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PEER 7 - Natural Barriers Data Qualification Peer Review

CAO-96-1188

CAO PLAN
Carlsbad Area Office

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Revision 1

Title: NATURAL BARRIERS PEER REVIEW (NBPR) PLAN 010

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

1. INTRODUCTION

This Natural Barriers Review (NBPR) 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 waste form and disposal room for disposal room closure and chemistry 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.

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 natural barriers for Salado and non-Salado flow and transport 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 natural barriers 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 natural barriers 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 NBPR 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 natural barriers 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 NBPR Plan defines the approach, methods, criteria, schedules, deliverables, and resources required for conducting the NBPR 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 natural barriers subsystem related to Salado and non-Salado flow and transport include:

Natural Barriers - Salado and Non-Salado Flow and Transport

Model	Code
Disposal System Geometry	BRAGFLO
Culebra Model Geometry	SecoFL/2D/SecoTP2D
Repository Fluid Flow	BRAGFLO
Salado	BRAGFLO
Impure Halite	BRAGFLO
Salado Interbeds	BRAGFLO
Disturbed Rock Zone	BRAGFLO
Actinide Transport (Salado)	BRAGFLO
Units Above the Salado	BRAGFLO
Dissolved Actinides (Culebra)	SecoTP2D

Colloidal Actinides (Culebra)	SecoTP2D
Exploration Boreholes	BRAGFLO/GRIDFLOW CUTTINGS/PANEL
Cuttings/Caving	CUTTINGS/PANEL
Spallings	CUTTINGS/PANEL
Blowout	CUTTINGS/PANEL
Castile and Brine Reservoir	CUTTINGS/PANEL
Multiple Intrusions	CUTTINGS/PANEL
Climate Changes	CUTTINGS/PANEL

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

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 NBPR 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 NBPR 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 NBPR Panel will be composed of a minimum of three individuals who meet requirements identified in TP 10.5. The duration of the NBPR Panel review process is expected to last between three to six weeks. The NBPR 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 for the original work. Experience areas to be represented on this panel include geohydrology and/or geology.

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 NBPR 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 natural barriers may be available at the beginning of the review. Therefore, it may be necessary to conduct the NBPR in a phased manner, depending upon the availability of information.

2.2 METHODOLOGY

The NBPR 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 natural barriers 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.

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 NBPR 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 NBPR will be submitted to DOE-CAO. A list of mandatory topics and suggested outline for the final NBPR 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 NBPR 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. NBPR 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 NBPR 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
DRZ Compressibility	Salado
Undisturbed Halite Pressure	Salado
Undisturbed Halite Compressibility	Salado
Undisturbed Halite Permeability	Salado
Undisturbed Anhydrite Pressure	Salado
Undisturbed Anhydrite Compressibility	Salado
Brine Salt Mass Fracture	Salado
Brine Viscosity	Salado
Brine Density	Salado
Brine Compressibility	Salado
Castile Brine Reservoir Rock Compressibility	Non-Salado/Castille
Castille Brine Reservior Porosity	Non-Salado Castile
Castile Brine Reservoir Permeability	Non-Salado/Castile
Castile Brine Reservior Pressure	Non-Salado/Castile
Castile Brine Reservoir Volume	Non-Salado/Castile
Non-Salado Bulk Compressibility	Units Above the Salado
Non-Salado Effective Porosity	Units Above the Salado

Non-Salado Presure	Units Above the Salado
Non-Salado Permeability	Units Above the Salado
Culebra Permeability	Units Above the Salado
Culebra Index	Units Above the Salado
Culebra Transmissivity	Units Above the Salado
Culebra Thickness	Units Above the Salado
Culebra Storativity	Units Above the Salado
Culebra Fluid Density	Units Above the Salado
Culebra Steady-State Heads	Units Above the Salado
Culebra Transient Pressures	Units Above the Salado
Culebra Dolomite Grain Density	Units Above the Culebra
Effective Culebra Thickness	Units Above the Salado
Advective Porosity	Units Above the Salado
Half Matrix Block Length	Units Above the Salado
Diffusive (Matrix) Porosity	Units Above the Salado
Diffusive (Matrix) Tortuosity	Units Above the Salado

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

NATURAL BARRIERS PEER REVIEW SCHEDULE

	DRAFT	FINAL
NBPR Plan	3/11	3/29
PR Panel Assigned	NA	4/29
NBPR Data Package to PR Manager	4/22	4/29
Initiate NBPR	NA	5/6
Complete NBPR	NA	6/14
Submit NBPR Report	6/14	6/28

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

NATURAL BARRIERS DATA QUALIFICATION

PEER REVIEW REPORT

FINAL REPORT

WASTE ISOLATION PILOT PLANT
NATURAL BARRIERS DATA QUALIFICATION
PEER REVIEW REPORT

A Peer Review
Conducted By

Florie Caporuscio, Paul L. Cloke, Darrel E. Dunn,
David A. Sommers, Charles Wilson, Chuan-Mian Zhang

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 use peer reviews, conducted in accordance with NUREG 1297, as a means of qualifying data and information for use in the demonstration of compliance.

This report contains the results of a peer review of specific natural barriers data 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.

ACRONYMS

CCA	Compliance Certification Application
CDF	cumulative distribution function
CH	contact-handled
DC	direct current
DOE	U.S. Department of Energy
DRZ	disturbed rock zone
DST	drill stem tests
EPA	U.S. Environmental Protection Agency
GTFM	Graph Theoretical Field Model
PA	performance assessment
QA	quality assurance
SNL	Sandia National Laboratory
TDS	total dissolved solids
TRU	transuranic (waste)
WAC	waste acceptance criteria
WIPP	Waste Isolation Pilot Plant

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TABLES

1.0 EXECUTIVE SUMMARY

The Natural Barriers Peer Review was conducted by six panel members (Panel) who evaluated the 142 parameters submitted to them by Sandia National Laboratories (SNL) for qualification. These parameters were organized into 32 parameter packages, some of which contained more than one parameter. The parameter packages were grouped into three subsystems, Salado, Castile, and Units Above the Salado, to facilitate the review process. Table 1.1 identifies the 32 parameter packages, the appropriate subsystem and the qualification status for each.

Table 1.1 Summary of Parameter Qualification Status

Parameter Package	Subsystem	Qualification of Parameter
DRZ Compressibility	Salado	Adequate
Undisturbed Halite Pore Pressure		Adequate
Undisturbed Halite Compressibility		Adequate
Effective Halite Porosity		Adequate
Undisturbed Halite Permeability		Adequate
Undisturbed Anhydrite Pressure		Adequate
Undisturbed Anhydrite Rock Compressibility		Adequate
Brine Salt Mass Fraction		Adequate
Brine Viscosity		Adequate
Brine Density		Adequate
Brine Compressibility		Adequate
Castile Brine Reservoir Rock Compressibility	Castile	Adequate
Castile Brine Reservoir Porosity		Adequate
Castile Brine Reservoir Pressure		Adequate
Castile Brine Reservoir Permeability		Adequate
Castile Brine Reservoir Volume		Adequate
Non-Salado Effective Porosity	Units Above the Salado	Adequate
Non-Salado Pressure		Adequate
Non-Salado Permeability		Adequate
Culebra Permeability		Adequate
Climate Index		Adequate
Culebra Transmissivity Data		Adequate*
Culebra Thickness		Adequate
Culebra Storativity		Adequate
Culebra Fluid Density		Adequate
Culebra Steady-State Freshwater Heads		Adequate
Culebra Dolomite Grain Density		Adequate
Effective Culebra Thickness		Adequate
Advective Porosity		Adequate
Half Matrix Block Length		Adequate
Diffusive Porosity		Adequate
Diffusive Tortuosity		Adequate

*The transmissivity value interpreted for one well (P-18) was found to be inadequate.

In summary, the Panel was able to qualify all 32 of the parameter packages. The only exception, as noted in the table, was the transmissivity value from one of the 43 wells used to determine the transmissivity field that was deemed to be inadequate.

2.0 PURPOSE

The purpose of the Natural Barriers Peer Review was to seek qualification of scientific data by performing a systematic review of unqualified parameters used in the models describing the natural barriers subsystems 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 six 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 (EPA).

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 natural barriers subsystem. The parameters selected for evaluation had not previously been fully qualified for use in PA. The conceptual models used in the PA on the natural barriers subsystem include components of:

1. Culebra Model Geometry
2. Repository Fluid Flow
3. Salado
4. Impure Halite
5. Salado Interbeds
6. Disturbed Rock Zone
7. Units Above the Salado
8. Dissolved Actinides (Culebra)
9. Colloidal Actinides (Culebra)
10. Castile and Brine Reservoir
11. Climate Changes.

3.0 DESCRIPTION OF WORK PERFORMED

The Natural Barriers Peer Review Panel evaluated 142 parameters against the eight review criteria cited in NUREG-1297. The evaluation of these parameters was organized into the following subsystems listed in Table 3.1: 1) Salado, 2) Castile, and 3) Units Above the Salado. In some subsystems, individual parameter values were evaluated and a determination made of their adequacy as used in the WIPP PA program. In others, sets of parameters were evaluated to determine their collective contribution to a combined parameter value.

Table 3.1 Summary of Parameters Reviewed

Parameter Package	Subsystem	Number of Parameters
DRZ Compressibility	Salado	2
Undisturbed Halite Pore Pressure		1
Undisturbed Halite Compressibility		1
Effective Halite Porosity		1
Undisturbed Halite Permeability		3
Undisturbed Anhydrite Pressure		2
Undisturbed Anhydrite Rock Compressibility		3
Brine Salt Mass Fraction		1
Brine Viscosity		1
Brine Density		1
Brine Compressibility		1
Castile Brine Reservoir Rock Compressibility	Castile	1
Castile Brine Reservoir Porosity		1
Castile Brine Reservoir Pressure		1
Castile Brine Reservoir Permeability		3
Castile Brine Reservoir Volume		1
Non-Salado Effective Porosity	Units Above the Salado	6
Non-Salado Pressure		4
Non-Salado Permeability		6
Culebra Permeability		3
Climate Index		1
Culebra Transmissivity Data		100 Values
Culebra Thickness		1
Culebra Storativity		1
Culebra Fluid Density		32 Values
Culebra Steady-State Freshwater Heads		31 Values
Culebra Dolomite Grain Density		1
Effective Culebra Thickness		1
Advective Porosity		1
Half Matrix Block Length		1
Diffusive Porosity		1
Diffusive Tortuosity		1

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. The Panel collectively devoted about 40 weeks of effort to the peer review and this report. In evaluating the existing unqualified data, the peer review panel members considered the following:

- The source of the parameters and data (e.g., professional judgment, published source material, field tests, and laboratory experiments).
- 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 PA.

The Panel, in conducting its work, reviewed 32 parameter packages provided by SNL. 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 principal investigators to more fully understand the concepts and parameter derivation and application in the PA. Table 3.1 identifies the parameter package names, the associated subsystem, and the number of parameters the Panel evaluated.

4.0 EVALUATION OF SALADO SUBSYSTEM PARAMETERS

4.1. Disturbed Rock Zone (DRZ) Compressibility

DRZ compressibility is a parameter that is used in the BRAGFLO modeling of fluid movement into and out of the repository. The parameter description follows:

Parameter:	DRZ Compressibility
ID#:	175, 191
Form 464:	WPO 32758, entered 2/12/96
Parameter Package:	WPO 32037
Distribution:	Constant
Value:	7.41E-10 Pa-1

Definition: Formation compressibility of DRZ rock. Formation compressibility is $\alpha = 1/VT\ (dVT/d\sigma e)$

where:

α = formation compressibility

VT = total volume (volume of solids plus volume of voids)

σe = effective stress (stress applied to the solids of the medium)

This parameter describes the change in volume of a unit of rock mass due to stress applied to the solids of the rock.

Intended use: Used as input for BRAGFLO modeling of fluid movement into and out of the repository. In BRAGFLO, formation compressibility is expressed in terms of porosity and fluid pressure:

$\alpha = 1/\phi\ d\phi/dp$

where:

ϕ = porosity

p = fluid pressure

which is equivalent to the defining equation given above.

Derivation: DRZ compressibility was developed from pressure testing nine boreholes in the underground facility. The tests are designated C2H01GZ-B, C2H01-C, S0P01, L4P51-A, L4P51-B, S1P71-B, S1P72GZ-A, S1P73-B, and S1P74-B (draft parameter data package for transition rock dated 1/19/96). The testing yielded a specific storage (Ss) value for each test interval. In the present case, specific storage is the volume of fluid released from a unit volume of rock due to expansion of the fluid and compression of the rock under a unit decline in hydraulic head. The following equation expresses specific storage in terms of compressibilities and was used to obtain formation compressibility for each borehole:

$$Ss = \rho_f g(\alpha+\phi\beta)$$

where:

ρ_f = fluid density

g = acceleration of gravity

α = formation compressibility

ϕ = porosity

β = formation fluid compressibility

Rearranging this equation results in:

$$\alpha = Ss/\rho_f g-\phi\beta$$

A spot check of a compressivity value indicated that the equation was solved for formation compressibility by supplying the following values:

$\rho_f = 1.22$ kg/l (SAND90-0083, p. 38)

$\phi = 0.01$ (SAND90-0083, p. 36)

$\beta = 3.0\text{E-}10\ \text{Pa}^{-1}$ (SAND90-0083, p. 38)

The mean value for the compressibilities thus obtained was 7.41E-10 Pa^{-1}.

4.1.1. Adequacy of Requirements and Criteria

An objective of the DRZ testing was to characterize quantitatively the parameters that are input to BRAGFLO. No written requirements or criteria were found in the documents accompanying the peer review parameter package. However, the data and analyses must adequately support the compressibility value that is supplied to BRAGFLO.

Optimum test conditions for obtaining adequate data supporting this parameter would include the following items:

- ☐ The test zone in each borehole represents the DRZ or a portion of it,
- ☐ The test tool works properly, and
- ☐ The data acquisition system works properly.

The required condition that the test zone in each borehole adequately represent the DRZ was not met on the basis of test zone location, because some tests (SOP01, L4P51-A, L4P51-B, and S1P71-B) were for intervals below Marker Bed (MB) 139, which puts them below the DRZ as it is represented in BRAGFLO. BRAGFLO treats the DRZ as the region extending from the floor of the repository downward to the base of MB139 and extending from the ceiling of the repository upward to the base of MB138 (memo from Palmer to Chu 1/24/96, WPO32288). Some of the tests were also at greater depths than the depth of the DRZ below the repository (simulated as 2.23 m).

The required condition that the test tool be working properly was satisfied. Examination of pressure curves for the tests revealed no test tool problems that precluded the use of the data. Also, the condition that the data acquisition system be working properly appears to have been satisfied. The pressure curves look normal, and test and guard zone pressures are consistent. However, it is noteworthy that significant pressure was transmitted from the test zone to the guard zone during C2H01B testing. This pressure was thought to be transmitted by tool compliance and was used to estimate formation hydraulic parameters.

In summary, optimum test conditions for obtaining DRZ compressibility were not met because test zones that are not in the DRZ were used. However, this deficiency does not preclude the use of 7.41E-10 Pa^{-1} if it adequately represents DRZ compressibility.

4.1.2. Validity of Assumptions

Assumptions related to DRZ compressibility are those involved in the analysis of the test data. Important assumptions of the mathematical models used to analyze the test data include the following:

- ☐ Darcy flow,
- ☐ Homogeneity and isotropy of concentric rings of materials in the zone of test influence, and
- ☐ Radial flow.

The assumption of Darcy flow has been adequately discussed in SAND92-0533 (Sections 6.2 and 7.2.2).. The observation that Darcy-flow models can match pressure curves produced by different pressure differentials applied to the same test intervals supports the utility of Darcy's law as applied to the interpretation of the tests. Using the same hydraulic parameters, including permeability, under different head gradients supports the assumption of a linear relationship between flow and head gradient contained in Darcy's law. As with many linear relationships used in scientific applications, it is probably not a completely accurate assumption, but rather a useful and practical simplification.

The assumption of homogeneity and isotropy is not completely satisfied in natural materials. However, these assumptions allow for practical quantitative testing that has been found by practicing hydrologists to be useful in predicting behavior of ground water systems. These assumptions are appropriate for the analysis of the Salado borehole test data, in that more realistic modeling methods would be unlikely to reduce uncertainty significantly.

The radial flow assumption is related to the assumptions of homogeneity and isotropy because inhomogeneities and anisotropy will result in deviation from truly radial flow. However, there will be radial flow components, and this fact results in the utility of such methods in estimating permeability and associated hydraulic parameters.

An additional assumption that is relevant to formation compressibility is that the volume of formation fluid released (or gained) from an elemental volume of porous material due to pressure change is proportional to the pressure change and is released (or gained) instantaneously. Again, the fit between pressure data and theoretical curves under different pressure pulses applied to the same test interval supports the utility of the assumption when applied to the test conditions. Some uncertainty is introduced into the modeling relative to the effects of long-term plastic deformation of the halite.

4.1.3. Alternate Interpretation

The sensitivity analyses reported in SAND90-0083 show that specific storage can vary as much as four orders of magnitude without much adverse effect on the fit of data to the theoretical curves. However, no alternate interpretations that would better satisfy the objectives of the testing were identified. The degree of effect of tool compliance on the pressure curve was analyzed (SAND90-0083), and tool compliance does not seem to affect the test results to a degree that can not be accommodated in the analysis of the data.

4.1.4. Uncertainty and Consequences

Uncertainties related to obtaining a DRZ compressibility value include the following:

- ☐ Uncertainty in specific storage values due to lack of a test method that provides a unique and accurate value for specific storage, and
- ☐ Uncertainty in the value for porosity that must be used to calculate formation compressibility from specific storage.

Uncertainty in the DRZ compressibility contributes to uncertainty in BRAGFLO modeling because the compressibility is related to porosity in the conservation equations. A high compressibility would be conservative in that it would increase simulated inflow and outflow from the repository when fluid pressure changes in the repository.

4.1.5. Appropriateness and Limitations of Methodology and Procedures

As indicated in the preceding sections, the methodology was appropriate and the limitations of the methodology are acceptable. The test procedures used are described in SNL reports (for example, SAND90-0083, Section 6). The SAND reports give references to scientific literature that is subject to technical review (for example, Pickens et al. 1987). No information was lost via the computerized data reduction used for redundant pressure data, as indicated by the frequency of the remaining points. Although the compressibility of the DRZ probably varies with time, the effects of such variation are covered by the treatment of uncertainty described above. The test equipment functioned well for the tests utilized for DRZ compressibility, and detection limits were adequate, as indicated by the pressure curves themselves. Specific storage values calculated from different segments of the data derived from pressure test data sequences provided checks on the general representativeness of the test results.

4.1.6. Adequacy of Application

As indicated in the preceding sections, the data used to develop the DRZ compressibility value were adequate except that some data did not come from the DRZ, as it is defined for BRAGFLO simulation. Examination of the times when adjacent boreholes were tested and examination of pressure curves yielded no evidence of test-to-test interference. Test irregularities and interruptions, such as malfunctions of tools, are shown on the test data curves and were adequately dealt with.

4.1.7. Accuracy of Calculations

No hand calculations or spreadsheet calculations were found in the records cited in the parameter package. Re-calculation of formation compressibility from QPP05 specific storage, as an example, showed that the value was correctly calculated. Inspection of other compressibility values indicated that calculated values, such as converted units, were properly executed.

