c	9.198 E-03	Munson, 1995, p. 3-4.	See Item 1 above.
14	α	-14.96	Munson, 1995, p. 3-4.	See Item 1 above.
15	β	-7.738	Munson, 1995, p. 3-4.	See Item 1 above.
16	δ	0.58	Munson, 1995, p. 3-4.	See Item 1 above. Also, see Item 16 in Table 5.7.5.

Table 5.7.7. Anhydrite Properties

#	Name	Value	Reference(s)	Comments
1	E (Young's) modulus	75.1 GPa	Munson, 1995, p. 18.	See Section 5.5.
2	ν (Poisson's ratio)	0.35	Munson, 1995, p. 18.	See Section 5.5.
3	a	0.45	Munson, 1995, p. 19.	See Section 5.5.
4	C	1.35 MPa	Munson, 1995, p. 19.	See Section 5.5.

Table 5.7.8. Waste Composition

#	Name	Value	Reference(s)	Comments
1	Metallic	122 kg/m^3	Baseline Inventory Report, 1995	See Section 5.1. These are not densities in the usual sense, but actually the actual mass of each material in a cubic meter of waste.
2	Sorbents	40 kg/m^3	Baseline Inventory Report, 1995	See Item 1 in this table.
3	Cellulose	170 kg/m^3	Baseline Inventory Report, 1995	See Item 1 in this table.
4	Rubber and Plastic	84 kg/m^3	Baseline Inventory Report, 1995	See Item 1 in this table.
5	Sludges	143.5 kg/m^3	Baseline Inventory Report, 1995	See Item 1 in this table.
6	Initial Waste Density	559.5 kg/m^3	Butcher, 1996, p. 16.	This is the sum of Items 1-5 in this table.

Table 5.7.9. Waste Solid Densities

#	Name	Value	Reference(s)	Comments
1	Metallic	7830 kg/m^3	Butcher, 1995, p. 1.	See Section 5.1.
2	Sorbents	3000 kg/m^3	Butcher, 1991, p. 9.	See Item 1 in this table.
3	Cellulose	1100 kg/m^3	Butcher, 1991, p. 14.	See Item 1 in this table.
4	Rubber and Plastic	1200 kg/m^3	Butcher, 1991, p. 40.	See Item 1 in this table.
5	Sludges	2200 kg/m^3	Butcher, 1991, p. 67.	See Item 1 in this table.
6	Waste Solid Density	1757 kg/m^3	Butcher, 1996, App. C.	This value is treated as a constant, even though some of the "solid" waste is compressible itself, such as wood, rags, sorbents, etc.

Table 5.7.10. Waste Volume Fractions

#	Name	Value	Reference(s)	Comments
1	Metallic	0.218	Butcher, 1996, p.17	Calculated from Tables 5.7.8 and 5.7.9 as described in reference.
2	Sorbents	0.071	Butcher, 1996, p.17	See Item 1 above.
3	Cellulose	0.304	Butcher, 1996, p.17	See Item 1 above.
4	Rubber and Plastic	0.150	Butcher, 1996, p.17	See Item 1 above.
5	Sludges	0.256	Butcher, 1996, p.17	See Item 1 above.
6	Initial waste porosity	0.681	Butcher, 1996, p.17	Calculated from above tables as described in reference. Note that 'waste porosity' here means drum porosity.
7	Initial waste solid volume	551.2 m^3	Butcher, 1996, p.17	Calculated from above tables as described in reference. Note that 'waste solid volume' here means the 'solids' within the drums, even though those solids may be themselves somewhat porous.
8	Initial room porosity	0.849	Butcher, 1996, p.17	Calculated from above tables as described in reference.

Table 5.7.11. Waste Mechanical Properties

#	Name	Value	Reference(s)	Comments
1	G (shear modulus)	333 MPa	Weatherby, 1991, p 922.	See Section 5.2.
2	K (bulk modulus)	222 MPa	Weatherby, 1991, p 922.	See Section 5.2.
3	a_0	1.0 MPa	Weatherby, 1991, p 922.	See Section 5.2. See also Stone, 1996.
4	a_1	3.0	Weatherby, 1991, p 922.	See Section 5.2. See also Stone, 1996.
5	a_2	0.0	Weatherby, 1991, p 922.	See Section 5.2. See also Stone, 1996.

Table 5.7.12. Waste Pressure-Volume Relation

#	P, MPa	$\ln(\rho/\rho_o)$	Reference(s)	Comments
1	1.53	0.510	Butcher, 1995, 1991.	See Section 5.2. Derived from experimental curves, with some assumptions.
2	2.03	0.631	Butcher, 1995, 1991.	See Item 1 above.
3	2.53	0.719	Butcher, 1995, 1991.	See Item 1 above.
4	3.03	0.786	Butcher, 1995, 1991.	See Item 1 above.
5	3.53	0.838	Butcher, 1995, 1991.	See Item 1 above.
6	4.03	0.881	Butcher, 1995, 1991.	See Item 1 above.
7	4.93	0.942	Butcher, 1995, 1991.	See Item 1 above.
8	12.0	1.14	Butcher, 1995, 1991.	See Item 1 above.

Table 5.7.13. Gas Generation

#	Name	Value	Reference(s)	Comments
1	Corrosion gas production rate	1 mole/yr/drum	Brush, 1991, p. A-35	Assumed to be inundated.
2	Corrosion gas potential	1050 moles/drum	Beraun and Davies, 1992, p. A-11	See also, Butcher, 1996, App. B.
3	Microbial gas production rate	1 mole/yr/drum	Brush, 1991, p. A-35	Assumed to be inundated.
4	Microbial gas potential	550 moles/drum	Beraun and Davies, 1992, p. A-11	See also, Butcher, 1996, App. B.
5	Scaling factor f	0.0-2.0	Butcher, 1996	A range variable of gas generation rates for input to BRAGFLO.
6	Gas constant R	8.23 m^3Pa/g-mole K	Handbook	
7	Gas temperature	300 K	Sandia WIPP, 1992	Design parameter

The porosity surface calculations using SANTOS, and with the parameters in the above tables as input, are described by Stone, 1996. The main features of these plane-strain calculations are the use of a simplified stratigraphic model with boundaries at 50 m from the disposal room, the inclusion of the main clean halite and argillaceous halite layers, and the inclusion of the two anhydrite layers of influence (MB 139 below and Anhydrite "b" above), but no explicit inclusion of clay seams. The waste containers are lumped into a single rectangular mass bounded by slip surfaces that correctly reproduces the initial waste density and porosity (Section 5.1). The simplified geometry used (as compared to the reference stratigraphy) is justified by Stone, 1996, with supporting calculations given by Osnes and Lebreche, 1995. In justifying the simplification, it is shown that the inclusion of at least two types of salt and the anhydrite beds are necessary to provide the model sensitivity needed to support observations, but that the clay seams and additional complexities do not contribute further to accuracy and sensitivity. Thus, only halite and anhydrite properties are included as formation material properties in the parameters listed for the porosity surface. No roof failure of the room is considered in these calculations. The porosity surface and its parameters have also been discussed by Butcher, 1996A, and Butcher et. al., 1995.

The first published full explanation of the porosity surface and its justification that the Panel can find appears in Butcher and Mendenhall, 1993. Since the pressure in the room depends on the amount of gas and the volume, and this pressure creates the "back stress" resisting closure, the porosity surface can uniquely represent the room behavior if the relationship between gas mass and time is known. Since that relationship is specified (by corrosion rates and/or intrusion scenarios) the porosity surface can be used as prescribed. A complication occurs, however, when brine is allowed to flow into or out of the room. Then, the porosity evaluated from the porosity surface is treated as the gas-filled porosity and added to the brine-filled porosity to become the total porosity required in the PA calculations using BRAGFLO. It is also possible that gas dissolution in the brine should be considered. Furthermore, BRAGFLO, which is a fluid flow code, must be used to provide the brine content of the room for this iterative calculation. This coupling is only valid if the fluid flow is slow, which is a good assumption in the case of WIPP. Also, it must be assumed that the brine pressure is the same as the gas pressure within the room, which is true for high waste permeability.