4.1.8. Validity of Conclusions

The constant value of 7.41E-10 Pa^{-1} selected for DRZ compressibility is conservative and reasonable for use in PA modeling. As noted in Section 4.1.4, high values for compressibility tend to be conservative. The value 7.41E-10 Pa^{-1} is exceeded by only two values from the nine boreholes included in the data Parameter Package. The range of the values for the nine boreholes is from 1.85E-13 to 3.27E-9.

Although some of the tests used to develop the DRZ compressibility were not in the DRZ, as represented in the BRAGFLO model, the value selected is adequate. The average compressibility from tests of rock in the DRZ between MB139 and the repository floor is 2.72E-10 Pa^{-1}, which is not significantly different from 7.41E-10 Pa^{-1}. The compressibilities used to calculate 2.72E-10 Pa^{-1} were from boreholes C2H01Gz-B, S1P72GZ-A, C2H01-A, and QPP05. The reason for calculating compressibility for rock above MB139 to check the adequacy of the value selected for BRAGFLO input is that it is material through which contaminants must traverse vertically to reach MB139. MB139 is an anhydrite interbed that might have an important role in lateral repository inflow/outflow.

4.1.9. Dissenting Views

None.

4.2. Undisturbed Halite Pore Pressure

The Parameter Package contains the Form 464, which has attached two data sheets from the 1992 PA showing undisturbed halite pore pressure data from boreholes QPPO5 and QPP15 drilled adjacent to Room Q and referencing the source document, SAND92-1172. The hydraulic tests conducted in these two boreholes need to be qualified by the peer review process to support this parameter.

Parameter: Undisturbed Halite Pore Pressure (brine far-field pore pressure)

ID #: 546

Form 464: WPO 34394, entered 2/8/96

Parameter Package: WPO 31221

Distribution: Uniform

Parameter Values: Minimum: 11.04 MPa

Maximum: 13.89 MPa

Ⓜ

Definition: The Brine far-field pore pressure (also known as the Undisturbed Salado Halite Pressure) is the pressure of the fluid in the halite unit within the Salado formation, under natural undisturbed conditions.

Intended Use: The intended use of the parameter is for entry into the BRAGFLO model as one of several specific initial scientific parameters describing the rock properties of the repository area within the Salado Formation in its natural state upon decommissioning.

Derivation: The Undisturbed Halite Pore Pressure is based on interpretation of Graph Theoretical Field Model (GTFM) 6.0 simulation of pressure, fluid volume withdrawal, temperature, axial test-tool movement, and radial borehole closure recorded during two hydraulic tests, of an isolated test interval of the undisturbed halite, performed in two boreholes, QPP05 and QPP15, adjacent to Room Q.

Discussion: No fluid movement could be clearly identified in the tested halite in either QPP05 or QPP15, due to the extremely low permeabilities of the test zones. Therefore, there are uncertainties about pressure values obtained from GTFM 6.0 analyses of the halite test zone data.

4.2.1. Adequacy of Requirements and Criteria

Inspection of the logs and tool configuration diagrams in SAND92-1172 indicates that the test zones in boreholes QPP05 and QPP15 were within the Salado halite unit and that the collected data most likely represent information from the halite unit.

The tests conducted in boreholes around Room Q were designed to help reduce uncertainties about brine flow and provide information on the Salado Formation pressure, permeability, and flow potential both within the zone of potential influence of the WIPP excavations and in the undisturbed, so called, "far field" parts of the Salado. Thus, in that sense, the tests did meet the adequacy of requirements, although there are some limitations on the interpretations, as discussed in SAND96-0435 (see Section 4.3.3).

4.2.2. Validity of Assumptions

The assumptions made during testing of the undisturbed Salado halite interval were that Darcy flow and borehole closure were the only forms of pressure/flow transmission during the hydraulic testing.

For those particular tests in boreholes QPP05 and QPP15, the absence of flow precludes confirmation of the assumptions.

4.2.3. Alternative Interpretations

A normal part of the analysis of hydrologic flow data involves use of standard "type curves" to match theoretical curves of different flow conditions with the collected data. Therefore, different interpretations may be possible depending on the assumptions used in the analysis. With regard to borehole QPP15 data for the constant-pressure flow test (SAND96-0435, Fig. 7-69), three alternative interpretations were analyzed for the curve, matching flow rate against elapsed flow time. These alternative interpretations were for spherical, radial, or linear flow. As can be seen in the Figure 7-69, the data match for radial flow is obviously the most reasonable fit, starting after one day of flow and ending slightly past 100 days, whereas, the linear flow type curve for the same data points does not match the data. Therefore, it appears that the interpretation used in selecting the values to estimate formation transmissivity is reasonable and appropriate.

4.2.4. Uncertainty and Consequences

With regard to the field data from boreholes QPP05 and QPP15, there is some uncertainty about the accuracy of these data as the pressures dropped a few tenths of a MPa after fluid injection and then stabilized at arbitrary and different pressures. This is thought to reflect extremely low pre-mining permeability of the halite (i.e., 1.1E-24 m^2 for QPP05). In addition, the GTFM 6.0 simulation could not match these pre-mining pressure decreases without adding a skin effect of higher permeability for a skin thickness of 0.87 cm around the borehole. It may be reasonable to assume that there was a thin layer of borehole "damage" around the borehole as a result of drilling. On the other hand, it may be possible that the early-time pressure changes and high early time flow rates are due to tool movement and/or packer-compliance effects.

According to SAND96-0435 (p. 81),

> "The simulation is non-unique because the pre-mining pore pressure could not be estimated with the available data. The value used in the simulation, 7.5 (sic) MPa was chosen arbitrarily and similar fits could be obtained by simultaneously adjusting the transmissivity and pore pressure."

The uncertainties in the data are: 1) the value (13.9 MPa) selected for the maximum pre-mining halite pore pressure in borehole QPP05, because this value was obtained by GTFM 6.0 simulation, which involves uncertainty; 2) in general, any of those parameters used to match the data measured in QPP05 during the post-mining time period for the reason that the test and guard zones were in hydraulic communication; and 3) the value (11.0 MPa) for the maximum pre-mining pressure of the undisturbed halite pore pressure in borehole QPP15, because this value was obtained by GTFM 6.0 simulation using post-mining test sequence parameters, which showed the effects of disturbance (i.e., after mining Room Q, the borehole QPP15 test zone was within the DRZ, as was the test zone in borehole QPP05).

4.2.5. Appropriateness and Limitations of Methodology and Procedures

The testing apparatus used in 1989 was fabricated from off-the-shelf components which, to a large extent, dictated the methodologies and procedures used to measure pressure and permeability directly in the boreholes.

The 0-200 psi strain-gage pressure transducers used to measure pressure in the test and guard zones were accurate to 1 psi over the rated pressure range. The packer pressures were monitored using 0-3000 psig pressure transducers accurate to 30 psi over their rated pressure range.

Data from the tests were reduced for presentation in SAND92-1172 by sorting according to borehole number, recording time, and measurement type, calculating all measurements to a time interval since zero-hour, converting all measurements from U.S. to metric units, and filtering out redundant values with a data filter. Although SAND92-1172 does not document that the reduced data are an accurate representation of all data, it is apparent by reviewing the curves of pressure vs time in the test zone that the data appear to be representative of test conditions.

The description of the test equipment, tool installation, test startup and results of testing presented in SAND92-1172 indicate that the test procedures were correctly implemented.

4.2.6. Adequacy of Application

Regarding possible test-to-test interference as shown in SAND96-0435, a visual comparison of QPP04 test-zone pressure (Fig. 6-28) and QPP05 test-zone pressure (Fig. 6-35) shows no obvious effects of QPP04 test activities on QPP05. Likewise, a comparison of QPP14 test-zone pressure (Fig. 6-66) and QPP15 test-zone pressure (Fig. 6-73) shows no obvious effects of QPP14 test activities on QPP15, as shown in SAND96-0435.

The observed pressure changes may have been affected by changes in the packer-inflation pressures brought about by borehole deformation resulting from salt creep, and possible associated movement of the borehole test tools.

There was no direct identification (i.e., measured core from the borehole) of the stratigraphic interval being tested in the borehole. Thus, it is possible that the test-intervals could overlie units above or below the expected test stratigraphic zone.

In Table 7-1 of SAND96-0435, which shows a pore pressure value of 13.9 MPa for borehole QPP05, there is a notation that the value has a high relative uncertainty. In Appendix C (SAND92-1172 p. c-30) there is a notation at the bottom of the operational log for borehole QPP15 that during the period 5/13/90-7/16/90 the QPP15 test region pressure transducer was being used in QPP14 and therefore the closure data should be ignored for this period.

There are no specific statements regarding data confidence in the SAND92-1172 report, although it can be inferred from the operational logs of each borehole (SAND92-1172, Appendix C) that the data can be considered reliable by the reason that data are specifically identified in the QAC and CAC section of the operational log.

4.2.7. *Accuracy of Calculations*

The source reference (SAND92-1172) listed in the 1992 PA does not contain calculations, nor does the interpretative report, SAND96-0435, which only shows graphs and charts of the results of interpretation from various analytical and numerical models.

4.2.8. *Validity of Conclusions*

Reportedly, the maximum pore pressure that would be expected to be found in the Salado halite at the WIPP repository, under a normal geothermal gradient, would be lithostatic pressure of approximately 14.8 MPa (~2150 psi). Therefore, using a value of 13.9 MPa (the maximum value of undisturbed halite pressure obtained by GTFM 6.0 simulation) in BRAGFLO, as the maximum pore pressure value of undisturbed halite, would appear to be reasonable.

The value of formation pore pressure of 11.0 MPa was obtained with GTFM 6.0 simulation by using a skin thickness of 1.5 cm around the borehole with corresponding skin transmissivity of 1.8E-15 m^2/s, whereas, the formation transmissivity value used was 2.8E-17 m^2/s. Therefore, it appears that the GTFM 6.0 simulation of the QPP15 borehole pressure data does not provide an accurate estimation of the undisturbed ("far field") halite pore pressure. It does, however, seem reasonable to use this value as a minimum, because it represents approximately 74% of lithostatic pressure at that depth. Plus, it is consistent for formations with a poor hydraulic connection to units under hydrostatic pressure.

In summary, considering all factors, the reliability of conclusions regarding the undisturbed halite pore pressure in the Salado evaporites, as obtained from the testing of boreholes QPP05 and QPP15, seems reasonable for use in the BRAGFLO model, as the maximum pressure value of 13.89 MPa is fairly close to the calculated maximum lithostatic pressure of 14.8 MPa at the depth of the testing in the Salado (i.e., ~ 2150 feet bgs).

4.2.9. *Dissenting Views*

None.

4.3. Undisturbed Halite Compressibility

The adequacy of undisturbed Salado halite bulk (or rock) compressibility data is addressed in this section.

Parameter: Bulk Compressibility

ID #: 541

Form 464: WPO 34210, entered 2/14/96

Parameter Package: WPO 31220

Distribution: Uniform

Parameter Values: Maximum: 1.92E-10

Minimum: 2.94E-12

Definition: Formation compressibility is $\alpha = -(1/VT)(\partial VT/\partial \sigma e)$

where:

VT = total volume of the rock

σe = effective stress.

Intended Use: This parameter is needed in BRAGFLO in order to simulate the flow from brines in the Salado formation into or out of the repository.

Derivation: The data were derived from two hydraulic tests in boreholes in undisturbed halite. The code GTFM 6.0 was used to obtain specific storage values which were used to calculate the compressibility.

Discussion: These data were developed from specific storage values determined from analysis of pre-mining hydrologic tests in Room Q boreholes QPP05 and QPP15. This methodology yielded rock compressibility values ranging from 2.94E-12 Pa-1 to 1.92E-10 Pa-1. These tests and analysis of the results obtained are presented in SAND92-1172 and SAND96-0435.

4.3.1. Adequacy of Requirements and Criteria

The requirements for the tests were not specifically stated in the source documents, but for purposes of this parameter they are inferred to have been to obtain data that represent the range of compressibilities of Salado halites for use in repository flow modeling. These requirements are adequate for purposes of the PA.

4.3.2. Validity of Assumptions

The compressibilities were calculated from specific storage parameters obtained from analysis of borehole tests using the GTFM 6.0 code. The relationship among these parameters is commonly expressed by the following equation:

$$Ss = \rho g(CR + \phi\beta)$$

where:

Ss = specific storage

ρ = brine density

g = acceleration of gravity

CR = rock compressibility

ϕ = rock porosity

β = brine compressibility

The test zones in boreholes QPP05 and QPP15 were found to have the lowest permeabilities of any zones tested around Room Q. The test zone in QPP05 is in halite map unit MU-6. It is probably the closest to pure halite of any of the tested zones around Room Q and has an average of less than 0.5% clay and polyhalite (SAND92-1172 p. A-5). The test zone in QPP15 includes part of halite unit 0 which contains up to 5% clay, and part of polyhalitic unit PH-4 which contains up to 3% polyhalite and scattered anhydrite and clay (SAND92-1172 p. A-6). The range of average degree of impurities in the tested units approximately spans the range typically observed in the Salado halites; however, the degree of impurities present in the actual test zones is not known and could be different from the average. If the test zone lithologies were typical of the units as a whole, the test results could be expected to provide an appropriate range of rock compressibilities. The very low permeability and storativity determined for

QPP05 suggests, however, that this test zone may not be typical of the Salado halites and that the calculated compressibilities may favor the low end of the range.

4.3.3. *Alternate Interpretations*

The very low permeabilities of the test zones resulted in the lack of a clear indication of fluid movement in the halite during the tests, which in turn made the analysis results highly uncertain. The test data were analyzed for a number of combinations of permeability and specific storage, each of which provided a good match to the test data, but most of which had unreasonably high or low values for specific storage. Although the adopted results provided a reasonable set of parameters, they were non-unique and other reasonable values of specific storage (and hence rock compressibility) could have been inferred.

4.3.4. *Uncertainty and Consequences*

The interpretations made in analyzing the test results are acknowledged in SAND96-0435 (p. 27) to carry a high relative uncertainty and a general discussion of test uncertainty is presented in SAND96-0435 (p. 23). In both QPP05 and QPP15 the principal uncertainty results from the aforementioned lack of a clear indication of fluid movement in the halite. Specific storage and permeability are linked in the analysis because to maintain a good match to field data, specific storage must be increased as permeability is decreased. Although the adopted test results published in SAND96-0435 (Table 7-1) provide a reasonable balance among permeability, specific storage, and the other parameters considered in the analysis, other parameter sets that would also be considered reasonable could have resulted in specific storage values that varied by at least an order of magnitude. The value of halite porosity is also uncertain, as described in Section 4.4 of this report (undisturbed halite porosity), which adds to the uncertainty of the calculated compressibilities. Further discussion of the uncertainty of results from these borehole tests is presented in Section 4.5.4 of this report (undisturbed halite permeability).

The consequences of error from using the derived compressibility values in hydrologic analysis would be to increase or decrease the rate at which pressure transients are propagated in the undisturbed Salado halites, with errors in early time flow rates resulting from these transients. Later time flow rates approach steady state and would be less affected. These consequences are not considered significant because of the long time periods over which pressure transients in the undisturbed halite occur in long term performance assessment calculations. A relatively low sensitivity of model results to variations in rock compressibility was found during studies reported in SAND93-1986 (pp. 6-7 to 6-10).

4.3.5. Appropriateness and Limitations of Methodology and Procedures

The test methodology and procedures are well described in SAND92-1172 and SAND96-0435. Further discussion of methodology and procedures is presented in Section 4.5.5 of this report (undisturbed halite permeability). The principal limitations of using the results of these tests to calculate rock compressibility are associated with the high degree of uncertainty in the specific storage values from which the compressibilities were calculated, and the lack of direct evidence that the compressibilities actually represent the range of compressibilities for the undisturbed Salado halites. A comparison with specific storage values determined from the results of tests in other Room Q boreholes (SAND96-0435, Table 7-1) supports the validity of this range, but most of the results of the other tests also carried a high degree of uncertainty.

If taken without the additional supporting information noted below, the approach adopted to determine halite bulk compressibility would not be adequate for use in performance assessment because of the high uncertainties in the results of the specific borehole tests and a lack of confirmation that the data appropriately represent the range of values for the parameter. To provide an independent check, halite compressibility (C_R) was determined from elastic theory using the following relationships for an isotropic medium:

$$CR = 1/K$$

and

$$K = E/\,(3(1-2\sigma))$$

where:

K = halite bulk modulus

E = halite Young's modulus

σ = Poisson's ratio.

Adopting values of $E = 31$ GPa and $\sigma = 0.25$ (SAND88-2948, p. 26), C_R was calculated to be 4.8E-11 Pa^{-1}. This value is considered to be on the low side (the method used to determine Young's modulus may overestimate that value), with roughly estimated uncertainty resulting in a range of approximately 3.0E-11 Pa^{-1} to 5.0E-10 Pa^{-1}. Although the calculated elastic theory value lies approximately in the middle of the performance assessment range of 2.94E-12 Pa^{-1} to 1.92E-10 Pa^{-1}, that range may also be on the low side because the very low values of permeability and specific storage obtained from the QPP05 test suggest an atypically tight test interval.

4.3.6. *Adequacy of Application*

Although the supporting information suggests that the low end of the range of undisturbed halite compressibilities used in performance assessment may not be realistic for the large scale rock mass behavior, the effect on the performance assessment is expected to be small for the reasons given in Section 4.3.5. This observation is supported by sensitivity studies of repository response to a variety of parameters reported in SAND93-1986 (pp. 6-7 to 6-10), where the sensitivity of selected performance measures to halite rock compressibility was found to be intermediate to low. However, the compressibility values evaluated in SAND93-1986 did not go so low as the low end of the range used in performance assessment. Application of the selected range of compressibility values to performance assessment is expected to be adequate; however the reliability of the low end of the range is questionable.

4.3.7. *Accuracy of Calculations*

The calculation of compressibility from the equation for specific storage in Section 4.3.2 was checked using the parameter values of $\rho = 1220$ kg/m^3, $g = 9.7917$ m/s^2, $\phi = 0.013$, and $\beta = 3.1\text{E-}10$ Pa^{-1} given in the Parameter Package, and was found to be accurate.

4.3.8. *Validity of Conclusions*

The results obtained from using a range of 2.94E-12 Pa^{-1} to 1.92E-10 Pa^{-1} for undisturbed halite compressibility as reported on Form 464 WPO 34210, entered 2/14/96, should be appropriate for use in performance assessment.

4.3.9. *Dissenting Views*

None.

4.4. Effective Halite Porosity

The data Parameter Package contains two major references as attachments for the data source for the constructed distribution of effective halite porosity. The first is p. A-II-5 in SAND93-1986, which is the data page for Salado Porosity dated 08/31/93. This, in turn, references the earlier "drying experiments" of samples of the Salado evaporites conducted by Powers (SAND78-1596) and the DC resistivity measurements made underground at the WIPP site by Skokan (SAND87-7174). The second major reference is p. 2-41 through 2-43, dated 12/29/92, of SAND92-0700/3.

Parameter: Effective Halite Porosity (Undisturbed)

ID #: 544

Form 464: WPO 34387, entered 2/22/96

Parameter Package: WPO 30601

Distribution: Cumulative

Parameter Values: Minimum: 1.0E-03 0.0 Prob

Maximum: 3.0E-02 1.0 Prob

Median: 1.0E-02 0.5 Prob

Definition: The Effective Halite Porosity is the ratio of the volume of interconnected pore space to the volume of the rock matrix within the halite unit in the Salado Formation under natural conditions, not disturbed by mining, or other man-induced activities.