5.7.2. Adequacy of Requirements and Criteria

The disposal room volume-pressure-time relationship is a key part of the WIPP PA model. Therefore, its description and associated parameters are also key. Justifiable simplifications are necessary to make PA calculations practical. To require a "porosity surface" and its parameters is an adequate approach to the solution of this problem.

5.7.3. Assumptions

Many assumptions apply to the determination of the porosity surface and its parameters. These assumptions are discussed fairly extensively in Butcher et al., 1995. The most general and important of the assumptions is the validity of the porosity surface concept itself. Other important assumptions are related to waste mechanical properties, halite and anhydrite mechanical properties, gas generation rates, and brine presence and inflow-outflow rates. The waste and halite/anhydrite mechanical properties have been addressed in Sections 5.1, 5.2, and 5.5. Gas generation rates are specified and qualified elsewhere in the project.

Brine inflow/outflow calculations are part of BRAGFLO and are also qualified elsewhere. However, the dissolution of gas within the brine in the room is apparently not accounted for in the SANTOS calculations leading to the porosity surface. This would have the effect of creating an error on the values on the gas quantity axis of the porosity surface.

An assumption not addressed elsewhere is that the halite above the rooms will deform continuously up to Anhydrite Bed "b" (Figure 5.6.1). Although the weakness in shear of the anhydrite is accounted for in the present porosity surface model, the possibility of discontinuous roof failure and collapse to the level of the bed is not explicitly accounted for. It seems that this would be a likely occurrence under many possible scenarios. This will be discussed further below. From the viewpoint of parameters, this means that a measure of halite tensile strength and the influence of associated blocky failure on the porosity surface have been ignored.

5.7.4. Alternate Interpretation

If roof collapse occurs to the level of Anhydrite Bed "b" (Figure 5.6.1), the porosity surface could be interpreted as that of a much larger room containing blocks of salt as well as gas, brine, and waste. The porosity surface model would still appear to be appropriate in this case. However, the "room" would now be a much larger (primarily taller) room. If the room is made taller, the creep closure rate might be changed. One possibility is that collapse is associated with stress redistribution that slows the rate. A range of new SANTOS calculations could help project participants understand whether this alternate is important. Given that the porosity surface appears appropriate in any case, one would expect that accounting for room collapse would change the magnitude of the surface but not the character, which is its most important aspect, but the alternate should still be investigated.

5.7.5. Uncertainties and Consequences

Uncertainties are associated with all of the porosity surface parameters. Most of these have been discussed in Sections 5.1, 5.2, and 5.5. Given the number of parameters involved, the porosity surface must be considered an approximation. It appears that with the exceptions of the brine dissolution and roof collapse scenarios, the porosity surfaces as currently provided reasonably bound expected behavior.

The impact of gas dissolution in brine would probably shift the values of the porosity with respect to the gas quantity axis. The shift would be approximately in proportion to the ratio of dissolved gas to free gas. The basic character of the surface would not change, and only near a few end points (high pressure, low gas volume), would the magnitudes change much. The impact of including the roof collapse scenario would be to create a larger room containing salt blocks, but with no instantaneous change in porosity. This means that the boundary conditions for creep would change at that time. It seems that the net effect of this on the porosity might be small, but the calculation has not been done.

5.7.6. Appropriateness and Limitations of Methodologies and Procedures

The porosity surface and its parameters are an appropriate method of approaching and simplifying the room closure problem. Full coupling with the other systems away from the disposal room is sacrificed in order to model the room in some detail. The important aspects of coupling, however, are retained.