Intended Use: The intended use of the parameter is for entry in the BRAGFLO model as the parameter defining the ratio of interconnected pore space through which fluids can migrate in the undisturbed halite of the repository zone.

Derivation: The effective halite porosity values have been inferred from the results of thermogravimetric analyses (water loss during heating) of Salado halite core from early drill holes in the repository, electrical resistivity experiments conducted at the WIPP site, and calculations of porosities based on parameters for Archie's Law used in core damage and Room-D seal studies (Borns 1996).

The maximum value for halite porosity of 0.03 (3%) was originally based on a reported 10-ohm DC-resistivity value made underground at the WIPP site (SAND87-7174, p. 13). However, upon scrutiny, it appears that SAND87-7174 (p.13) contains a typographical error in that the 10-ohm value actually should have been reported as 100 ohms. A 100-ohm value used in Figure 7 (SAND87-7174, p. 6) instead of the 10-ohm value, would yield a weight percent of water reasonably close to the bulk water content in the salt, about 2% by weight stated in the report (SAND87-7174, p. 13). This would translate into a porosity volume of approximately 3.4% for a maximum effective halite porosity as discussed below.

A maximum effective halite porosity value of 0.034 also is supported by other calculations showing effective Salado halite porosity of 0.036 based on parameters entered in Archie's Law equation as used in core damage and Room-D seal studies (Borns 1996).

The lower limit (minimum) of 0.001 (0.1%) effective halite porosity was inferred from the drying experiments of Powers (SAND78-1596).

Discussion: The median effective porosity value of 0.01 listed on Form 464 was inferred from geophysical resistivity measurements at the WIPP site. A similar value can be calculated from grain density and bulk density of halite, using the formula:

$$\rho b = (1 - \phi)\rho g$$

where:

ρb = bulk density

ρg = grain density

Using a measured halite bulk density value of 2.14E+03 kg/m^3 from tests on collected Salado halite samples, and a referenced halite grain density of 2.163E+03 kg/m^3 (p. 2-22 of SAND92-0700/3), a median value of 0.01 (1%) for halite porosity was calculated (SAND92-0700/3, p.2-42).

The relationship between volume percentage of effective porosity and weight percent of water (brine) is dependent upon the brine density (approximately 1.22 g/cm^3) and salt density (approximately 2.2 g/cm^3). Therefore, the volume percentage of effective porosity will be greater than the weight percentage of brine by a factor of approximately 1.7, or conversely, the weight percentage of brine would be approximately 60% of the volume of effective porosity.

As previously discussed under derivation, the 10-ohm value cited in the Parameter Package (WPO 30601) is considered to be erroneous. Therefore, the discussions herein regarding the DC electrical resistivity studies do not consider a 10-ohm value for the lower limits, but rather a 100-ohm value.

4.4.1. Adequacy of Requirements and Criteria

The estimation of the undisturbed effective halite porosity parameter value from geophysical studies of electrical resistivity of the evaporite beds at the WIPP site (SAND87-7174), introduces some uncertainty. The resistivity data collected by the Geonics model EM-31, which uses induction coils separated by a distance of 3 m, measures rock resistivity at shallow penetration depths (1-2 m). The EM-31 data probably are representative of the resistivity of the halite (and other evaporite beds) as measured near the edge of the shaft excavation in a disturbed zone. Thus, the resistivity values indicating possible moisture contents as high as 0.8 to 2.0%, interpreted from Figure 7 and reported in SAND87-7174, may represent resistivity of partially saturated rocks in the DRZ.

The resistivity data collected by the Geonics model EM-34 measures resistivity at greater depth penetrations (10-20 m) and it shows resistivity values considerably lower than those measured by the EM-31 for the same lithology in nearly the same location. This suggests, using Figure 7 (SAND87-7174), that the same salt at greater distance from the shaft excavation has a higher water content (2-3%) than the salt adjacent to the shaft. A possible explanation for the higher water content away from the shaft may be that the salt adjacent to the shaft had been dried by the air flow in the shaft and was only partially saturated with brine.

4.4.2. Validity of Assumptions

The gross results (interpretations) of the geophysical survey measuring earth resistivity as presented in the report (SAND87-7174) tend to show a general agreement among the different methods used, for example, 1) source DC current from the land surface, and 2) electromagnetic coupling equipment using two different induction coil separation distances. Therefore, it appears that the assumptions used regarding the three-layer earth model are probably valid for the DC electrical resistivity measurements.

The results of the static heating experiments on halite (SAND78-1596) provide reasonable data useful for the calculation of free water content in halite, which is indicative of effective porosity assuming that all the water released by heating is from the interconnected pore spaces. This suggests that the test design, data collection and analysis were appropriate for the intended use of the data.

Measurement of moisture content in halite by thermogravimetric analysis and static heating could include moisture released from the total porosity (including inclusions) of the halite, depending on the maximum temperature to which the sample was heated. The moisture content would also depend on the composition of individual samples, and could include moisture from dehydration of clay minerals. As long as the definition of undisturbed halite is for a pure halite with only trace amounts of impurities, then the measurement reported by SNL of moisture content released during heating up to 102° C should be a reliable indicator of the total amount of free water within the total effective porosity in the halite.

4.4.3. Alternative Interpretations

In the case of the static heating tests of the halite (SAND78-1596), there do not appear to be alternative interpretations, other than explaining those minor differences in weight loss among different samples. This apparently was a result of differing amounts of different trace mineral impurities in the halite tested, and, possibly, loss of water from sample handling and storage techniques.

The DC electrical resistivity investigations are subject to alternative interpretations, depending on which earth model is used to calculate apparent resistivities. The three-layer model was used to account for the stratigraphy at the WIPP site and accepted as appropriate, whereas the uniform earth model was used to model the site and determined to be inadequate.

4.4.4. Uncertainty and Consequences

There is no discussion in SAND87-7174 of the uncertainty of results for the geophysical resistivity measurements.

The static heating experiments on halite (SAND78-1596) indicate that, depending on sample constituents, the moisture loss at 70°C ranged from zero to 1.9% by weight, with values typically in the 0.20 to 0.30% range. The range of weight loss at 102°C was from zero to 3.5%, with the majority of samples showing less than 0.5% weight loss. This would suggest a range of effective porosities of the heated halite from near zero to approximately 5.9%. Thus, it seems apparent that the low end value of 0.001 (0.1%) for effective porosity listed on the Form 464 would be within the low-end range of weight loss values indicated by the static heating experiments. The high end value of 5.9% (weight loss of heated sample at 3.5%) may reflect the result of impurities, (e.g., clay) in the sample that may have released water. Thus, the high end values from the heating experiments are probably not representative of pure halite.

4.4.5. Appropriateness and Limitations of Methodology and Procedures

It would appear that the DC-source geophysical resistivity values obtained (SAND87-7174) for the halite at the WIPP site would represent gross values averaged over several tens to hundreds of meters distance. As such, the values obtained would provide a reference value to compare with other values representing more discrete zones that might be obtained through other scientific methods.

At the time (1978) the static heating experiments were conducted with the halite samples (SAND78-1596), the methods used were appropriate and remain so today (1996). However, the static heating and thermogravimetric methods of Powell (1978) were subject to uncertainty due to probable water loss in samples during sampling, transport and preparation in the laboratory. This water loss, the result of evaporation of the pore fluids, may have left chemical precipitates in the pore throats which would reduce the degree of interconnectivity and plugged pore throats. This could have reduced the amount of water that escaped the sample upon heating, thus, indirectly resulting in a reduction in the estimate of effective porosity.

4.4.6. Adequacy of Application

The geophysical resistivity data originally were collected to determine if this technique could be used to detect and map fractures and brine concentration in the salt layers. The investigation and data collection were not conducted with the specific purpose of determining a value for halite porosity. Estimation of halite porosity for the PA was made by inferring values of porosity from Figure 7 (SAND87-7174), a chart diagram of apparent resistivity vs water content. The estimated 1.0 to 3.0% weight of water as interpolated from Figure 7 using the EM-31 and-34 resistivity measurements, is equivalent to an upper limit for effective porosity of approximately 1.7 to 5.1% of undisturbed halite, whereas, the interpretation of a 100-ohm resistivity value from the DC resistivity survey using Figure 7 would provide a weight percent water content of approximately 3.0%, equivalent to approximately 5.10% effective porosity. Thus, the results of the two geophysical methods are in fairly close agreement.

The static heating experiments (SAND78-1596) indicated a range of weight loss values at 102 ± 5° C for the Salado salt samples from 0.0 to 3.5% with the majority of samples showing losses less than 0.5%. Thus, the effective porosity values for the Salado halite, based on the static heating experiments, would range from approximately zero to 5.9%, but the majority of the values would be less than 0.85%. For use in the PA, the low end values are probably more appropriate; thus, a value of minimum effective halite porosity of 0.001 or even less than 0.001 appears reasonable.

4.4.7. Accuracy of Calculations

It is not possible to check the accuracy of the calculations for the geophysical resistivity investigation (SAND87-7174) because critical numbers used in the equations presented are not provided in the report, nor are tables of the collected data. Likewise, calculations of weight loss are not shown for the static heating experiments (SAND78-1596). Thus, checking the accuracy of these calculations is not easily accomplished.

4.4.8. Validity of Conclusions

Geophysical resistivity data supporting the porosity interpretation in SAND87-7174 are not presented. However, the conclusions are supported indirectly by the results of other investigations of the halite, e.g., static and thermogravimetric heating studies (SAND78-1596) and core damage and Room-D seal studies (Borns 1996).

From the results of the static heating studies (SAND78-1596) it has been estimated that the lower limit of undisturbed halite is 0.001 (0.1%). This minimum porosity value could be high, but is considered a conservative and realistic number. Some of the test results on halite indicated no measured weight loss upon heating to 102° C, which suggests that a minimum value of porosity for some volumes of undisturbed pure halite approaches zero.

The results of the static heat weight loss studies on some samples of halite heated to 102°C were recorded as 0.0%, the split of one of these 0.0% weight loss samples analyzed by thermogravimetric techniques showed a weight loss of 0.15 % at 70° C. Thus, it appears that a lower limit at 0.001 (0.10%), for construction of the distribution of undisturbed halite, is probably a reasonable minimum value for this parameter.

The maximum value of 0.03 (3%) for effective porosity of the halite is based on the interpretation of electrical resistivity from geophysical investigations conducted at the WIPP site. This value may be slightly low, as discussed in Sections 4.4.4 and 4.4.6. The minimum, maximum and mean values selected for the cumulative distribution are reasonable for use in BRAGFLO.

4.4.9. Dissenting Views

None.

4.5. Undisturbed Halite Permeability

This section reviews the data from which the logarithm of intrinsic permeability for intact Salado halite was derived.

Parameter: Log of intrinsic permeability, x direction

ID #: 547

Form 464: WPO 34397, entered 3/6/96

Parameter Package: WPO 31218

Distribution: Uniform

Parameter Values: Maximum: -21.0 [log(m2)] (1.0E-21 m2)

Minimum: -24.0 [log(m2)] (1.0E-24 m2)

Parameter: Log of intrinsic permeability, y direction

ID #: 548

Form 464: WPO 34399, entered 3/6/96

Parameter Package: WPO 31218

Distribution: Uniform

Parameter Values: Maximum: -21.0 [log(m2)] (1.0E-21 m2)

Minimum: -24.0 [log(m2)] (1.0E-24 m2)

Parameter: Log of intrinsic permeability, z direction

ID #: 549

Form 464: WPO 34401, entered 3/6/96

Parameter Package: WPO 31218

Distribution: Uniform

Parameter Values: Maximum: -21.0 [log(m2)] (1.0E-21 m2)

Minimum: -24.0 [log(m2)] (1.0E-24 m2)

Definition: The intrinsic permeability is defined as $k = K\mu/\rho g$

where:

K = hydraulic conductivity

μ = fluid viscosity

ρ = fluid mass density

g = gravitational constant

Intended Use: The intrinsic permeability is required by BRAGFLO for modeling the brine flow in and out of the repository.

Derivation: The data were derived from two hydraulic tests in boreholes in undisturbed halite. The code GTFM 6.0 was used to estimate the permeability.

Discussion: The adequacy of undisturbed halite permeability data from hydraulic tests in boreholes QPP05 and QPP15 is addressed in this section. These boreholes were two of fifteen test holes drilled as part of the Room Q experiment. Parameter numbers 547, 548, and 549 refer to the components of the undisturbed halite permeability tensor in the x, y, and z directions. The following discussion addresses only those parts of the field tests performed under undisturbed conditions before Room Q was excavated.

4.5.1. Adequacy of Requirements and Criteria

The requirements and criteria for the tests were adequately defined. The test objectives, as stated in SAND92-1172, Section 1.3 and SAND96-0435, Section 6.1, and as applicable to this parameter, were to "determine formation permeability [under undisturbed conditions] ... before ... Room Q mine-by." (SAND92-1172, p. 2). The tests were conducted within the Salado halites at ambient temperatures using a dual test-packer/guard-packer configuration and brine as a test fluid. The data are considered representative of the halite in the immediate vicinity of the tests; however, because of limited test durations and the extremely low permeability of the tested halite, the permeability of the halite could not be uniquely determined.

4.5.2. Validity of Assumptions

The tests were designed and analyzed assuming Darcy flow in isotropic porous media. Temperature, borehole closure, and residual pressure transients from prior test activities were accounted for in the analysis. Temperatures were monitored inside the test tool in the guard zone but not in the test zone. Temperatures in both holes were seen to rise when Room Q was mined, and then drop back over time to the premining ambient level of about 26.7 ± 0.1°C. The long test duration, lack of significant short-term transients, lack of significant heat sources within the test tool, high thermal conductivity of the salt, and close proximity of the guard zone to the test zone suggest that the temperature of brine in the guard zone is an adequate surrogate for the temperature of brine in the test zone.

The assumption of Darcy flow appears to have been appropriate for tests conducted in adjacent boreholes where the halite was more permeable, and by inference is considered appropriate for the tested halite. However, this assumption cannot be confirmed by the test results because no fluid movement could be clearly identified in the tested halite in either QPP05 or QPP15, due to the extremely low permeabilities of the test zones.

The assumption that the tested halite behaves as an isotropic porous medium is probably inaccurate: the test zone in QPP05, although probably the closest to pure halite of all zones tested around Room Q, has an average of less than 0.5% clay and polyhalite, which could cause anisotropy. The test zone in QPP15 includes part of halite unit 0 and part of polyhalitic unit PH-4, which have different fractions of polyhalite and are likely to have different permeabilities. In both test zones, the vertical permeability would be expected to be less than the horizontal permeability. Despite these limitations in the validity of the assumption of isotropy, field tests for anisotropy require measurement of pressure perturbations at multiple points around the test zone, which would not have been feasible in the nearly impermeable halite. Further, the test results are likely to be biased toward the higher conductivity flow directions and, therefore, conservative for purposes of performance assessment. Given the limitations in field testing and the conservative nature of the test interpretations, the assumptions made in test design and analysis are adequate and appropriate.

4.5.3. Alternate Interpretation

In very low permeability media such as pure halite the influence of molecular forces not considered in Darcy flow may become significant and cause a model (BRAGFLO) based on Darcy flow to overestimate flux. However, the Darcy flow assumption is clearly shown to be appropriate for impure and disturbed halite, based on the success in modeling pressure changes during tests in these more permeable media, and provides a conservative approach to BRAGFLO modeling. On the basis of these observations, the Darcy flow model is considered adequate and appropriate for both test analysis and performance assessment.

4.5.4. Uncertainty and Consequences

The interpretations made in analyzing the test results are acknowledged in SAND96-0435 (p. 27) to carry a high relative uncertainty. A general discussion of test uncertainty is presented in SAND96-0435 (p. 23). In both QPP05 and QPP15 the principal uncertainty results from the aforementioned lack of a clear indication of fluid movement in the halite. This response is appropriately considered by SNL to indicate that the undisturbed halite has a very low permeability. This response is not likely to have resulted from an equipment or design problem because fluid movement was detected in these test zones when the halite was disturbed and the permeability increased following excavation of Room Q. Because of a lack of formation response in the undisturbed halite, the key parameter of formation pressure could not be measured or approximated from the test data, and instead was estimated from the results of other pressure measurements at Room Q and elsewhere in the repository, the applied lithostatic pressure, and an awareness of the very low permeabilities of the test zones.

Permeability is sensitive to formation pressure, and the lack of formation pressure data resulted in a non-unique and therefore uncertain estimate of permeability. The published test results, 1.1E-24 m^2 for QPP05 and 5.4E-24 m^2 for QPP15, should therefore be considered rough, order-of-magnitude estimates and not precise quantitative values. This conclusion is also noted in SAND96-0435 for both tests, where it is stated: "The sole purpose of presenting this simulation is to provide an indication of how low the transmissivity of the QPP05 test zone would need to be to produce the observed pressure responses." (See p. 46 and a similar statement for QPP15 on p. 81.)

The test results support the conclusion that the test zone permeabilities are very low. Based on the sensitivity of the test design and instrumentation inferred from the results obtained in other boreholes, the test zone permeability in QPP05 and QPP15 is probably less than 1.0E-22 m^2, and values on the order of 1.0E-24 m^2 are considered reasonable estimates. The consequences of errors in these estimates are not likely to be significant if they are properly used as lower bounding values for undisturbed halite in the performance assessment.

4.5.5. Appropriateness and Limitations of Methodology and Procedures

The test design and analysis methodology and procedures closely approximate the state-of-the-art at the time they were performed and are well described in SAND92-1172 and SAND96-0435. The test procedures were appropriately implemented and no interference was detected from adjacent tests or activities prior to mine-by. Brief compressibility tests conducted to detect air trapped in the test zones and power supply problems in QPP15 did not appear to influence test results.

The principal limitations of the approach are related to the difficult task of measuring test-induced pressure responses in the field in very low permeability rock in relatively short periods of time. Although the test methodology was appropriate for most of the test zones around Room Q, it was not capable of measuring the very low permeabilities in QPP05 and QPP15. Another limitation of the undisturbed halite tests is the assumption of two-dimensional, radial flow in test analysis. This limitation is discussed in SAND96-0435, but is of relatively minor consequence compared with the already large uncertainty in the QPP05 and QPP15 results.

4.5.6. Adequacy of Application

The undisturbed halite permeability values from the QPP05 and QPP15 tests are appropriate for use in performance assessment, with the aforementioned limitation that they be considered lower bound rather than precise, quantitative values.

4.5.7. Accuracy of Calculations

Although the data were analyzed where feasible using published analytical solutions (SAND96-0435, p. 20), the primary data analysis tool was the numerical wellbore simulator GTFM 6.0. Although no checks were made of the numerical model results, the hand calculations were spot-checked and found to be accurate.

4.5.8. Validity of Conclusions

The results from QPP05 and QPP15 are among the lowest permeability values measured in the Salado halites and were properly used to establish a lower bound of 1.0E-24 m^2 for the permeability of the Salado halite in the performance assessment model. Uncertainty in the halite permeability is accounted for by establishing an upper bound of 1.0E-21 m^2 and assuming a uniform distribution between the upper and lower bounds. The basis for these limits is explained in the SNL memos Davies to Tierney dated March 7, 1996, and Lappin and Beauheim to Harper-Slaboszewicz dated May 15, 1996. In summary, permeability measurements made at distances of greater than approximately 10 m from the underground workings are considered to represent undisturbed conditions as demonstrated by an approximate stabilization of both pore pressures and halite permeabilities.

The trend of the supporting permeability data presented in the SNL memos was informally compared by the peer review team with pre-mining permeability estimates from Room Q borehole tests that were made at a distance of about 23 m from the underground workings. These are technically adequate for comparative purposes, but were apparently not considered by SNL as supporting information because they were not obtained under current QA standards. Permeability data from five of the six Room Q borehole tests for which halite permeabilities were estimated were found to lie within the range of values used in the PA.

Review of undisturbed halite permeability data supports the range of values used in the WIPP PA, and the lack of a central tendency due to the scatter in the data supports use of a uniform distribution. The results obtained from the QPP05 and QPP15 borehole tests, and the use of those results in supporting the WIPP PA are reasonable and appropriate.

The results from QPP05 and QPP15 are among the lowest permeability values measured and were properly used to establish a lower bound of 1.0E-24 m^2 for the permeability of the Salado halite in the performance assessment model as reported on Forms 464 WPO 34397, WPO 34399, and WPO 34401, entered 3/6/96.

4.5.9. Dissenting Views

None.

4.6. Undisturbed Anhydrite Pressure

This section reviews the data from which the brine far-field pore pressure in Salado MBs 138 and 139 were derived.

Parameter: Brine far-field pore pressure

ID#: 569

Form 464: WPO 34863, entered 2/13/96

ID#: 590

Form 464: WPO 34532, entered 2/13/96

Parameter Package: WPO 31185

Distribution: Student-t

Parameter Values: Mean: 11.63E+06 Pa

Median: 11.63E+06 Pa

Std. Dev.: 1.273E+06 Pa

(**Note:** no upper or lower bound was placed on the range to be sampled)

Definition: The brine far-field undisturbed anhydrite pore pressure is that pressure exerted by brines existing within the interconnected pore spaces of the Salado anhydrite beds 138 and 139 in regions sufficiently remote from mining, drilling, and other human activities that might disturb the environment.

Intended Use: The brine far-field pore pressure is used in BRAGFLO as the initial pressure in these anhydrite marker beds. Anhydrite beds exhibit higher permeabilities than the surrounding halite and represent potential pathways to the accessible environment. Consequently, the initial pressure must be reasonably well known in order to calculate the influx of waste-contaminated brine into these units.

Derivation: The parameter was derived from tests in boreholes QPP03, QPP13, C2H02, L4P51-C1, and SCP01-A. At the beginning of these tests the test zones were cleaned, packers installed, the test and guard zones filled with NaCl saturated brine to a low initial pressure, and the holes shut in. The subsequent pressure buildup toward static conditions, along with the rest of the borehole history (e.g., the length of time that the borehole was left empty after being drilled), was modeled with the code GTFM 6.0 to estimate the undisturbed pressure. The five results of this modeling were averaged to obtain the mean of 11.63E+06 Pa. The standard deviation reported on Form 464 was calculated from $\sqrt{}\{[n\Sigma x2 - (\Sigma x)2]/n2\}$, which applies to an entire population.

Discussion: The five boreholes investigated pressure histories in different anhydrite beds and at different locations. QPP03 was drilled at a small upward angle from horizontal above Room Q; QPP13 at about the same angle downward below Room Q; C2H02 westward at 45° downward from room C2; SCP01-A at 13° below horizontal at S45°W from the Core Storage Library; and L4P51-C1 vertically downward from room L4. Most of the interval tested in borehole QPP03 lies within the lower part of map unit 9 of the Salado, but it also intersects anhydrite bed b, to which most of the flow and pressure buildup is attributed. Most of the test zone in QPP13 lies in MB 139. Hole L4P51, as originally drilled, intersected MB 139, underlying halite, polyhalitic halite, and clay D. Later it was deepened to intersect MB 140 within which tests labeled L4P51-C1 were performed. Only data from boreholes QPP03, QPP13 and C4P51-C1 require qualification.

4.6.1. Adequacy of Requirements and Criteria

One objective of the analysis was to provide initial pore pressures for input to BRAGFLO. The formation pressure is also needed for the design of effective plugs and seals for waste panels and evaluation of backfill performance. No written requirements or criteria were found in the relevant documents; however, the data must satisfy these objectives.

The procedures for obtaining the formation pressure were 1) measuring pressure buildup in shut-in boreholes for a limited time (short of achievement of constancy; for example, before the mine-by in Room Q), and 2) fitting the data with the code GTFM 6.0 to obtain the desired pressure. This constitutes an inverse problem.

Test conditions required for obtaining adequate data on the formation pressure in undisturbed anhydrite beds are:

1. Pressure buildup in the test zone in each borehole must result from inflow of brine dominantly from the anhydrite beds and not from other units (notably from halite rock).
2. The test tool must work properly.

3. The test must provide results from essentially undisturbed anhydrite.
4. The data acquisition system must work properly.

The first condition was addressed by: 1) Intentionally drilling boreholes into or through anhydrite beds, or using boreholes for which post-drilling examination showed the presence of anhydrite; 2) Using boreholes which intersected only halite and anhydrite, because data for halite and from zones drilled exclusively in halite indicate essentially zero permeability.

The handling of the second condition varied from hole to hole. In QPP03, the test-zone packer never functioned but the guard packer apparently did. The test consisted first of closing in the hole and observing the pressure rise, interrupted part way through by a pulse withdrawal of brine. The next stage consisted first of lowering the pressure in the test zone and excavating Room Q (a large borehole). Then the hole was shut in again and the pressure rise observed, followed by intentional withdrawals to measure brine flow. At that time the packer was removed and replaced by another one set up to isolate the same portion as before, namely from the guard packer to the end of the hole. Finally, the pressure rise was measured after the installation of the new tool. Because the post-mining test zone pressure began to stabilize at about the same level as during the first interval following the mine-by, it might be inferred that the guard packer in the initial shut-in test functioned correctly. This does not seem to be stated explicitly in the relevant documents, but is taken here, together with the consistency of results with other measurements, to indicate acceptability of the data.

The pressure recovery in borehole QPP13 following the pulse withdrawal was anomalous. This probably resulted from communication through the formation of the test zone with the guard zone, which was depressurized sometime between the day before the pulse test and about 20 days later (p. 62, SAND96-0435). Indeed, comparison of Figure 6-58 in SAND92-1172, test-zone pressure, with Figure 6-60, guard-zone pressure, suggests that this communication existed throughout the entire pressure buildup; the pressures are nearly the same, which would be consistent with slow leakage past the test-zone packer throughout the test. If so, the pressures measured in the test zone would likely be lower at any given time than they would have been had the test-zone packer been working correctly. In turn, this would have led to a low estimate in the undisturbed pressure as calculated by GTFM 6.0. The guard packer may have functioned properly, but no data were found to confirm this. This does not bolster confidence in the reliability of the results but, because the pressure attained is close to that found in hole QPP03, does not rule out acceptability.

A draft document (Chace 1996) provides some detail about the tests in L4P51-C1. The log for the hole indicates some problems with the tool, including replacement early in the test period, but the report does not discuss the interpretation of the data nor provide details of how the pressure curves were fitted. The information provided does not permit a full evaluation of the adequacy of the data.

The third condition, obtaining data from essentially undisturbed anhydrite, was addressed by drilling boreholes from the outermost portions of the excavations. In addition, for QPP03 and QPP13, pressures were measured both before and after a mine-by to evaluate the effect of excavation, thereby providing at least an approximate measure of the difference between disturbed and undisturbed conditions. Hole C2H02 was intentionally placed to intersect MB 139 below a rib (wall), rather than an excavation in order to minimize the effects of mining on the test. Hole SCP01-A was drilled from the Core Storage Library because that excavation was only ten months old at the time and no other excavations existed nearby. The test zone was 10 m from the excavation. Both of these conditions tend to minimize the effect of mining on the test. L4P51, however, was bored vertically downward from Room L4, which is less desirable from the perspective of meeting this third condition.

The fourth condition, proper functioning of the recording equipment, was met, as evidenced by the large amount of data plotted in graphs (e.g., Figures 6-17 to 6-23, SAND91-1172). Whereas some of this equipment did fail, it did so only after the tests relevant to this parameter were completed.

In summary, it is clear that not all of the requirements were met for tests in all boreholes. This casts some doubt on the adequacy of the data for the intended purpose.

4.6.2. Validity of Assumptions

Heavy reliance was placed on the use of the code GTFM 6.0. Assumptions used in the development of this code were (Pickens et al. 1987): 1. The formation whose response is being simulated is homogeneous (vertically), is confined, has a constant thickness, and has a finite radius centered upon the borehole. 2. The major influences on the formation behavior are the borehole and conditions imposed in the borehole. 3. All flow is radially away from or toward the test interval of the borehole. 4. The pressure in the formation is uniform and constant radially at the start of a drilling period or a test sequence. 5. The borehole and formation fluids are homogeneous within the test interval. 6. The effects of fluid temperature changes in the formation may be neglected in comparison to any thermally induced pressure changes in the borehole during testing.

Because the anhydrite beds in question are confined between significantly less permeable halite zones, assumption 1 appears reasonable. Assumption 3 involves the additional assumption that, although the flow into the borehole was from beds that were, in most cases, not perpendicular to the hole, an equivalent radial flow can be considered adequate. This is of greatest concern for holes QPP03 and QPP13 because the deviation between the plane of the bed and the direction of the hole is notably larger than 75°, the maximum deviation to which the equivalent flow has been evaluated as resulting in little error (SAND96-0435, p.22). Nevertheless, consideration of the likely consequences, the geometry of the hole and anhydrite beds, and the constraints on flow directions, it seems likely that little error, compared to other uncertainties, would have resulted. Thus, assumption 3 appears to have been sufficiently well satisfied. In respect to assumption 6, temperatures were measured in the test zones in boreholes L4P51-C1 (and, incidentally, in C2H02 and SCP01A); temperatures varied by only a few tenths of a degree C. Thermocouples were also mounted outside the test zone in holes QPP03 and QPP13. Comparison with Figure 7 in Pickens et al. (1987) suggests that this would produce correspondingly a few tens of meters of water head change (i.e., a few tenths of a MPa). This is small compared to the measured pressures and their uncertainties.

Assumption 2 is handled through knowledge of the borehole conditions as required for input to the code. The remaining assumptions, 4 and 5, are judged adequate for the intended use and application.

Assumptions stated in SAND96-0435 are that hydraulic properties are constant during the test (Section 6.2) and flow is radial toward borehole (Section 6.3). The latter implies an isotropic state, which, as pointed out in the report, probably does not correspond to the actual case in anhydrite. A second assumption in Section 6.3 is that the equivalent-vertical-borehole approach is acceptable for QPP03 and QPP13 (see discussion above). For some boreholes, available data show that the assumptions on homogeneity, isotropy, and radial flow seem to have been met. On this basis, these assumptions are judged to have been adequately met for this parameter.

4.6.3. Alternate Interpretation

An alternative to the representation that the measured pressures and modeling produce reasonable far-field pore brine pressures is that most of the measured pressures are low, for one reason or another. The expectation was that the formation pressure for the Salado undisturbed anhydrite should be approximately lithostatic, about 14.8 MPa (SAND92-1172, p. 3). By contrast, the formation pressure derived from modeling is considerably less, about 11.63 MPa. Also expected is that the undisturbed anhydrite pressure would approximately, if not exactly, equal the undisturbed halite pressure. Form 464 for the undisturbed halite pressure (WPO 34394) lists a mean and median of 12.47 MPa; on this Form 464 the parameter name is "Brine far-field pore pressure." See Section 4.2 of this report for discussion of the reliability of these data. The parameter name on the Forms 464 WPO 34532 and 34863, corresponding to the parameters under evaluation here ("Undisturbed Anhydrite Pressure"), is the same: "Brine far-field pore pressure." For these purposes the designation "undisturbed" is taken to mean conditions sufficiently far from any drilling or excavation that no perceptible effects from these operations have occurred. Thus, the various data and expectations appear inconsistent. This suggests that the various problems encountered during testing, perhaps exacerbated in some cases by the long times that corresponding holes were left open, gave rise on average to a somewhat low mean value. If, in spite of some indications that the guard packers in boreholes QPP03 and QPP13 operated properly, they instead leaked slightly, then the measured pressures in these boreholes could have been systematically low.

An observation that may explain a low measured pressure in borehole C2H02 was the presence of 91% hydrogen in gas recovered at the end of the test. This hydrogen evidently resulted from the corrosion of aluminum components of the tool caused by the reaction of water with the metal, producing aluminum oxides and hydroxides, and thereby reducing the partial pressure of water and increasing that of hydrogen in the pores. Hydrogen is notorious for its high rate of diffusion through most materials; possibly it diffused through the packers, thereby resulting in the rather low measured pressures. The net result of these changes is not obvious, but almost surely would produce some net change in the pressure. No statements were found to the effect that the modeling code GTFM 6.0 can take this gas pressure buildup into account and compensate for it. It is concluded that use of the pressure data from this hole is questionable, without evaluating the resultant change.

Because the pressure is measured directly, alternate interpretations (such as that above) could only mean that the formation pressure is different than that obtained by the fitting and modeling procedures. These procedures are intended to compensate for the fact that it was impractical to run the tests long enough to reach steady state conditions and to take into account several disturbing factors (e.g., conditions prior to the beginning of the test and temperature effects on pressure).

4.6.4. Uncertainty and Consequences

Numerous difficulties in conducting the tests gave rise to notable uncertainty. For tests conducted in association with Room Q, these problems are described in SAND96-0435 (p. 9) where failure of closure measurement devices is noted (p. 14), where computer failure is noted (p. 19), where it is pointed out that the shut-in tests were not run for as long as should ideally have been done (p. 24), and specific tests described in Section 7 -- pressure changes caused by changes in packer-inflation pressures, movement of test tools, leaks around the packers, etc. The discussion on pp. 23-24 also indicates that there is some uncertainty as to the actual stratigraphy within the test zone, including the thickness of the anhydrite beds. In QPP03 the test-zone packer never functioned. After the flow test in QPP13 the test tool in this hole was replaced and the test region was filled with nitrogen and shut-in. This resulted in initially slow pressure buildup in the subsequent test. The anomalous pressure recovery after the pulse withdrawal was interpreted as communication with the guard zone. Test-zone and guard-zone packer pressures are poorly documented, and an apparent release of test-zone pressure is undocumented. Late in the test in QPP13, test-zone pressure decreased and was evaluated as probable equipment failure. In addition, of course, there is always some uncertainty in parameters obtained by fitting curves to data. These potential sources of error gave rise to concern by the panel on the adequacy of the data.

The alternative interpretation presented in Section 4.6.3 could be viewed as, in effect, a statement about the uncertainty. The estimated lithostatic pressure, 14.8 MPa for the anhydrite bed at the repository level, differs by more than two standard deviations from 11.63 MPa. The halite brine far-field pore pressure, 12.47 MPa (WPO 34394) lies less than one standard deviation (WPO 34532) above 11.63 MPa, and 11.63 MPa lies just slightly more than one standard deviation (WPO 34394) below 12.47 MPa. The number of data points (five) is small. Difficulties encountered for three of the boreholes give reason to view the derived pressures with some skepticism. The pressure for a fourth well, L4P51-C1, seems anomalously low. The pressure for C2H02, 11.11 MPa, lies well below the expected lithostatic pressure and below the average of all five data points. Also, at the conclusion of the test in C2H02, a high content of hydrogen was detected in the gas and brine collected, indicating corrosion of the aluminum parts. The effect of this corrosion on brine pressure remains unknown. The corrosion reaction would result from reaction of water with metal to produce aluminum oxides and hydroxides plus hydrogen. Presumably, the consumption of the water would cause pressure changes in the brine.

Some potential impacts of uncertainties were not discussed. Specifically, leaving the test regions of borehole QPP03 open for one month and QPP13 open for two months prior to shut-in may have allowed the rock surrounding the holes to dry out partially. The subsequent filling of the test and guard zones with brine would presumably result in imbibing some of this brine into the walls of the holes. It is rather unlikely that this brine would have been in equilibrium with the rock and, through dissolution or precipitation of soluble solids such as halite and anhydrite, would likely have changed the hydrological properties. The swabbing of QPP13 prior to testing may have produced a similar effect. This type of impact appears not to have been evaluated. Nevertheless, any effect should be limited to the vicinity of the boreholes (i.e., within the "skin") and, because the analysis discounts changes in that zone, should not have affected the quality of the data. Thus, only one test, in SCP01, appears to be free of recognized concerns.

4.6.5. Appropriateness and Limitations of Methodology and Procedures

As indicated in the previous sections, the methodology was appropriate and the intrinsic limitations of the methodology are acceptable. In practice, several difficulties arose which make the appropriateness of the data for the intended application doubtful. Several documents describe the procedures (e.g., SAND92-1172, SAND96-0435, SAND90-7000, and SAND90-7072). No information was lost as a consequence of the computerized data reduction used for pressure data..

4.6.6. Adequacy of Application

As indicated in preceding sections, it appears that data from only one borehole are entirely free of doubts about their accuracy. It is hard to justify using data from a single hole as being representative. Reasons for doubt include partial failures of the downhole tools, communication between guard and test zones, lack of documentation of pressure changes induced by temperature changes and tool corrosion, and discrepancies with the undisturbed halite pressure and the estimated lithostatic pressure.

4.6.7. Accuracy of Calculations

No hand or spreadsheet calculations were found in the relevant documents. Hand calculation of the mean of the mean pressures derived from the GTFM 6.0 fits for the five boreholes confirmed the mean reported on the Form 464. The results of the computer calculations fit well with the measured data and visual extrapolation from the plots for boreholes QPP03 and QPP13 to estimate the pressure that would result from extremely long tests matches the derived formation pressures satisfactorily. Pickens et al. (1987) cite several examples of comparison calculations using other codes and applied to several problems; all show good agreement with the GTFM 6.0 calculations for the same cases. All these results indicate that the calculations are sufficiently accurate.

4.6.8. Validity of Conclusions

In evaluating the adequacy of the data for their intended use, the Panel considered the impact of using the questionable data on conservatism. It was agreed that low undisturbed anhydrite pressure values would lead to higher rates of flow and enhanced estimated releases from the repository. Thus, the consequence of using the data is to increase conservatism by some factor that only relevant modeling would reveal.

Moreover, a Student-t distribution, properly limited so as not to allow sampling of the distribution at pressures greater than lithostatic nor less than hydrostatic, would appropriately incorporate some of the uncertainties noted in preceding subsections into PA calculations. Because of the conservatism of the impacts and the uncertainty incorporated by means of the Student-t distribution, the data are found to be suitable for the intended use. Specifically, this refers to the mean value of 11.63E+06 Pa and the standard deviation of 1.273E+06 Pa reported on Form 464, WPO 34863, entered on 2/13/96.

4.6.9. Dissenting Views

None.

4.7. Salado Undisturbed Anhydrite Rock Compressibility

Three individual Form 464s listing bulk compressibility as a parameter for the Salado anhydrite beds a and b (ID# 521), the Salado MB 138 (ID# 560), and the Salado MB 139 (ID# 580), are provided in the Parameter Package. All three Form 464s list the identical values for the parameter and both beds a and b and MB 138 Form 464 are referenced to the analogue of COMP_RCK for MB 139.