5.7.7. Adequacy of Application

The application of the porosity surface is in PA using BRAGFLO. If this code couples to the surface smoothly (that is, time steps are not too large), the application of the porosity surface is adequate. (It is not within the scope of this review to investigate the validity of the BRAGFLO code itself.) The parameters used to calculate the porosity surface are also adequate. Adequacy issues mentioned above with regard to brine flow, gas dissolution, and roof fall, do not appear to affect significantly the adequacy of application, although if any opportunities arise to investigate these areas, the project should consider doing so.

5.7.8. Accuracy of Calculations

The calculational methods of determining the porosity surface using SANTOS and its parameters are adequately described in the references. The accuracy of SANTOS itself is assumed in this review. It is not within the scope of this review to determine the accuracy of SANTOS.

5.7.9. Validity of Conclusions

The porosity surface is a valid method of describing disposal room closure as an input to BRAGFLO. Although full explicit coupling with the repository system away from the disposal rooms is sacrificed, the improvement in overall simplicity and disposal room modeling accuracy are well worth the sacrifice. The parameter values leading to the porosity surface have been checked by survey and spot-checked in detail. They appear to be valid. Some questions that still exist with regard to brine flow, gas dissolution, and roof fall do not substantially affect the validity of the porosity surface and its parameters, although further investigation of these areas might improve the accuracy of results.

Overall, the porosity surface is a good concept, and the final porosity surface data, as defined in WPO#35697, appear to be valid and adequate for their intended use.

5.7.10. Dissenting Views

None

6.0 EVALUATION OF DISTURBED ROCK ZONE PARAMETER

6.1. Characterization of Disturbed Rock Zone

6.1.1. General Evaluation

This section presents the Panel's evaluation of the DRZ as it relates specifically to the shaft seals program. Although the DRZ has associated parameters, such as porosity, permeability, and time, this evaluation focuses on the mechanistic properties of the DRZ, including its generation and healing concepts. The Panel was not asked to evaluate specific parameter values. A final conclusion relates to the impact the DRZ has on the permeability of the shaft zone.

The engineering behavior of the DRZ is being qualified because some of the data used in characterizing the behavior of the shaft DRZ have not previously been qualified. This behavior is not incorporated directly into the PA calculations. Instead, it is used to develop an effective permeability for each shaft seal member, which incorporates the DRZ effect into the seal member permeability. Hence, the engineering behavior of the DRZ is supporting information for the permeabilities of the individual seal members, the values of which are to be found in the respective Form 464.

As continuum creep deformation of the salt adjacent to an underground opening occurs, conditions for formation of microfractures are favorable. The salt experiences a progressive increase in microfracturing and as the fractures become interconnected, a zone of increased permeability in the formation surrounding an excavated opening develops. This region, known as the DRZ, was first identified and technically addressed by Borns and Stormont (1988, 1989), and Stormont et al. (1987, 1990, 1991, 1992).. It was measured using geophysical methods by Pfeifer et al., (1989) and found to be irregular in thickness. Tests in the WIPP air intake shaft (Dale and Hurtado, 1996) investigated this phenomenon through permeability measurements in three radial boreholes spaced 120 degrees at two levels 283 meters apart. They found the permeability reached its ambient conditions at approximately 2.3 m maximum, which translates to about 0.7 times the shaft radius.

Laboratory testing has been used to show that a halite DRZ is self-healing. The investigations of Wawersik and Hannum (1989), Brodsky (1990), Holcomb and Shields (1987), and others have shown that, given the proper confining pressures and adequate time, fractured halite will reconsolidate. In the case of shaft seals, once the seals are in place they provide the near rigid support needed to resist creep, resulting in literal re-establishment of the ambient stress field (Chan et al., 1994) and erasing the evidence of the micro-fractured zone. The Chan analysis, in collaboration with SNL, shows this phenomenon can be effective within a projected 25 years.