Four data points given in the source document (SAND92-1172) were used to fit a Student-t distribution for the mean value of rock compressibility. These four data points, attached to the Form 464, are themselves the mean values of rock compressibility derived from GTFM 6.0 simulation of measurements from each of four boreholes drilled adjacent to Room Q. These boreholes are QPP03, QPP13, C2H02, and 5CP01-A. Only the data associated with boreholes QPP03 and QPP13 are required to be qualified by the peer review process to support this parameter.

Parameter: Undisturbed Anhydrite Rock Compressibility (Bulk Compressibility)

ID #: 521, 560, 580

Form 464: WPO 34135, 34439, 34574, entered 2/14/96

Parameter Package: WPO 31186

Distribution: Student-t

Parameter Values: Mean: 8.263E-11 Pa-1

Median: 8.263E-11 Pa-1

Std Dev: 1.115E-10 Pa-1

Definition: The Salado anhydrite rock compressibility is the change in volume of the rock induced by an applied stress. The rock compressibility (CR) is considered the reciprocal of the rock's bulk modulus, i.e., CR = 1/K

where:

K = Bulk modulus, Pa

Intended Use: The intended use of the parameter anhydrite rock compressibility is for entry into the BRAGFLO model as the amount of change in the volume of anhydrite rock as a result of an applied stress, such as removal (withdrawal) of fluid from the interconnected pore spaces (effective porosity).

Derivation: The anhydrite rock compressibility values are obtained from GTFM 6.0 simulation of pressure vs time data, collected from specific boreholes having test zones within the anhydrite, and using specified ranges of input parameters for fluid density, formation porosity, and fluid compressibility in Domenico's (1972) equation for Specific Storage, Ss:

$$Ss = \rho f g(\alpha + \phi\beta)$$

where:

ρf = fluid density

g = acceleration of gravity

α = vertical formation compressibility

ϕ = formation porosity

β = fluid compressibility

Knowing the volume of fluid released (Ss) during the testing period, the equation is rearranged and solved for α, the formation compressibility.

Discussion: In strict rock mechanics terms, the bulk modulus is considered as the slope of the pressure-volumetric strain curve in the elastic strain region after fissures have closed as a result of an applied stress. For the BRAGFLO model, the fissure closing region of the pressure-volumetric strain curve must be considered. Therefore, using only the reciprocal of bulk modulus (as obtained from laboratory testing of small rock samples) to calculate anhydrite rock compressibility using Green and Wang's (1990) equation, may underestimate the effect of fracture porosity in the anhydrite. The anhydrite rock compressibility values provided by GTFM 6.0 simulation employing a range of input parameters based on hydraulic tests of anhydrite in boreholes, using Domenico's equation, may provide more reliable values than may be obtained using bulk modulus.

4.7.1. *Adequacy of Requirements and Criteria*

The estimation of the undisturbed Salado anhydrite compressibility parameter was determined from tests conducted in boreholes (QPP03 and QPP13) around Room Q. The tests were designed to help reduce uncertainties about brine flow and provide information on the Salado formation pressure, permeability, and flow potential both within the zone of influence of the WIPP excavations and in the undisturbed far field parts of the Salado. Thus, in that sense, the results of the interpretation of the data provided from the tests met the adequacy of requirements, although there are minor limitations on the interpretations as discussed in SAND96-0435.

4.7.2. *Validity of Assumptions*

The major assumptions used in the performance of the tests conducted on boreholes QPP03 and QPP13 were: 1) fluid flow is radial toward the test boreholes; 2) the hydraulic test responses in the test zones of the slanted boreholes can be accurately portrayed by an equivalent vertical borehole geometry, with length equal to the vertical thickness of the tested strata and a borehole diameter equal to the average of the major and minor axes of the ellipse formed by the intersection of the slanted borehole and a horizontal plane; 3) fluid flow obeys Darcy's Law; and 4) borehole closure and Darcy flow are the only forms of pressure/flow transmission during the hydraulic testing in undisturbed anhydrite.

The validity of these assumptions is supported by the analysis and interpretation of the data as presented in SAND96-0435. For instance, the best fit match points on the curves of pressure flow test and pressure buildup test data are those for radial flow, and the data can be modeled quite reliably using analogs with Darcy flow. Numerical modeling of the slanted borehole equivalent borehole geometry indicates that the tests can be interpreted with little error for boreholes with slants up to 75° from vertical and for horizontal-to-vertical permeability ratios greater than or equal to 10 (SAND96-6435, p. 22). However, it was concluded that "the tests of anhydrite layers conducted in bores QPP01, QPP03, and QPP13 can probably be interpreted reliably using the equivalent-vertical borehole approach" (SAND96-6435, p.22).

4.7.3. *Alternative Interpretations*

As reported in SAND96-0435, for many analyses of pressure data, there is often more than one method of analysis that can be applied and more than one interpretation of analyses results. For instance, the test results for QPP13 post-mining, test zone pressure were analyzed by four GTFM 6.0 simulations (SAND96-0435, pp. 62 - 71); i.e., test-zone pressure vs time, brine production vs time, brine flow rate vs time, and post-flow test pressure buildup. The specified and fitted parameters were the same for all four simulations, which showed an anhydrite test zone compressibility value of 1.0E-09 Pa^{-1}.

4.7.4. *Uncertainty and Consequences*

SAND92-1172 is a data report and, consequently, does not contain a discussion of uncertainty of results. SAND96-0435, on the other hand, is an interpretative report and data uncertainties are discussed, although the consequences of the uncertainties are not discussed.

There was no direct identification (i.e., measured core from the borehole) of the stratigraphic interval being tested in the borehole. Thus, it is possible that the test-intervals could overlie units above or below the expected test stratigraphic zone. However, post-testing video logging completed on the boreholes verified the position of the test zones in selected boreholes.

Although there is uncertainty in some of the data (for instance, the anomalous pressure recovery after the pulse withdrawal in borehole QPP13 during day 151 [1989] of the pre-mining period was probably due to communication with the guard zone which was depressurized at the time, according to SAND96-0435 [p.62]), the uncertainty associated with the cumulative data appear to be low enough so that decisions can be made, as shown by the numerous examples of the interpretation of the data through numerical simulation in SAND96-0435 (Section 7.2 Test Interpretation, p. 114).

In addition, the late-time data of the pressure recovery following the flow test shows a decreasing pressure trend for well QPP13 (SAND96-0435, Fig. 7-54, p. 66), which has been attributed to equipment problems and not changes in the formation properties, although limited storage of brine in the formation may have contributed to the pressure decline.

Based on the review of the source documents and the interpreted values for undisturbed Salado anhydrite compressibility, it seems evident that the range of values presented are a reasonable estimation of true values that might be expected in far field conditions.

4.7.5. *Appropriateness and Limitations of Methodology and Procedures*

The testing apparatus used at the time was state-of-the-art equipment fabricated from off-the-shelf components which, to a large extent, dictated the methodologies and procedures used to measure pressure and permeability directly in the boreholes. The description of the test equipment, tool installation, test startup and results of testing, as presented in SAND92-1172, indicate that the test procedures were correctly implemented.

Data from the tests were reduced for presentation in SAND92-1172 by sorting according to borehole number, recording time, and measurement type, calculating all measurements to a time interval since zero-hour, converting all measurements from U.S. to metric units, and filtering out redundant values with a data filter. In addition, it is apparent by viewing the graphs of pressure vs time of the test zone pressures (SAND92-1172) that the reduced data are representative of the collected data.

The SAND96-0435 report contains the results of interpretations gleaned from analyses of the data using standard and customized analytical and numerical methods, which were appropriate for the data.

A review of SAND92-1172 and the conclusions in SAND96-0435 indicates that the assumptions, calculations, extrapolations, methods and conclusions pertinent to the data were appropriate for the development of the parameters to be used as input to the WIPP PA.

4.7.6. Adequacy of Application

The SAND96-0435 report provides interpretation of the results (i.e., values for required parameters) from analytical and numerical simulation of the data that demonstrates the adequacy of the application.

A visual comparison of the various graphs (Figures 6-17 through 6-25, SAND92-1172) for test zone pressure, packer pressure, and guard zone pressure in borehole QPP03, against similar graphs (Figures 6-26 through 6-31) for borehole QPP04 (the closest borehole to QPP03) indicates no obvious interference effects between the two boreholes. A visual comparison of QPP13 vs QPP14 also reveals no obvious interference effects between the two boreholes.

The description of the test equipment, tool installation, test startup and results of testing presented in SAND92-1172 indicate that the test procedures were correctly implemented.

SAND92-1172 is a basic hydrologic data report for tests conducted at Room Q. It summarizes thousands of data points into simplified diagrams to illustrate graphically the results of the testing. An explanation of corrective actions for the testing is presented in SAND96-0435, the interpretative report for the Room Q tests.

There are no specific statements regarding data reliability in SAND92-1172, although it can be inferred from the operational logs of each borehole (Appendix C) that the data can be considered reliable by the reason that poor data are specifically identified in the QOC and CAC section of the operational log.

The close match of the simulated flow rate to that measured during the tests (Fig. 7-16, p. 39, SAND96-0435) suggests that the hydraulic properties of the formation and the near-borehole region are adequate for their intended use.

The processes used to produce the parameters involved the collection of the field data (measurements of *in situ* rock properties, e.g., pore pressure, brine flow, and temperature over time), the filtering, reduction, cataloging, and presentation of the data in data plots, and the interpretation of the data through the use of analytical and numerical techniques. These processes are appropriate to produce the parameters for their intended use in the BRAGFLO model.

4.7.7. Accuracy of Calculations

Neither source reference (SAND92-1172 or SAND96-0435) contains calculations that can be checked for accuracy. The calculations are all completed within the analytical and/or numerical models and GTFM 6.0 simulations. Because the GTFM 6.0 simulations provide such close fits to the collected data, it is assumed that the calculations have been done accurately.

4.7.8. Validity of Conclusions

The graphs and charts of the results of interpretation from various numerical model simulations of pressure vs time for QPP03 and QPP13, as presented in SAND96-4035, demonstrate the validity of the conclusions regarding the testing of the Salado evaporites. Those conclusions are that the changes in hydraulic properties and pore pressures can be attributed to one or a combination of three processes: stress reduction, changes in pore connectivity, and flow toward Room Q. Due to redundancy in data of the same type of tested intervals, interpretation of the data has provided several reliable estimates of anhydrite compressibility.

4.7.9. Dissenting Views

None.

4.8. Brine Salt Mass Fraction

The adequacy of values obtained for brine chemical analyses (salt mass fraction = 32%) from samples 195776, 195777, 195778, and 195779 are addressed in this section. The brine was sampled from the floor of Room Q in late 1991 and early 1992 by either sponge collection or vacuum techniques. The brine samples were then sent to Chem-Nuclear Geotech Lab for chemical analyses. Specific elements were analyzed by flame atomic absorption spectrometry, inductively coupled plasma atomic emission spectrometry, and ion chromatography. Specific gravity and Total Dissolved Solids (TDS) values were obtained by comparison to deionized water and EPA Methods 160.1-160.4, respectively. The brine salt mass fraction was calculated by dividing TDS by specific gravity. The objective for brine salt mass fraction determination is as follows. The final value will be used for density calculations and determination of amount of pure water available for chemical reactions.

The parameter description is as follows:

Parameter:	Brine Salt Mass Fraction WTF 57 (Mass Fraction of Salt and Brine)
ID#:	57
Form 464:	WPO 31552, entered 2/13/96
Parameter Package:	WPO 31171
Distribution Type:	Student-t
Parameter Value:	Mean: 0.324
	Std Dev: 0.00983
	Minimum: 0.302
	Maximum: 0.332
Definition:	The TDS (Kg/L) of a brine divided by its specific gravity (Kg/L).

Intended Use: Parameter will be used for density calculation and pure water budget determination.

Derivation: Brine samples collected from Room Q and analyzed by Chem-Nuclear Geotech Lab for Total Dissolved Solids and specific gravity.

4.8.1. Adequacy of Requirements and Criteria

The requirements and criteria for this parameter determination are adequately defined. No rationale for obtaining this parameter was given in SAND92-1173. The Parameter Package states that the data were collected "for input to the WIPP Data Entry Form and for use by Performance Assessment personnel making parameter estimates." The criteria and requirements were adequately addressed in writing by an issue resolution response (memo, Christian Frear to Caporuscio, 5/15/96).

4.8.2. Validity of Assumptions

Originally, it is unclear what assumptions were used in making a determination of the Salt Mass Fraction. Two major assumptions should have been addressed, at a minimum. The assumptions are : 1) that the Room Q brine is representative of Salado Formation brine, and 2) that TDS is truly a good indication of dissolved ions in the brine. The first assumption was qualified by issue resolution. Hundreds of analyses were evaluated and these four samples represent halite brine. If anhydrite brine were included, the final mean value of salt mass fraction would be approximately 30%. The second assumption was also reasonably addressed by issue resolution (memo, Christian-Frear to Caporuscio, 5/15/96). Therefore the brine salt mass fraction value would be of use in estimating brine density in the Salado Formation.

4.8.3. Alternate Interpretations

The brine composition of the Salado Formation was determined solely from a series of four samples taken in Room Q. It would have been reasonable to take other brine samples from undisturbed locations in the repository to confirm that the brine is homogeneous. DOE/WIPP 91-009 contains 171 brine chemical compositions. These brine samples from the repository may be contaminated with fresh water used to abate the dust. This issue was addressed by the Principal Investigator, who concluded that the DOE/WIPP 91-009 values could not be referenced, but that the four samples in question are representative of halite brine.

4.8.4. Uncertainty and Consequences

Since the chemical compositions of the four brine samples were all the information provided for this parameter, it is difficult to assess the uncertainty of the results. There is an apparent difference between the TDS value and the sum of analyzed cations and anions for each brine sample (typically 10 to 14% difference). It was unresolved what the unidentified cations and anions were. This difference may have a consequence if in fact the TDS analyses are systematically high. In fact, TDS is a reasonable value to use for this definition of salt mass fraction. A second uncertainty is the aforementioned question concerning the degree of homogeneity in Salado Formation brine. The consequence of the accuracy of this value involves how this parameter is used in BRAGFLO. Since this parameter is primarily used to calculate the density of the brine, it may not have large consequences if the results are variable.

4.8.5. Appropriateness and Limitations of Methodology and Procedures

Two items are worthy of discussion in this section for the determination of brine salt mass fraction. The items involve the actual physical collection of the brine in Room Q and the types of chemical analyses performed on the brines.

Of the two methods used for brine collection in Room Q, the vacuum technique would be preferable over that of collecting brine with a sponge. The former collection method dictates that an appreciable amount of liquid be present, while the latter can collect thin layers of fluid. Although the vacuum technique requires more brine to be present, it is much less likely that the brine will become contaminated. It was never apparent how the four brine samples of concern were collected. The reason for this concern is that one sample (195776) has a chemistry that is substantially different from the other three. It was found by issue resolution response that the sample with slightly lower values was collected by vacuum and a "small amount of sediment was left in the original sample bottle" (memo, Christian-Frear to Caporuscio, 5/15/96).

The chemical analyses of the brines may be questioned. Because of the systematic difference in the totals of the two analyses, it is presumed that TDS analyses determined a fuller suite of constituents.

Other than these two minor concerns, it is felt that the methods and procedures used to obtain the brine salt mass fraction parameter are appropriate.

4.8.6. Adequacy of Application

The brine salt mass fraction parameter, as calculated by TDS divided by specific gravity, is probably reasonable for the application of determining brine density.

4.8.7. Accuracy of Calculations

Without the accuracy and precision determinations of the analyses, one cannot determine the accuracy of the calculations. The final calculation to provide the mean value for the brine salt mass fraction is straightforward and would provide an adequate result.

4.8.8. Validity of Conclusions

The brine salt mass fraction value (32%) calculated from the chemical analyses of brine in Room Q is acceptable for halite brine. If anhydrite-bearing brine were included, the resulting mass fraction would be decreased to 30%.

4.8.9. Dissenting Views

None.

4.9. Brine Viscosity

The adequacy of Salado brine viscosity data is addressed in this section.

Parameter:	Viscosity
ID#:	55
Form 464:	WPO 31548, entered 2/16/96
Parameter Package:	WPO 31168
Distribution:	Constant
Parameter Value:	2.1 E-03 Pa-s (units of Pascal-second)

Definition: The viscosity of a fluid is the property that allows fluids to resist relative motion and shear deformation during flow. The viscosity, or dynamic viscosity, is equal to the shear stress divided by the velocity gradient.

Derivation: The viscosity data were developed from capillary viscometer measurements using brine collected from borehole QPB02. This borehole extends approximately 3.1 m into the floor of the repository, penetrating strata PH-4, MB-139, and H-4. The results of these measurements are described in SAND92-1911.

4.9.1. Adequacy of Requirements and Criteria

The requirements for the tests were not specifically stated in SAND92-1911, but are inferred to have been to obtain viscosity data for Salado brine over a range of temperatures, including the repository ambient temperature, for use in repository flow modeling. These requirements are adequate for purposes of the PA.

4.9.2. Validity of Assumptions

The tests were performed assuming the brine collected from borehole QPB02 was representative of Salado brines. The observed variations in Salado brine chemistry are not expected to significantly affect viscosity, and this assumption is considered adequate.

4.9.3. Alternate Interpretation

Viscosity is a well-known and routinely measured fluid property. No significant alternate interpretations need to be considered.

4.9.4. Uncertainty and Consequences

Uncertainties in the results of the viscosity measurements are discussed in SAND92-1911, p. 72. Brine flow rates are inversely related to brine viscosity in a linear manner; however, while the uncertainty in viscosity may be a few percent, the uncertainty in other parameters (such as permeability) may be orders of magnitude and would dominate the aggregate uncertainty in the flow calculation. The uncertainty in the brine viscosity measurements is expected to be low and of small consequence to the PA calculations.

4.9.5. Appropriateness and Limitations of Methodology and Procedures

The test methodology was not well described in SAND92-1911; however, standard testing equipment was used and the manufacturer's procedures for this test are expected to have been followed. Other, slightly lower values of brine viscosity have been used in previous WIPP-related studies and reports. These include values of 1.6 centipoise (cp) (1cp = 1.0E-03 Pa-s) in SAND88-0112 and SAND92-0533 for analysis of brine inflow experiments; 1.77 cp in TME 3153 1983 and EEG-17 1982 for studies of Castile brine reservoirs; and 1.8 cp in SAND92-0700/3 for the 1992 Performance Assessment. None of these values, however, appear to have been derived from direct measurement of Salado or Castile brines and are therefore considered less appropriate than the directly measured value of 2.1 cp selected for the CCA PA. Based on these observations, the methodology and procedures are considered to have provided appropriate Salado brine viscosity data for use in the PA.

4.9.6. Adequacy of Application

A single value of brine viscosity (2.1 cp) is used for Salado brines in the PA. Viscosity is temperature sensitive, and this value is for 28°C. This temperature is used elsewhere in the WIPP as representing ambient repository conditions (for example, SAND88-0112, p. 16). Although the repository temperature may rise several degrees from the heat output of the waste (CCA Appendix SCR Section 2.2.2), and temperature data from other sources suggest slightly lower ambient temperatures (on the order of 26.5 to 27°C -- see temperature data in SAND92-1172 for the Room Q borehole tests), the viscosity change in this temperature range is expected to be on the order of only -0.01 cp/°C. Small changes in temperature are therefore expected to have no significant effect on brine viscosity. Use of a single value instead of distributed values for viscosity is also expected to have little effect on the PA because of the relative accuracy with which this value is known. Overall, application of this parameter to the PA is considered appropriate.

4.9.7. Accuracy of Calculations

The calculation of viscosity from raw test data was not checked; however, brine viscosity increases with increasing solute mass fraction, and comparison of the brine viscosity value proposed for the PA with projected values for NaCl solutions presented in the CRC Handbook of Chemistry and Physics (75th edition 1995, p. 6-246) indicates that a viscosity of 2.1 cp is reasonable and appropriate for the solute mass fraction of 32.4% used in the PA. Minor changes in solute mass fraction will have relatively minor effects on brine viscosity.

4.9.8. Validity of Conclusions

The constant value of 2.1 cp for brine viscosity is reasonable and appropriate for use in performance assessment.

4.9.9. Dissenting Views

None.

4.10. Brine Density

This section reviews the estimation of the Salado brine density. The information about the parameter presented in the Form 464 is as follows:

Parameter: Brine Density

ID#: 49

Form 464: WPO 031541, entered 2/2/96

Parameter Package: WPO 31175

Distribution Type: Constant

Parameter Value: 1,220 kg/m3

Definition: The Salado brine density is defined as the density of brine at the WIPP site at the approximate depth of the repository. Brine density is a function of temperature and pressure.

Intended Use: The intended use of the Salado brine density is as one of the initial scientific parameters in BRAGFLO. In BRAGFLO, the Salado brine density is calculated as a function of pressure based on the assumption that the Salado brine compressibility was assumed to be a constant.

Derivation: The Salado brine density was estimated based on the Brine Sampling and Evaluation Program (BSEP) Phase II Report (DOE/WIPP 87-010). The measured brine density values were presented along with the geochemical analysis results (Table 3-1, page 27, DOE/WIPP87-010) based on the ten samples collected from April 1987 to June 1987. The mean of the ten values of the measured brine density is 1,220 kg/m3, with a maximum value of 1,224 kg/m3 and a minimum value of 1,215 kg/m3.

4.10.1. Adequacy of Requirements and Criteria

The requirements and criteria for estimation of the Salado brine density were not defined in the referenced documents. Based on the intended use, the parameter should adequately represent the average formation fluid density in the vicinity of the repository. This requirement is satisfied by the sampling processes.

4.10.2. Validity of Assumptions

No assumptions were stated specifically for brine density estimation. In the BSEP Phase II Report, it was stated that the ten brine samples were collected by repeatedly bailing over a sufficiently long period of time so that any contamination resulting from compounds introduced during drilling is considered minimal. The brine samples collected from the bottom of those 15-m drillholes were considered to result in some mixing of brine from discrete sources. In addition, the locations of these boreholes include upholes and downholes monitored during the BSEP in Rooms A1, A2, A3, B, and G. Therefore, the collected data were assumed to well represent the spatial variability.

4.10.3. Alternate Interpretation

Density is a well known and routinely measured fluid property. No significant alternate interpretations need to be considered. However, another set of data was found in the BSEP 1989 report (DOE/WIPP 91-009). In that report, analytical results of 169 additional Salado brine samples were presented for geochemical analysis, including brine density. The values of brine density in this report present a slightly greater variation than reported in the Phase II report (DOE/WIPP87-010), ranging from 1,140 kg/m^3 to 1,260 kg/m^3. However, most of the values are equal to 1,220 kg/m^3, which is identical to the mean value reported in the Form 464.

Therefore, the additional brine density measurements in the 1989 report are in support of the conclusion presented in the Form 464. Since the sample size from the BSEP 1989 report is much larger than the Phase II report, support from these additional data makes the conclusion more representative of the Salado Formation brine density.

4.10.4. Uncertainty and Consequences

Uncertainties and consequences of the estimated results were not discussed in the related documents. Brine density is used in many ways, such as in estimation of fluid pressure and fluid compressibility. If brine density estimation is off by a few percent, the impact on fluid pressure or fluid compressibility is limited. In addition, fluid pressure and fluid compressibility will not dominate the aggregate uncertainty in the flow and transport calculations in the PA calculations. The uncertainty in the Salado brine density estimation is expected to have minimal consequences on the PA evaluations.

4.10.5. Appropriateness and Limitations of Methodology and Procedures

The brine samples were collected with care regarding the representativeness of naturally occurring Salado Formation brines for the geochemical analysis, as documented in the BSEP Phase II report.

Measurement of fluid density in the laboratory is a standard procedure. For these reasons the methodology and procedures are judged to be appropriate and acceptable.

4.10.6. Adequacy of Application

The Salado brine density was estimated to be a constant in the Form 464. As fluid density is a function of pressure and temperature, it is necessary to provide the reference conditions for the estimated value. However the calculation of the brine density under the *in situ* conditions by the reviewer illustrated that the change of the density with pressure was negligible. Thus, the estimated Salado brine density is adequate for the intended application.

4.10.7. Accuracy of Calculations

The calculation was checked and the results are the same as provided in the Form 464.

4.10.8. Validity of Conclusions

The estimated average Salado brine density of 1,220 kg/m^3 provided in the Form 464 is adequate for the intended use.

4.10.9. Dissenting Views

None.

4.11. Brine Compressibility

Brine Compressibility is a parameter used in the BRAGFLO modeling of fluid movement into and out of the repository. The parameter description follows:

Parameter:	Brine Compressibility
ID#:	48
Form 464:	WPO 31540, entered 2/9/96
Parameter Package:	WPO 31174
Distribution Type:	Constant
Value:	3.1E-10 Pa-1

Definition: Compressibility of brine in the Salado Formation. Brine compressibility is $\beta = 1/Vw\ (\partial Vw/\partial pf)T$

where:

β = brine compressibility,

Vw = volume of a given mass of brine,

pf = fluid pressure

Intended Use: Used as input for BRAGFLO modeling of fluid movement into and out of the repository.

Derivation: Brine Compressibility was developed from reported values for laboratory brine composed of NaCl dissolved in distilled water and from reported values of the compressibility of water saturated with gas.

4.11.1. *Adequacy of Requirements and Criteria*

No written requirements or criteria were found in the primary documents. However, the brine compressibility value supplied to BRAGFLO must satisfy the requirements of the PA. It must adequately represent the physical behavior of the brine and not introduce significant uncertainty that is not treated by the PA modeling. It is reasonable to expect the physical behavior of the Salado brine to be close to the behavior of the laboratory brine. The amount of uncertainty introduced due to the effects of dissolved gas and dissolved chemical species is not significant compared to the uncertainties in other model parameters that are treated via frequency distributions.

4.11.2. *Validity of Assumptions*

No significant assumptions were involved in developing the value for brine compressibility.

4.11.3. *Alternate Interpretation*

No alternate interpretations are relevant to brine compressibility.

4.11.4. *Uncertainty and Consequences*

The uncertainty related to brine compressibility is so low compared to uncertainties related to other parameters used in Salado modeling that it should have no significant effect on the PA.

4.11.5. *Appropriateness and Limitations of Methodology and Procedures*

As indicated in the preceding sections, the method of estimating brine compressibility using values reported in the literature was appropriate and the limitations of the method are acceptable.

4.11.6. *Adequacy of Application*

The application of a value for brine compressibility obtained from the scientific literature is acceptable and reasonable. The value selected is consistent with other values reported in the literature.

4.11.7. *Accuracy of Calculations*

No hand calculations or spreadsheet calculations related to brine compressibility were in the primary references. Inspection of other brine compressibility values reported in the scientific literature indicated that the brine compressibility value is reasonable; therefore, any calculated values, such as converted units, must have been properly executed.

4.11.8. *Validity of Conclusions*

As indicated in the preceding sections, the compressibility value developed for input to the PA model is an adequate representation of Salado brine compressibility, and the uncertainty related to the value is not significant.

4.11.9. Dissenting Views

None.

5.0 EVALUATION OF CASTILE SUBSYSTEM PARAMETERS

5.1. Castile Brine Reservoir Rock Compressibility

This section reviews the data from which the bulk compressibility in the hypothesized Castile brine reservoir were derived.

Parameter: Bulk Compressibility

ID#: 61

Form 464: WPO 31561, entered 4/12/96

Parameter Package: WPO 31084

Distribution: Triangular

Parameter values: Minimum: -11.3, log Pa^{-1} (5.0E-12 Pa^{-1})

Maximum: -8.0, log Pa^{-1} (1.0E-08 Pa^{-1})

Mode: -10.0, log Pa^{-1} (1.0E-10 Pa^{-1})

Definition: The definition of bulk compressibility is $\alpha = -(1/V)(\partial V/\partial p)_T$

where:

V = volume,

p = pressure,

T = constant temperature.

Thus, bulk compressibility means this relationship as applied to a medium consisting of an essentially homogeneous mixture of phases, such as solid and void space.

Intended Use: This parameter is needed in BRAGFLO in order to simulate the flow from a hypothesized brine reservoir in the Castile Formation should a borehole penetrate such a reservoir after closure of the repository.

Derivation: Laboratory strain tests and acoustic logs in borehole WIPP-12 were used to derive bulk compressibility of fractured anhydrite. The laboratory strain tests provide direct measurements of compressibility of dry unfractured samples. The acoustic logs provide data on *in situ* (hence, wet) compressibility for essentially unfractured anhydrite. These measurements provided, on average, identical compressibilities. The compressibility for fractured anhydrite was approximated by multiplying these measurements by a factor of 2 to 10 to obtain the low end and the mode of the distribution, respectively. The high end was taken from Freeze and Cherry (1979) as the high end of the range for rock compressibility for a fractured or jointed rock.

5.1.1. Adequacy of Requirements and Criteria

The primary need for this parameter is to provide quantitative data on compressibility of anhydrite in the Castile formation, envisaged as possibly being a reservoir rock for brine underlying the repository. This was accomplished through laboratory measurements of unfractured rock and interpretation of acoustic logs in "intact Anhydrite III" in borehole WIPP-12, coupled with estimates of the magnitude of increased compressibility for fractured anhydrite. No written requirements or criteria were found in the relevant documents. However, the data must adequately satisfy this objective of the testing.

Conditions required to obtain adequate data for determining bulk compressibility are:

- ☐ Proper operation of laboratory testing equipment.
- ☐ Proper operation of *in situ* testing equipment.
- ☐ Proper operation of data acquisition systems.

The first condition was presumed to be met by proper calibration procedures, which should exist in the archival records for these tests. Calibration and testing procedures are referenced in SAND81-7063, but not in SAND81-0858.

It is also presumed that calibration procedures would have indicated any difficulties in the data acquisition systems and that any relevant documentation exists in archival records. No difficulties were noted in the documents reviewed, except that in one instance the volumetric strain data were poor and the data were not used.

Upon a request for documentation on acoustic logs, the Panel was given "Log Review 1 (1974), Dresser Atlas, Dresser Industries, Inc." This document is older than the reference given in TME 3153, which cites "Dresser Atlas (1981) Acoustic Logs, Dresser Industries, Inc." This reference does provide sufficient detail to indicate how in general the tests were done. However, the 1974 documentation provided does not state which of several downhole tools was actually used and provides no calibration guidance for acoustic tools. The acoustic logs were not run by SNL, but were acquired through an independent contractor (Westinghouse). It is presumed that the procurement for these services specified the accuracy required. Investigating those records is beyond the scope of this review.

5.1.2. Validity of Assumptions

Assumptions relate primarily to whether the values obtained from dry samples in the laboratory, or the data obtained from acoustic logs in borehole WIPP-12 (bearing in mind the boring will to some extent disturb the formation), properly represent conditions in a saturated reservoir. Because the same value was derived from the laboratory tests on dry specimens and from the acoustic tests in WIPP-12, the available evidence suggests that any effect of wet vis-a-vis dry conditions is insignificant. The taking of cores for the laboratory tests does, of course, allow expansion of the specimens compared to *in situ* conditions. However, the specimens all still consist of unfractured rock, whereas the objective is to obtain an adequate representation of fractured rock. Thus, any increase in compressibility in the test specimens, or in the borehole, will be small compared to the increase needed to adjust the measured values to properly represent *in situ* conditions in the formation as a whole. Thus, the assumptions are judged to be valid.

5.1.3. Alternate Interpretation

The interpretations of laboratory and acoustic log data were proper and straightforward. No others are needed.

5.1.4. Uncertainty and Consequences

The uncertainty of individual laboratory measurements is far less than the range of likely values in the formation or reservoir. The range of values for unsmoothed data is quite large, but is generally greatly reduced by the smoothing procedure. Nevertheless, after smoothing, the data are quite consistent, such that the suitability for the objectives is judged adequate. The uncertainty in the cumulative laboratory measurements is far less than the range of likely values in the formation or reservoir. The application can readily accommodate the intended usage. The uncertainty is sufficiently low for laboratory data. The consequences for the application are judged to be inconsequential.

Examination of the Dresser Atlas Log Review 1 (1974) shows that numerous sources of uncertainty exist in respect to acoustic logs; whereas the magnitudes of these uncertainties are not discussed. Therein, the variability shown in example logs, taken together with estimates of other uncertainties (e.g., effect of the tool being canted in respect to the hole, accuracy of measurement of travel times), was estimated at being perhaps 10% of the measurement. This uncertainty is far less than others involved in deriving the parameter and is thus judged acceptable.

5.1.5. Appropriateness and Limitations of Methodology and Procedures

As indicated in the previous sections, the methodology for laboratory tests was appropriate and the limitations of the methodology are acceptable. All of the data obtained from laboratory experiments were used. For each anhydrite interval of the boreholes tested by acoustic logging only an average of the velocity in the unit is needed. This can be obtained within a few percent by visual examination of the log. Alternatively, some form of electronic smoothing or averaging may have been used. Neither case really amounts to data reduction in the usual sense.

The laboratory and acoustic log estimations of the bulk modulus agree very well, as shown by converting the units in TME-3153, p. G-33, and data tables in SAND81-0858 and SAND81-7063 to the same units. These correspond to unfractured rock. The conversion to conditions for fractured rock is less certain, but agrees with the limited data (Ibrahim et al. 1989; Freeze and Cherry 1979). Ibrahim et al. (1989) is an expanded abstract. Also relevant is Jung et al. (1991), pp. 37-39. Their measurements in salt pillars showed compressional velocities on corners and sides to be less than those in undisturbed salt by factors of about 2 to 4, which equate to increases in bulk modulus by factors of 4 and 16, respectively. The velocity decrease is attributed to post-mining fracturing. The factor 2 was obtained from the abstract and used in SAND90-0082. The effect of fracturing estimated in obtaining the bulk compressibility in the Castile reservoir was conservatively estimated to be considerably larger than this measured effect.

The methods used are well established for the laboratory data. The data from acoustic logs were input into well known equations relating velocity to seismic velocities and solved for the bulk modulus. No hand calculations or other means of demonstrating the accuracy were noted in the relevant documents. However, during this review a few approximate calculations were done that adequately confirmed the data derived from laboratory results.

No problems were identified in the examination of the primary laboratory data reports (SAND81-0858 and SAND81-7063). The acoustic data are also judged adequate.

5.1.6. *Adequacy of Application*

The data are judged adequate for the intended application.

5.1.7. *Accuracy of Calculations*

No hand calculations or other means of demonstrating the accuracy were noted in the relevant documents. However, during this review a few approximate calculations were done that adequately confirmed the data derived from laboratory results.

5.1.8. *Validity of Conclusions*

The data presented on Form 464, WPO number 31561, as indicated at the beginning of Section 5.1, are judged adequate for the intended application. Specifically, these are a minimum of 5.0E-12 Pa^{-1}, a maximum of 1.0E-08 Pa^{-1}, a mode of 1.0E-10 Pa^{-1}, and a triangular distribution.

5.1.9. *Dissenting Views*

None.

5.2. Castile Brine Reservoir Porosity

Castile Brine Reservoir Porosity is a parameter used in BRAGFLO modeling of flow of brine from a hypothetical brine reservoir for a borehole intrusion scenario. The parameter description follows:

Parameter:	Porosity
ID#:	64
Form 464:	WPO 31610, entered 1/31/96
Parameter Package:	WPO 31083
Distribution:	Student-t
Value:	Mean: 0.0087
	Std Dev: 0.0057
	Minimum: 0.002
	Maximum: 0.016
Definition:	Interconnected porosity of Castile brine reservoirs

Intended use: Used in BRAGFLO modeling of flow of brine in a borehole that could result from a hypothetical brine reservoir below the repository being penetrated by a borehole as part of an intrusion scenario.

Derivation: Core analysis of three pieces of Castile anhydrite by saturating dried core with toluene. Two pieces were from WIPP-12, located less than 3.2 km north of the waste panels, and one piece was from ERDA-6, located over 8 km northeast.

5.2.1. Adequacy of Requirements and Criteria

No written requirements or criteria were found in the primary documents. However TME 3153 (page G-29) states that estimates of porosity of the anhydrite that forms the brine reservoir in the Castile Formation are important to hydrologic evaluations and are used to approximate formation compressibility and reservoir volumes. Consequently, an implicit requirement is that the porosity estimate be adequate to support the development of such parameters, and to support the PA modeling of borehole intrusion.

5.2.2. *Validity of Assumptions*

The statistical assumption involved in developing the t-distribution is that Castile brine reservoir porosity measured from three core samples of anhydrite reservoir rock obtained from two wells can be treated as random samples of Castile brine reservoir rock. This treatment may not be strictly correct because one well, ERDA-6, was drilled on the crest of a domal structure and would tend to encounter higher fracture porosity than wells located elsewhere, biasing the sample toward higher porosity. Since the sample is biased toward higher porosity, it would be in the conservative direction of overestimating the brine volume and yield of the reservoir.

5.2.3. *Alternate Interpretation*

No alternate interpretations are relevant to Castile brine reservoir porosity.

5.2.4. *Uncertainty and Consequences*

The uncertainty associated with the Castile brine reservoir porosity is expressed in the t-distribution. As discussed above, the treatment of this uncertainty is conservative, tending to overestimate the brine volume and reservoir yield.

5.2.5. *Appropriateness and Limitations of Methodology and Procedures*

As indicated in the preceding sections, the method of estimating the Castile brine reservoir porosity is conservative. The actual core analyses were performed according to API standards, which is appropriate. It is difficult to measure fracture porosity at such low values, and some of the fractures might be induced or opened by the coring process. This limitation tends to produce error in the conservative direction. Geophysical borehole logging and fracture aperture analysis also indicated very low porosity.

5.2.6. *Adequacy of Application*

The application of values for reservoir porosity parameters obtained from core analysis to the development of a frequency distribution for the PA is adequate and conservative.

5.2.7. *Accuracy of Calculations*

No hand calculations or spreadsheet formulas related to Castile brine reservoir porosity were found in the primary documents. The porosity values reported are reasonable, and porosities obtained by more than one method are in agreement.

5.2.8. *Validity of Conclusions*

As indicated in the preceding sections, the Castile brine reservoir porosity parameters developed for input to the PA indicate very low porosity. The maximum and minimum values (0.002 and 0.016) are reasonable, and the t-distribution is conservative because it is biased toward high porosity. The spread of the t-distribution, for the small number of samples, adequately represents the uncertainty.

5.2.9. *Dissenting Views*

None.