Within the repository the disturbed zones are considered to be part of potential pathways for release of repository gases, brines, and radioactive materials. This evaluation of the DRZ encompasses only the rock zones surrounding the shafts and boreholes, as opposed to other DRZ locations such as those that pertain to rock surrounding the waste storage rooms where the stress field is different and there is no rigid back support to effect the healing process in the early years. Numerous parameters are associated with a DRZ in the proposed WIPP repository. The most important parameters are porosity, permeability, and creep properties that most significantly impact calculations relative to the storage rooms. Since it is concluded for PA that the shaft DRZ can be considered as part of the seal permeability, no additional parameter qualifications beyond those addressed in the Natural Barriers Peer Review (1996) are important to this qualifying evaluation.

6.1.2. Adequacy of Requirements and Criteria

The objective of evaluating a DRZ is to characterize a potential enhanced ability to transmit gases and fluids in the rock mass that surrounds openings, thereby providing a basis for the mitigation of DRZ flow pathways in shaft seal design. No requirements were found to be met for this evaluation but the criteria are that the properties of the zone, its extent, and any transition behavior must be determined. Munson (1995) considers the DRZ to be primarily the result of microfracturing during tertiary creep and believes that it can account for as much as 3% of the total strain due to creep. Constitutive equations have been developed to account for this phenomenon. Munson (1995), and Chan et al. (1994), have found reasonable correlation to DRZ behavior. Both Munson's and Chan's further analyses suggest that the DRZ behavior in salt under continued stress can be described by two mechanisms: fracture closure and fracture healing. Analysis has shown that both mechanisms are positive factors to the seals program at WIPP.

Chan et al. (1995) characterized the DRZ thickness in layers exposed in the air intake shaft and estimated the healing time in salt for different shaft seal material zones for an assumed DRZ thickness of 0.8 of shaft radii. Analysis of the data showed results similar to data from the Q-room experiments; extension of the curves suggests that full healing can be realized within as little as 25 years following placement of the rigid shaft seals. Therefore, the permeability of a DRZ surrounding vertical shafts and boreholes becomes lower than that of the seals and the DRZ then does not appear to be the dominant contributor to the permeability of the shaft zones. In order to account for a DRZ contribution to this permeable zone, its permeability is incorporated into the shaft seals models as a fractional addition to the overall seal material permeability. The concepts for understanding the DRZ, its extent, and behavior to resume the original rock conditions are believed to adequately resolve that the conditions created initially by a DRZ by mining are appropriately addressed.

6.1.3. Assumptions

In order to mitigate the risk of seal failure due to deteriorating performance of any one seal material, it is assumed that a series of shaft plugs made of uniquely different materials would be used. These include recompacted crushed halite, neat and sand-rich asphalts, compacted clay, and saturated brine concrete. It is assumed that the outer reaches of the DRZ will heal in the near term; and that the DRZ fractures will close and heal once seal material is placed in the open shaft. Early data developed at SNL clearly support these conclusions (Knowles et al., 1996). A disk-shaped collar (kerf) around the shaft filled with non-permeable asphalt will effectively interrupt any flow that might penetrate the DRZ. Given these assumptions, all potential flow in the shafts is attributed to the permeability of the shaft seals materials with an adjustment to account for any DRZ component to the permeability. The shaft DRZ then is not a unique input as a parameter to the PA exercise in relation to the shaft seals.

6.1.4. Alternate Interpretation

Fracture zones in the walls of excavations have always been of concern to the mining and construction industries. In most cases, however, this fracturing occurs in brittle materials with elastic behavior, which is largely not the case in the WIPP repository viscoelastic host rock. Resolution of the salt formation DRZs, as described in this report, would be applicable within most salt formations. However, other than in the Salado formation at the WIPP site, such as in the Culebra, Magenta and other members of the Rustler formation, the DRZ will not obey the concepts put forward. The DRZ in Marker beds 138 and 139 do pose a concern for the open fractured DRZ, but this concern is dealt with in the seals design (Sandia WIPP, 1996).