5.3. Castile Brine Reservoir Pressure

The purpose of estimating the Castile brine reservoir pressure is to provide the initial Castile brine reservoir pressure for model BRAGFLO in PA. The information about the parameter in the Form 464A is as follows:

Parameter Package:	Brine reservoir pressure
ID#:	66
Form 464A:	WPO 31612, entered 3/2196
Parameter Package:	WPO 31072
Distribution Type:	Triangular
Values:	Mode: 12.7 MPa Minimum: 11.1 MPa Maximum: 17.0 MPa

Definition: The Castile brine reservoir pressure is defined as the initial brine reservoir pressure that may be encountered by a hypothetical borehole drilled through the repository into a hypothesized pressurized brine reservoir in the Castile Formation below the repository.

Intended Use: The estimated Castile brine reservoir pressure and its statistical distribution are used as the potential initial pressure in model BRAGFLO under the hypothetical case that a borehole is drilled through the repository and into the hypothesized pressurized brine reservoir in the underlying Castile Formation.

Derivation: The Castile brine reservoir pressure estimation was based on several documents, including SAND92-0700/3, SAND89-7069, SAND89-0462, and TME-3153. Basic data of the Castile brine reservoir pressure in the WIPP area include the measured pressures at WIPP-12, ERDA-6, Belco, and Gulf Covington, and the estimated pressures at nine other locations (Table H-1, TME-3153). The measured pressures range from 12.6 MPa to 14.3 MPa at various depths and different locations in the vicinity of the WIPP. Among those, the measured pressure at WIPP-12 of 12.7 MPa is considered most representative of the site conditions because it is the closest one to the waste-storage area, and the reservoir encountered at WIPP-12 has been studied and characterized through many tests and analyses.

The possible range of the initial brine reservoir pressure was estimated by extrapolating the measured pressures at various depths to the WIPP-12 depth (140 m above sea level [masl]). Pressure extrapolation using either a hydrostatic adjustment or a lithostatic adjustment was completed by the following equation:

$$P_a = P + \rho g\,(h - 140) / 1.0\text{E-}06$$

where:

P_a = adjusted pressure [MPa]

P = measured/estimated pressure [MPa]

ρ = assumed density [kg/m^3]

g = gravitational constant [9.8 N/kg]

h = brine reservoir elevation at measurement point [masl]

An average brine fluid density of 1,240 kg/m^3 was used for hydrostatic adjustment and an average formation density of 2,400 kg/m^3 was used for lithostatic adjustment.

The maximum pressure in the Castile brine reservoir was estimated to be 85% of the lithostatic pressure at WIPP-12 depth. The minimum pressure was estimated to be the smallest value among the hydrostatic adjusted pressures, and the lithostatic adjusted pressures reduced by 15%. The measured WIPP-12 pressure of 12.7 Mpa was assigned to be the value of mode.

5.3.1. Adequacy of Requirements and Criteria

The requirements and criteria for the estimation were not specifically stated in the Parameter Package. Based on the intended use of the initial Castile brine reservoir pressure, the estimation should be representative of the most likely reservoir conditions at the WIPP site. Since the Castile brine reservoirs are heterogeneous, discontinuously fractured zones of limited extent within the Castile anhydrites, the initial pressure at the time when a hypothetical borehole is drilled through may vary. This requires the estimation to cover this spatial variability of the pressure, and to present the most likely pressure associated with a high probability, based on the existing data. The data collection, interpretation, and parameter estimation processes have met these requirements.

5.3.2. Validity of Assumptions

The primary assumptions involved in the estimation of the initial reservoir pressure at the center of the brine reservoir at WIPP-12 depth, based on measured and estimated Castile brine reservoir pressures, include the following:

<u>Assumption 1</u> Initial pressures of the Castile brine reservoir lie between hydrostatic pressure and lithostatic pressure.

This is a reasonable assumption because the Castile brine reservoirs could be either interconnected or isolated by impermeable zones. Hydrostatic adjustment would be appropriate if the reservoirs are interconnected and lithostatic adjustment would be appropriate if the reservoirs are isolated.

<u>Assumption 2</u> The fluid pressures in the Castile brine reservoirs are assumed to be no greater than 85% of the lithostatic pressures.

This assumption was developed based on the examination of the relationship between the fluid pressures at the reservoir depths and the interpreted lithostatic pressures at the reservoir depths using the WIPP-11 density log. The data involved in the examination include both measured and estimated pressures in anhydrite units in the Castile (13 data points) and Salado (5 data points) Formations. The percentages of fluid pressure vs lithostatic pressure range from 50% to 86%, with an average ratio of 67% and a median ratio of 64%. Assumption 2 is based on the site-specific conditions and is considered appropriate. Based on this assumption, the pressure value obtained by lithostatic adjustment using the equation was further adjusted by reducing it by 15%.

5.3.3. Alternate Interpretation

The interpretation based on the first assumption discussed in Section 5.3.2 led to two sets of interpreted pressures using hydrostatic and lithostatic extrapolations. The measured or estimated pressures at 12 locations other than WIPP-12 were converted to equivalent pressures at the depth of WIPP-12. Interpreted results provide a greater range of brine reservoir pressures varying from 10.7 MPa to 20 MPa, which could potentially cover the uncertainty due to the formation heterogeneity.

Based on the second assumption discussed in Section 5.3.2, the estimation was changed to a slightly smaller range varying from 11.1 MPa to 17.0 MPa. Since this estimation was developed based on the site-specific analysis by examining the relationship between measured or estimated fluid pressures and calculated lithostatic pressures, it is considered more representative of the site conditions.

5.3.4. Uncertainty and Consequences

The uncertainties of the initial Castile brine reservoir pressures may be primarily related to different origins of the Castile brine reservoirs, and related to the heterogeneity of the Castile formation. These uncertainties have been well exhibited in the measured and estimated brine pressures at 13 borehole locations.

The uncertainty is expressed as the estimated distribution of the parameter. The assigned distribution in the Form 464A is a triangular distribution with a mode value of 12.7 MPa, which is the measured value at WIPP-12. Based on the characteristics of a triangular distribution, a high probability was assigned to the mode. This is reasonable because the location of WIPP-12 is the closest to the center of the repository room (1.5 km away), and the measured pressured of 12.7 MPa has been supported by various tests and evaluated by many analyses.

The possible consequence of the uncertainty of the estimation was not documented in the related parameter package. As discussed in SAND89-7069, the Castile brine reservoir pressure was identified as the second most sensitive parameter in the estimation of peak-release and 10,000-year cumulative release under the hypothetical case. The initial brine reservoir pressure is one of the components used in calculation of change of pressure with time. The possible consequence of underestimating or overestimating the initial pressure would underestimate or overestimate the potential flow rate of brine through a borehole under the hypothetical borehole intrusion case. However, the dominant factor in calculation of the potential release is identified as borehole transmissivity, as stated in SAND92-0700/4.

5.3.5. Appropriateness and Limitations of Methodology and Procedures

The test methodology and procedures for measurement of brine reservoir pressure at WIPP-12 were well documented in TME-3153. Summary of appropriateness and limitations of measurements and interpretations of the brine reservoir pressure at WIPP-12 was given in SAND89-7069. Pressure was measured with downhole transducers, surface transducers, and mechanical pressure gages at the wellhead. Downhole transducers could not be left downhole for long periods, because of the extremely corrosive nature of the brine. Measured surface pressures were extrapolated to pressures at brine reservoir depth based on an estimated fluid column density of 1,240 kg/m^3. Uncertainties related to the estimation of fluid column density, and related to the influence of a gas cap formed during the pressure buildup period, were evaluated to be minor.

5.3.6. *Adequacy of Application*

Since the estimated parameter and its distribution are representative of the site-specific conditions and the potential variation, they are considered adequate for the intended use in BRAGFLO.

5.3.7. *Accuracy of Calculations*

The calculation for interpretation was spot-checked, showing that the interpretation results provided in the package are correct in calculation.

5.3.8. *Validity of Conclusions*

The estimation of the initial Castile brine reservoir pressure, following a triangular distribution with a mode of 12.7 MPa, a minimum of 11.1 MPa, and a maximum of 17.0 MPa, is considered adequate for the intended use.

5.3.9. *Dissenting Views*

None.

5.4. Castile Brine Reservoir Permeability

Castile Brine Reservoir Permeability is a parameter that is used in BRAGFLO modeling of the borehole intrusion scenario. The parameter description follows:

Parameter:	Castile Brine Reservoir Permeability
ID#:	67, 68, 69
Form 464:	WPO 31613, entered 2/16/96
Parameter Package:	WPO 31070
Distribution type:	Triangular
Values:	Mode: 1.5E-12 m^2 Maximum: 1.5E-10 m^2 Minimum: 2.0E-15 m^2

Definition: Permeability of hypothetical brine reservoir in the Castile that might be intersected by a well penetrating the repository.

Intended use: Used in BRAGFLO modeling of the borehole intrusion scenario, wherein a borehole intersects a fractured anhydrite layer in the Castile formation and conducts brine upward into the repository.

Derivation: The Castile brine reservoir permeability parameters are based on testing of WIPP-12 and ERDA-6, which are the only Castile wells near the WIPP site that have been subject to detailed quantitative testing (TME 3153, page H-3). WIPP-12 is located about a mile from the site center, and ERDA-6 is about five miles northeast of the site center. The mode $10^{-11.8}$ m^2 of the triangular distribution is from GTFM analysis of WIPP-12 flow and pressure buildup tests (SAND89-7069). The minimum value 2.0E-15 m^2, is from Flow Test #2 of ERDA-6, and is the lowest value from any flow test of ERDA-6 and WIPP-12. The maximum 1.5E-10 m^2 is an order of magnitude higher than the highest measured value.

5.4.1. *Adequacy of Requirements and Criteria*

No written requirements or criteria were found in the primary documents. However, an objective of WIPP-12 and ERDA-6 testing was to determine reservoir transmissivity (TME 3153, page H-7). Consequently, an implicit requirement is that the test data be adequate to support quantitative estimation of Culebra brine reservoir transmissivity. These requirements were addressed by performing drill stem tests (DSTs) and flow tests and analyzing the data via Horner analysis and GTFM 6.0 analysis, respectively.

5.4.2. *Validity of Assumptions*

The critical assumptions related to quantitative estimation of transmissivity of the Castile brine reservoirs are those related to the analysis of the test data. The assumptions of greatest interest with respect to adequate characterization of brine reservoir permeability are:

- ☐ Darcy flow,
- ☐ Radial flow to the well, and
- ☐ Concentric zones of homogeneous permeability.

The details on assumptions of GTFM 6.0 analysis are presented in Pickens et al. (1987).

The Darcy flow assumption may be applied to large scale flow in fractured media within commonly encountered flow velocity ranges due to the analogy between equations for porous media flow and flow between parallel plates, and due to the similar behavior of fractured media to porous media at large volume scales. The assumption of radial flow is commonly made and is reasonable for flow to a borehole, even though there will be deviations from radial flow due to heterogeneity and anisotropy in permeability caused by variation in fracture spacing, openness, and orientation. The assumption of concentric zones of homogeneous permeability is not likely to be met, due to the complexity of fractured reservoirs and the low probability that a borehole would be drilled in the place where permeability is highest or lowest. Nevertheless, the concentric permeability zone model allows a simplified treatment that is realistic enough to deal with the complex system. The concentric model is reasonable because permeability in an isolated reservoir will begin to change at some distance from a well that penetrates the reservoir.

5.4.3. Alternate Interpretation

No alternate interpretations were identified that would improve the estimate of Castile brine reservoir permeability. More complex models could be used in the analysis of the data, but they are not warranted by the amount of data available. The amount of data available is adequate for the purpose of supplying permeability frequency distribution parameters for the intrusion scenario modeling.

5.4.4. Uncertainty and Consequences

The uncertainty associated with the Castile brine reservoir permeability is expressed in the triangular distribution. Since the maximum and minimum permeabilities used in the distribution are extremely large and small values, the treatment of this uncertainty is conservative, tending to overestimate the degree of uncertainty. The consequence of this overestimation will be to increase uncertainty in the PA modeling.

5.4.5. Appropriateness and Limitations of Methodology and Procedures

The methodology of testing the boreholes by flow testing and DSTs, as documented in TME 3153 and SAND89-7069, is appropriate. The flow testing and GTFM 6.0 analysis is in accordance with hydrologic theory and the observation that fracture systems behave like porous media at large volume scales. Drill stem testing is in accordance with established practice in the petroleum industry, and the analysis of DST data by the Horner method is supported by hydrologic theory, including the similar form of equations describing flow in porous media and flow between parallel walls. The field methodology included the use of flow meters in parallel, so that when salt deposition affected meter performance a second meter could be used while the first was cleaned.

5.4.6. Adequacy of Application

The application of values for reservoir permeability parameters obtained from GTFM 6.0 and DST analysis to the development of a frequency distribution to be sampled during intrusion scenario modeling is adequate and conservative. More than one test was performed in each borehole. Descriptions of the field tests and the results presented on the pressure graphs indicate that the conduct of the tests was adequate for the analyses to be performed. Test irregularities such as gas liberation, salt buildup in flow lines and meters, and choke effects were described and appear to have been dealt with adequately. Potential interference by pressure recovery from previous tests was evaluated. The main tests for estimating permeability were WIPP-12 Flow Test 2 and Flow Test 3. GTFM 6.0 analysis was used for these tests. Consequently, pre-test history could be included directly in the analysis of the data. Horner analysis showing relatively high permeability near the WIPP-12 borehole supports the GTFM 6.0 concentric double-permeability interpretation.

5.4.7. Accuracy of Calculations

No hand calculations or spreadsheet formulas related to Castile brine reservoir permeability were found in the primary documents. The permeability values reported are reasonable, and permeabilities obtained by more than one test and more than one method are in reasonable agreement with the concentric double-permeability model used in the interpretation of the data.

5.4.8. Validity of Conclusions

As indicated in the preceding sections, the Castile brine reservoir permeability parameters developed for input to the PA modeling are reasonable and adequate. The uncertainty in the permeability of the Brine Reservoir that might be penetrated by an intrusion borehole is adequately treated by the triangular frequency distribution. The estimated mode, minimum, and maximum permeability, were adequately supported by the data and analyses reported in TME 3153 and SAND89-7069. Conclusions were supported by GTFM analysis applied to two flow tests and their recovery (Horner analysis indicating relatively high permeability near the WIPP-12 borehole), and adequate treatment of field problems (salt deposition, gas dissolution).

5.4.9. Dissenting Views

None.

5.5. Castile Brine Reservoir Volume

Parameter:	Castile Brine Reservoir Volume
ID #:	2918
Form 464A:	WPO 31625, entered 3/20/96
Parameter Package:	WPO 31082
Distribution:	Constant
Parameter Values:	Minimum: 4.0E+06 m^3

Definition: The Brine Reservoir Volume is the volume of reservoir rock within the Castile Formation that is hypothesized to contain a brine reservoir located approximately 250 m below the WIPP repository.

Intended Use: The intended use of the parameter is to provide a value of the rock reservoir volume that can be used to calculate a brine volume for entry in the BRAGFLO model. The value in BRAGFLO would be a determination of the volume of brine that would be present in the Castile Formation to enter a borehole that might penetrate the repository and intercept the hypothesized brine reservoir in the Castile Formation. Using the reservoir volume of 4.0E+06 m^3 and an effective porosity of 0.008, the volume of brine has been calculated as 32,000 m^3.

Derivation: The total brine reservoir volume parameter is based on measured pressure and volume of brine as produced from drill stem tests (DSTs) and flow tests of the Castile Brine Reservoir zone conducted during 1981 to 1983 in boreholes (wells) WIPP-12 and ERDA-6. The pressure and brine volume data used for the parameter calculation are contained in SAND89-7069 and TME 3153.

The brine reservoir volumes shown in the Table of Calculated Castile Reservoir Volumes appended to the Form 464A were calculated using the following equations based on Domenico's (1972) equation:

$$\Delta V = S\ A\ \Delta h$$

where:

ΔV = volume of brine released from storage over an area A

Δh = given pressure head change

S = storage coefficient.

The storage coefficient is:

$$S = \rho \, g \, \Delta z \, (C_R + \phi \, C_W)$$

where:

ρ = fluid density

g = acceleration of gravity

Δz = aquifer thickness

C_R = bulk rock compressibility

ϕ = porosity

C_W = fluid compressibility.

By combining terms, these equations can be rewritten as:

$$V = \Delta V \, / \, (C_R + \phi C_W) \, \Delta p$$

Thus, the total volume of the rock reservoir (V) can be calculated knowing the total pressure change (Δp) that has occurred as a result of fluid volume release (ΔV), making assumptions about the reservoir rock and fluid compressibilities.

Discussion: The volume of the brine reservoir listed on the Form 464A is not the actual value used in BRAGFLO. The volume of the brine reservoir on Form 464A is used to calculate the brine volume, by multiplying the reservoir volume of 4.0E+06 m^3 times its effective porosity of 0.008. The reservoir volume of 4.0E+06 m^3 was calculated using a maximum rock compressibility value of 1.0E-08 Pa^{-1}. The actual parameter being used in the BRAGFLO model is a brine volume (Sommers 1996). As per the memo to Martin Tierney (Larson 1996), the volume of brine to be used in the BRAGFLO calculations is 32,000 m^3 per brine reservoir. The memo further states that for any particular realization there may be between one and five reservoirs, some or all of which might be contiguous (*what is really meant is interconnected*). Therefore, the volume of brine (stored in effective porosity) to be used in the performance assessment could range from 32,000 to 160,000 m^3. The rationale for the brine reservoir volume parameter is provided in a pre-signature final draft memo of record dated May 27, 1996 (Freeze 1996), attached to the Parameter Package.

5.5.1. Adequacy of Requirements and Criteria

The technical information used for the computation of the brine reservoir volume in the Castile Formation is gleaned from the hydrology section of the TME 3153 report (pp. H-46 to H-48 for ERDA-6 and pp. H-53 to H-55 for WIPP-12). The report presents the results of the geological, hydrological, and geochemical investigation of the brine reservoirs in the Castile Formation. The objectives of the study were not clearly stated in the report. However, it can be inferred that the objectives were to determine the potential impact of the brine reservoirs on the integrity of the WIPP facility and determine the origin and nature of the brine reservoirs.

The requirements and criteria of the data are not indicated in the TME 3153 or SAND89-7069, so it is difficult to judge whether adequacy of requirements and criteria have been met. However, using the data from the tests of WIPP-12 and ERDA-6 in combination with other data from the TME 3153 investigation, it is possible to calculate a valid estimate of brine reservoir volume. This was accomplished by using the aforementioned reservoir volume equations under assumed conditions of Castile brine reservoir rock compressibility.

5.5.2. Validity of Assumptions

The assumptions made for the calculations in the Parameter Package are that the brine reservoir volume can be calculated from the volume of fluid produced and the corresponding decline in pressure in the reservoir using the equations of Domenico (1972). Using the data from the tests of WIPP-12 and other parameter values of porosity, brine compressibility, brine reservoir rock compressibility, reasonable value of reservoir volume has been calculated which demonstrates the validity of the assumptions.

5.5.3. Alternate Interpretations

It is obvious from the aforementioned reservoir volume equations that the brine reservoir volume can be changed by varying the rock compressibility values. Thus, there can be alternative interpretations of brine reservoir volume, depending on the values of the rock compressibility chosen for use in the reservoir volume equation.

5.5.4. Uncertainty and Consequences

Although erroneous data were identified and eliminated from use in the analyses of the pressure/flow data from WIPP-12, there was no discussion of the consequences of the uncertainty of the results in TME 3153. In SAND89-7069 (p. A-5) mention was made of the fact that the possible impact of multi-phase flow on long-term brine reservoir behavior has not been quantified and that it should be considered a potentially important cause of uncertainty in brine reservoir breach simulations.