6.1.5. Uncertainties and Consequences

It is projected that a concrete monolith will be placed in the shaft station drifts to aid the seal from the repository horizon and to support the shaft seals components as they are placed. Because this monolith in essence provides a base plate for the seals column, it in effect provides a base reference on the floor of the repository rather than at the roof where it can float with the salt mass as it creeps to fill the repository void. It is conceivable that because of the far field repository creep closing effects, as envisioned the designed monolith might cause sufficient stress on the walls to create a shear zone with increased permeability at that interface. No evidence could be found that this situation has been addressed and found to be benign.

A DRZ thickness of 0.8 shaft radius appears to be conservative. Munson et al., 1994 (SAND94-2134C) states that from the air intake shaft data (Dale and Hurtado, 1996) the extent of the damaged rock zone, at 6 years, is certainly less than 1.0 shaft radii, and probably only 0.7 radii. From using these same data, Chan et al., 1994, show a reasonable correlation between the test data and calculations from the MDCF model. No data were found to evaluate the effects of time between excavation and closure on this relationship.

6.1.6. Appropriateness and Limitations of Methodology and Procedures

Mitigation of the deleterious conditions produced by the DRZ appear to be positively addressed in two ways: 1) taking advantage of the creep closure mechanisms of salt, and 2) providing an impermeable waterstop ring around the shafts that protrudes beyond the zone, as revealed by the Sandia Shaft Seals testing program. This asphalt waterstop is even more plastic than the host salt rock and should provide an excellent barrier. However, its placement by means of a mechanically produced kerf introduces its own DRZ that extends the primary DRZ even further out from the shaft wall. This "secondary" kerf should be far less invasive because of the size and constraints of the opening and the short time the kerf is open. Application of the MDCF model would be expected to show that this DRZ extension would heal quickly. However, no suggestions are found of what has been done, or is possible to do, to mitigate this secondary event. Comments on this secondary DRZ are offered only to be especially conservative in discussions of the DRZ. Because of what is stated above, it is probably not important to consider further research into the extent, effects, and mitigation of this secondary DRZ surrounding the shafts and boreholes.

6.1.7. Adequacy of Application

Recognition of the DRZ phenomenon around the shafts and measurements of its effects is an important contribution to waste containment; these effects are among the few WIPP conditions that can be dealt with in an engineering fashion. It was important to find that the DRZ nearly completely heals once there is adequate support within the shaft or borehole against which the creeping salt will reestablish its original state of stress. Because of the healed state and because tests show conservatively that the DRZ areas of influence are within 1.0 shaft radii, it is possible to demonstrate that the DRZ permeability is lower than that of the seals. This appropriately allows the PA calculations to treat the DRZ permeability as an integral part of the seal. It is important to recognize that this healing factor is a function of the seal's mechanical properties and its time of placement.

6.1.8. Accuracy of Calculations

Several significant calculations were made concerning the DRZ around a shaft. The air intake shaft data (Dale and Hurtado, 1996) was reduced to show the extent of damage resulting from the shaft excavation to be less than one shaft radii. Other analysis from related data and observations from the air intake shaft tests (Munson 1995; Chan et al. 1994) also show that the extent of the DRZ is related to the shaft size, which makes the phenomenon amenable to incorporation in a mechanistic model. The collaboration of Munson et al. (1989) and Chan et al. (1994) has produced one such model through coupling the DRZ fracture to the creep model (the MDCF model). Other calculations include the determination of fracture healing time and projections of the effects of shaft seals' mechanical properties on fracture healing. Permeability calculations are straightforward and in accordance with well-tested technology. It should be recognized that the modeling results largely represent an early stage in this technological development and are subject to corrections as more data become available.

Because of predicted low impact of the DRZ on sealed shaft permeability a few years after seal placement (see section 6.1.2), it appears totally appropriate to adjust permeability of the shaft seal components for the small contribution that the DRZ will contribute to the PA calculations.

6.1.9. Validity of Conclusions

All observed considerations of analysis, study, and proposed engineered applications regarding the DRZ and its impacts on effective shaft sealing appear to be valid. The understandings developed of DRZ phenomena reveal that the increased permeability of the DRZ, with a relatively short time frame, can have a significant affect on the overall performance of sealing the shaft areas. From analysis of the relatively small amount of data, however, it appears that all considerations of this impact and the conclusions discussed here are sound and valid.

6.1.10. Dissenting Views

None

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7.0 CONCLUSIONS

The Panel carefully reviewed the 14 parameters (or parameter sets) and data sets submitted for peer review. Each is considered in Sections 4 through 6. The reader is referred to the individual conclusions for details of qualification information on each parameter in its respective section.

As an overall summary:

The Panel is in general agreement with the parameter values chosen for:

- Porosity of SMC (Section 4.1)
- Bulk modulus of crushed salt (Section 4.3)
- Permeability of SMC (Section 4.5)
- Permeability of compacted clay (Section 4.6)
- Initial density of waste (Section 5.1)
- Mechanical properties of waste (Section 5.2)
- Initial water content of waste (Section 5.3)

In the Panel's opinion, changes should be made to two of the parameters:

- Pore volume compressibility of SMC (Section 4.2)
- Permeability of consolidated waste (Section 5.4)

Three of the "parameter" packages involved overviews of parameter subsets or concepts rather than detailed evaluations of individual parameters. The Panel's findings with regard to these parameters are as follows:

- Properties of halite and anhydrite: An overview of this parameter group indicated that they are valid (Section 5.6).

- Data on final porosity surface: The Panel is in agreement with the validity of the concept, its parameters, and the calculated porosity surfaces (Section 5.7).

- Characterization of disturbed rock zone: The Panel is in general agreement with the scientific work and with SNL's level of understanding of the DRZ for modeling studies and for guiding actions to mitigate its adverse effects (Section 6.1).

The conclusions with regard to the two remaining parameters are:

- Strength of waste for blowout: The Panel agreed with the concept, but concludes that the data are insufficiently developed to qualify the value of this parameter at this time (Section 5.5).

- Permeability of crushed salt: The Panel concludes that the permeability of crushed salt should be re-evaluated. Based on current data, the assigned values and ranges may be too low, but new data now being analyzed may establish the validity of existing values or cause a modification of these values (Section 4.4).

During its work, the Panel became aware of the many complexities involved in developing Form 464 for use in the PA at the WIPP. The work reviewed appeared to be well thought through, and the supporting data were generally good. SNL's investigations at WIPP involve a broad range of scientific disciplines and the investigators are to be commended for the overall quality of their work.

8.0 SIGNATURES

I, by signature, acknowledge that I concur with the findings and conclusions within my area of expertise of this Engineered Systems Peer Review Report.

Dermot Ross-Brown, Ph.D. ESPR Panel Chairman	Rock Mechanics
John Gibbons, Ph.D. ESPR Panel Member	Geomechanics
Darrell Porter, Ph.D. ESPR Panel Member	Mineral Engineering
John Schatz, Ph.D. ESPR Panel Member	Geophysics

9.0 PEER REVIEW MEMBERS AND ACCEPTABILITY

Dermot Ross-Brown, Panel Chairman, is an independent consultant, as well as a part-time consulting employee with SAIC, based in Golden, Colorado. Dr. Ross-Brown has a Ph.D. in Rock Mechanics from the University of London, and an M.S. in Foundation Engineering and a B.S. in Mining Engineering, both from the University of Birmingham, England. He has six registrations as a Professional Engineer, and has more than 30 years of experience as a mining/civil engineer. Relevant experience includes working underground as a shift boss in production and shaft sinking, as well as conducting numerous rock mechanics investigations. For four years Dr. Ross-Brown was an expert witness involved in all geotechnical aspects of a major lawsuit resulting from a brine flood into the world's largest potash mine; the initial leak was followed by more than 30 subsequent leaks. He has been heavily involved in nuclear waste disposal since 1975, including the GEIS, and planned repositories in salt, granite and tuffs. He has been an independent reviewer on many aspects of this work (including mining, rock mechanics and regulatory compliance) for several clients including DOE/ONWI, DOE/YM, DOE/WIPP, NRC, AECL and EPRI.

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

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

John Schatz, Panel Member, is an independent geosciences consultant residing in Del Mar, California. Dr. Schatz has a Ph.D. in geophysics and a B.S. in physics, both from the Massachusetts Institute of Technology, and is an expert in the physical properties of geologic materials. He has 29 years of experience in rock properties testing and analysis, including nuclear waste-related activities at the national laboratories and in commercial industry. This includes some aspect of testing, analysis, project or peer review contributions to virtually all of the DOE nuclear-waste projects. Dr. Schatz has obtained or analyzed data on repository geologic media and backfill materials for crystalline rock and salt repositories, and has acted on review panels (including the DOE/WIPP TSG and IRT Panels over the past 4 years) with the special purpose of independently reviewing parameter packages and conceptual models

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Determination of Peer Review Member Independence Form

M

Currently employed by DOE or DOE Contractor? Yes/No
Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

- EMPLOYED BY SAIC (A DOE CONTRACTOR) FROM 1978 - 1983 AND 1985 - PRESENT. WORKED ON NUMEROUS DOE PROJECTS ALL OVER USA - SEE RESUME.
- HAVE NOT WORKED ON THE WIPP EXCEPT AS A REVIEWER THROUGH WTAC.

Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: 4/17/96

Peer Review Manager Approval: [signature] 4/25/96
John A. Thies Date

Determination of Peer Review Member Independence Form

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Battelle, Alb., IRT reviewer of WIPP Data Packages 1994-1995
ARA, Alb. Site Characterization Technology Research 1992-1993
SNL' Civil Systems Inc., High Level WIPP Experiment Planning
1977-1978

NO Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature] II

Date: NOV 29/96

Peer Review Manager Approval: [signature] John A. Thies 4/8/96 Date

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yes Employed by DOE or DOE Contractor previously? Yes/No

If yes, give dates, location, company, position type work performed.

SAIC, my employer, has been active as a DOE Contractor for many years. To date I have had no work or other relationship to work on the DOE WIPP program.

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Signature: Darrell Porter

Date: March 29, 1996

M

Peer Review Manager Approval: John A. Thies 4/8/96

Date

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NO Currently employed by DOE or DOE Contractor? Yes/No
YES Employed by DOE or DOE Contractor previously? Yes/No

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(1) 1992 - 1993 - ALBUQUERQUE - DOE/TSG SUB TO SAIC AND ASI - PRIMARILY WORK ON PARAMETER REVIEW - LOOKING AT THE BACKGROUND OF PARAMETER VALUES - NO DESIGN WORK DONE, NO FORMAL REVIEW
(2) 1995 - CARLSBAD SUB TO J.M. STOWER - IAT TEAM WORK - STRICTLY QA RELATED

NO Do you or have you had any direct involvement or financial interest in the work under review? Yes/No

If yes, describe involvement.

I hereby certify that the above information is correct to the best of my knowledge. I was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed, and to the extent practical, I have sufficient freedom from funding considerations to ensure the work is impartially reviewed.

Signature: [signature]

Date: 4/18/96

Peer Review Manager Approval: [signature] 4/25/96
John A. Thies Date