Section 3.2, Measurements (TME 3153, pp. H-10 to H-14) discusses: 1) the problems of gas liberation upstream of the flow meters at the surface during the DSTs, causing the meters to register erroneously high flow rates, 2) the salt precipitation in the flow lines restricting flow and incapacitating recording instruments, and 3) the choke effects during the DST flow periods which caused higher pressure readings to be recorded than would have occurred without the choke effect.

The problems of gas/brine separation were rectified when gas/liquid separators were installed and the brine flows subsequently measured downstream from the separator after the gas had been removed from the flow line. However, in order to operate the separator, the well was backpressured during Flow Test 1 and the corresponding pressures and flow rates were not reported in D'Appolonia reports; therefore, the reservoir parameters for that test could not be interpreted, according to SAND89-7069 (Appendix A, p. A-4). Other factors affecting the quality of the measurements, such as corrosion of flow meters from brine and hydrogen sulfide, are discussed in TME 3153, pp. H-10 to H-14. Further discussion of these is beyond the scope of this review.

5.5.5. Appropriateness and Limitations of Methodology and Procedures

At the time of testing of boreholes ERDA-6 and WIPP-12, there were industry-accepted standard procedures for the performance, analysis, and interpretation of DSTs and flow tests which had been used for a number of years by the petroleum industry. The results of the flow tests were analyzed by traditional petroleum industry analytical techniques (i.e., Horner method) and classical U.S. Geological Survey ground water aquifer flow analysis techniques. These techniques were the classic Theis and Jacob-Lohman methods, and standard petroleum reservoir engineering methods involving interpretation of DSTs by the Horner semi-log plot of pressure buildup vs the log of lapsed buildup time.

According to TME 3153, the actual details of the flow tests and analyses are contained in a series of reports from D'Appolonia to Westinghouse Electric Co., another SNL subcontractor. These reports and others regarding the drilling and testing are archived at SNL. These detailed reports were not reviewed.

There is no discussion of detection limits of the instrumentation used in the DSTs in TME 3153 or SAND89-7069. This information is provided in the earlier D'Appolonia reports, which were not reviewed.

There were two sets of DSTs and three flow and recovery tests performed on the Castile brine reservoir penetrated by WIPP-12. Although the tests were of different durations and at different times, there was enough redundancy to provide checks on the data.

The methods and procedures used to obtain the pressure/flow data from WIPP-12 and ERDA-6 were standard for the petroleum industry and ground water resources investigations. Some of the limitations of the testing were caused by the corrosive nature of the hydrogen sulfide-laden brine fluid and the evolution of gas, which required modifications to the equipment and procedures.

By comparison of the results of analyses (TME 3153, pp. H-15 to H-35) of the pressure/flow data from WIPP-12 by several different analytical techniques, it is apparent that the data quality is adequate. A review of TME 3253 and SAND89-7069 indicates that the assumptions, calculations, extrapolations, methods, and conclusions pertinent to the data were appropriate for the calculation of the brine reservoir parameter on the Form 464A.

5.5.6. Adequacy of Application

Based on the data provided in TME 3153, it appears that test-to-test interference did not occur between wells WIPP-12 and ERDA-6, which were approximately 10 km apart. However, it is not clear whether subsequent tests within the same well might have been affected by the previous testing. The report (p. H-35) does acknowledge that considerable amounts of data had to be rejected as unreliable because of technical limitations of the instrumentation used (i.e., the choke effect in DST tool entry ports) or operational /mechanical deficiencies (e.g., heavy mud in the hole affecting flow rates, and leaky blowout preventers or lubricator). However, it is reported that only the most reliable data and only the analytical methods best suited to the actual reservoir conditions were used to quantify reservoir properties in the report. TME 3253 (p. H-35) states that, "All data acquired during the present testing program were thoroughly examined." In many cases, however, the data had to be rejected as unreliable because of technical limitations of the instrumentation used or operational deficiencies. The description of the testing equipment and testing procedures as presented in TME 3153 (Section 3.1 Testing, pp. H-7 to H-10, Section 3.2 Measurements, pp. H-10 to H-15) indicate that the test procedures were correctly implemented.

The interpretations of analyses of these physical data (i.e., water pressures and flow rates), are not affected by the age of the data. The basic physical properties of the brine reservoir are not believed to have changed materially through natural causes in thousands of years.

In order to estimate the change in reservoir pressure during the length of the testing period, it was necessary to extrapolate surface pressures at the well head to pressures at brine-reservoir depth by assuming an estimated fluid column density. This estimation of fluid column density was complicated by the buildup of a gas cap at the well head in WIPP-12. Unfortunately, adequate records of the gas cap evolution were not recorded because the gas cap formed slowly and the amount of gas produced during buildup reportedly was small. The effect of the gas cap over time would be that of decreasing the density of the brine fluid column and thus, producing anomalous pressure responses at the well head.

In using the Jacob-Lohman method for analyzing constant-pressure flow data (TME 3153, pp. H-24 and H-25), it was determined that only flow tests ERDA-6/Flow test #3 and WIPP-12/Flow test # 2 meet the requirements of: 1) constant friction head loss in the well casing and discharge line; 2) constant fluid density; and, 3) constant backpressure or unrestricted flow which are necessary for maintaining constant pressure. Therefore, only these two tests were analyzed by the Jacob-Lohman method, as other flow tests were eliminated due to non-constant fluid density and changing backpressure caused by salt crystallization in the flow lines.

Of the two flow tests presenting data that could be used for analysis, Flow test #2 had a flow period of 0.23 days and recovery of 2.69 days, while Flow test # 3 had a flow period of 7.0 days and a recovery period of 278.4 days. Thus, the number of data points was enough to provide an adequate level of confidence in the results, but only for the reservoir's short-term behavior. There is internal consistency between data sets in that both tests show pressure buildups and flow rates. However, the Horner plot of pressure vs elapsed time for Flow tests #2 and #3 shows different curves with widely different characteristics (SAND89-7069, p. A-7) for each test. The calculated transmissivities determined by Horner's semi-log method for each test differ by nearly three orders of magnitude. The reason for these inconsistencies is that Flow test #2 was short and may have stressed the well-connected fractures near the wellbore, which may have yielded a higher permeability (transmissivity). However, Flow test #3 lasted 7 days and had a buildup of 278 days. Thus, over the greater time period of Flow test #3, it may have stressed a much larger portion of the brine reservoir, reaching into areas with a lower permeability (transmissivity).

Nevertheless, the data appear to be complete enough to make reasonable estimations of brine reservoir volume based on interpretation of flow tests and pressure changes during the flow tests. The calculation of the brine reservoir volume has utilized the data analyzed from the pressure/flow tests of WIPP-12 and shown the adequacy of application.

The interpreted results of the type-curve analyses (SAND89-7069) and the GTFM 6.0 simulation of the pressure/flow data from WIPP-12 and ERDA -6 indicate that the data are sufficient to support the intended use.

5.5.7. Accuracy of Calculations

The value for the volume of the brine reservoir listed on Form 464A was checked against the original well data interpretations in the TME 3153 report. Reservoir volumes were hand calculated using the TME 3153 data and values provided in the tables within the Parameter Package for the Form 464A. The hand calculated volume estimations were nearly identical to those on the Form 464A, thus verifying the reasonableness of the calculations.

5.5.8. Validity of Conclusions

The brine reservoir volume value listed on the Form 464A and recorded in the Parameter Package was interpreted from used values of initial pressure, final pressure, pressure change and volume of brine produced during the hydraulic testing of ERDA-6 and WIPP-12, as reported in TME 3153 (pp. H-46 to H-48 and H-53 to H-55). These data have been checked and found to be reasonable values representing the brine reservoir conditions at the time of testing. The analysis and interpretation methodology and results also were found to be appropriate. Thus, the parameter value of 4.0E+06 m^3 for the brine reservoir volume is considered to be reasonable for its intended use.

5.5.9. Dissenting Views

None.

6.0 EVALUATION OF UNITS ABOVE THE SALADO SUBSYSTEM PARAMETERS

6.1. Non-Salado Effective Porosity

The estimated effective porosity values for six Non-Salado Formations, including Culebra, Dewey Lake, Forty-niner, Magenta, Tamarisk, and unnamed, were reviewed in this section. Information provided in the Form 464s are as following:

CULEBRA:

Parameter: Effective Porosity

ID#: 140

Form 464: WPO 32769, entered 2/9/96

Parameter Package: WPO 30608

Distribution Type: Constant

Parameter Values: 0.151

DEWEY LAKE:

Parameter: Effective Porosity

ID#: 158

Form 464: WPO 2731, entered 2/20/96

Parameter Package: WPO 30608

Distribution Type: Student-t

Parameter Values: 0.143

FORTY-NINER:

Parameter: Effective Porosity

ID#: 2088

Form 464: WPO 32995, entered 2/20/96

Parameter Package: WPO 30608

Distribution Type: Student-t

Parameter Values: 0.082

MAGENTA:

Parameter: Effective Porosity

ID#: 2100

Form 464: WPO 32531, entered 2/9/96

Parameter Package: WPO 30608

Distribution Type: Student-t

Parameter Values: 0.138

TAMARISK:

Parameter: Effective Porosity

ID#: 2186

Form 464: WPO 34568, entered 2/20/96

Parameter Package: WPO 30608

Distribution Type: Student-t

Parameter Values: 0.064

UNNAMED:

Parameter: Effective Porosity

ID#: 2200

Form 464: WPO 34692, entered 2/20/96

Parameter Package: WPO 30608

Distribution Type: Student-t

Parameter Values: 0.181

Definition: The effective porosity is defined as the ratio of the interconnected pore volume to the bulk volume of the rock. The term porosity is used in the following discussion for simplicity.

Intended Use: The values of non-Salado porosity for each unit above Salado are used as initial input into BRAGFLO. Specifically, initial porosity is used to calculate pressure-dependent porosity (Compliance Certification Application (CCA) Section 6.4 contains the Conceptual Model descriptions) under three scenarios: (1) undisturbed conditions, (2) a borehole intrusion penetrating the repository and a Castile brine reservoir, and (3) a borehole intrusion penetrating only the repository. The use of the initial porosity is expressed in the following equation:

$$\phi = \phi o \exp [C(p - p_o)]$$

where:

ϕo = initial porosity, the parameter that needs to be reviewed in this section

po and p = initial pressure and pressure at a subsequent time

C = bulk rock compressibility.

Derivation: Non-Salado porosity was estimated for six units above the Salado, including the Culebra, Dewey Lake, Forty-niner, Magenta, Tamarisk, and unnamed. The data for Culebra were based on two sources: (1) the core analyses for selected samples from the Culebra dolomite from 20 boreholes at the WIPP site (SAND90-7011), and (2) the data from borehole H-19b4 and AIS obtained from the memorandum, Terra Tek, dated Jan. 8, 1996. The measurement processes for effective porosity were documented in detail in SAND90-7011. The data for the other five units using core analyses were based on samples from borehole H-19b1 and analyzed by Terra Tek recently. This recent work was done under a qualified quality assurance (QA) program and is not part of this peer review.

6.1.1. Adequacy of Requirements and Criteria

The objectives of the core analyses, clearly stated in SAND90-7011, were to understand the physical properties of the pore structure of the Culebra better and to augment the Culebra data base for site characterization and performance assessment studies. The sampling and analyses processes documented in SAND90-7011 have demonstrated that the requirements and criteria were adequate to meet the objectives. The adequacy of the requirements can be summarized as follows:

- ☐ More than 100 samples, including whole-core and core-plug samples from 22 boreholes located in the WIPP area were used.
- ☐ Results from different phases and different laboratories were evaluated and were consistent.
- ☐ Tests were performed under a quality assurance plan.

6.1.2. Validity of Assumptions

One assumption related to the estimation of porosity of the Culebra is that the selected samples are a reasonable representation of the Culebra dolomite, which statistically represents the porosity distribution of the Culebra physical textures. This appears to be a reasonable assumption based on the large number of samples collected from 22 boreholes at different locations. However, as stated in SAND90-7011, the selected core samples were based on the availability of samples. Since many core samples that were in apparently porous and fractured parts of the Culebra have been destroyed and not recovered during coring, the measured samples may not completely represent the physical characteristics of the Culebra.

In the porosity estimation for the other units, the underlying assumption is that the core samples collected from borehole H-19b1 are a reasonable representation of the entire unit at the WIPP site. This assumption in general may not be acceptable if the objective was to characterize the physical texture of the formation. However, for the intended use of the porosity in BRAGFLO, this assumption can be accepted because the objective of BRAGFLO is to estimate the brine flow rate entering the Culebra under the intrusion senarios. All the other units are much less transmissive than the Culebra; whether the parameter is representative is not important.

6.1.3. *Alternative Interpretations*

Porosity estimation by the helium method is a standard and well known process. No significant alternate interpretations need to be considered.

6.1.4. *Uncertainty and Consequences*

The primary uncertainty related to the pore volume measurements used to estimate the porosity for Culebra is stated in SAND90-7011. Specifically, for many WIPP wells the incomplete core recovery may correspond to the porous and fractured parts of the Culebra. Therefore, the parameter distributions obtained from the recovered core samples may represent only the relatively less fractured and competent parts of the Culebra at the WIPP site.

The uncertainty of the porosity estimation may have only minor effect on the calculation of the flow rate entering the Culebra because the dominant factors for flow rate calculation are the borehole transmissivity and pressure gradient (SAND89-7069). The uncertainty associated with estimation of porosity may be well covered by the uncertainty associated with the estimation of borehole transmissivity and pressure gradient.

The estimation of porosity for units other than the Culebra is less important. The permeability value for the Forty-niner, Tamarisk, and unnamed units have been set equal to zero (Memorandum from L. Dotson, February 1, 1996) for the purposes of the PA. These units in BRAGFLO are treated as impermeable so that the model will not allow fluid flow from a borehole or shaft that penetrate these formations. Therefore, the porosity in these formations will have no effect in the model.

The estimation of porosity for the Dewey Lake and Magenta is considered adequate for the intended use. The objective of BRAGFLO is to simulate the brine flow rate entering the Culebra in the vicinity of the WIPP site under the hypothetical borehole intrusion scenario. The potential flow rate entering Dewey Lake and Magenta would be significantly less than the potential flow rate into the Culebra, based on the significant differences in permeability and pressure values. The consequences and uncertainty associated with the estimation of porosity for these two units are negligible.

6.1.5. Appropriateness and Limitations of Methodology and Processes

The methodology and processes for the measurement of porosity for the Culebra were documented in detail in SAND90-7011. They are considered appropriate for the characterization of the physical properties of the Culebra.

The basic approach used for measurement of porosity is the helium method based on Boyle's Law. Helium is a non-adsorbing gas and has a minimum deviation in behavior from an ideal gas. The helium method is supposed to provide an approximation of total interconnected porosity. Advantages of the Boyle's Law helium method are that it is: (1) very accurate, (2) fairly rapid except for extremely low-permeability (< 1.0E-18 m^2) samples, and (3) non-destructive, allowing the samples to be reused for other analyses (SAND90-7011).

The water resaturation method was also used to measure porosity. The resaturation method is supposed to provide an estimate of the interconnected porosity for ground water flow, and also to have the advantage of determining the void volume when the mineral samples are wet, as the *in situ* condition. The resaturation method using deionized water was applied on part of the samples that had been used to measure porosity using the helium method. Results of applying both methods show close agreement.

The core analyses documented in SAND90-7011 were performed in two phases from 1985 to 1986 and from 1987 to 1988, and were conducted by two laboratories, Terra Tek and K&A Laboratories. Consistency between the two phases and the two laboratories was checked by duplicate analyses on the same samples. The results were consistent.

Based on the description in SAND90-7011, the methodology and procedures used for measurement of porosity are considered appropriate.

6.1.6. Adequacy of Application

The estimated porosity, as constant values for each unit above the Salado, is used as the initial porosity under referenced conditions in BRAGFLO. BRAGFLO calculates the porosity as a function of change of pressure under the borehole intrusion scenario. The estimated average values of porosity for the Culebra, and for other units, are considered adequate for the intended use.

6.1.7. *Accuracy of Calculations*

Calculations for estimation of porosity based on measured bulk volume and pore volume were not presented in the report. The average porosity based on each core sample measurement for the Dewey Lake was recalculated and found to be correct.

6.1.8. *Validity of Conclusions*

For the intended use of porosity in BRAGFLO, the estimated average porosity in the Form 464s, as presented at the beginning of this section, are considered adequate.

6.1.9. *Dissenting Views*

None.

6.2. Non-Salado Pressure

This section reviews the data from which the brine far-field pore pressures in units overlying the Salado were derived.

Parameter: Brine far-field pore pressure

ID#: 2101

Form 464: WPO 32539, entered 2/20/96

Parameter Package: WPO 30713

Distribution: Constant

Parameter value: 9.17E+05 Pa

ID#: 142

Form 464: WPO 32774, entered 2/20/96

Parameter Package: WPO 30713

Distribution: Constant

Parameter value: 8.22E+05 Pa

ID#: 343

Form 464: WPO 33544, entered 2/20/96

Parameter Package: WPO 30713

Distribution: Constant

Parameter value: 1.01325E+05 Pa

ID#: 160

Form 464: WPO 32733, entered 2/20/96

Parameter Package: WPO 30713

Distribution: Constant

Parameter value: 1.01325E+05 Pa

Definition: The brine far-field pore pressure is that pressure exerted by fluids existing within the interconnected pore spaces in the stratigraphic units above the Salado in regions sufficiently remote from mining, drilling, and other human activities that may have disturbed the environment.

Intended Use: The brine far-field pore pressure is used in BRAGFLO as the initial pressure in these stratigraphic units. The Magenta and Culebra units in particular exhibit significantly higher permeabilities than the surrounding rocks and represent potential pathways to the accessible environment. Consequently, the initial pressure must be reasonably well known in order to calculate the influx of brine contaminated with waste into these units.

Derivation: The pore pressures in the Magenta and Culebra Members were determined by isolating these units in separate wells (e.g., H-4A for the Magenta and H-4B for the Culebra) drilled 100 feet distant from H-4A. The wells were drilled to a depth just above the unit of interest, cased, and grouted, and then drilled deeper through the strata to be investigated. After cleaning and bailing the wells, water/brine was allowed to flow into the well over long time spans (up to several years). Knowledge of the depths below surface of the resultant water level and the depths to the top and bottom of the respective member in the well, and also the measured density of the saline water, permitted calculation of the pressure at the mid-point of the unit. Pressures obtained in this way were averaged for several wells to get an estimate of the average over the area covered by the WIPP site. This was entered as a constant into the data base (Form 464) for input to BRAGFLO. Pore pressures in strata above the water table were assumed equal to atmospheric.

Discussion: Six wells were used for the estimation of the average pore pressure at the mid-depth of the Magenta Member, and nine for the Culebra. The calculated pressures showed considerable variability -- a standard deviation of about 30% as calculated by the reviewer. Differences were noted between the initial reports of depths to water level and formation boundaries and later reports, possibly due to observations of depth to water at later times and to relogging of cores, but generally suggesting an uncertainty of perhaps 10% in the pressures.

The Parameter Package for initial pore pressures above the Salado supports four Data Entry Forms 464, one each for the Magenta Member, the Culebra Member, the Santa Rosa Formation, and the Dewey Lake Red Beds. The Santa Rosa and the upper part of the Dewey Lake are unsaturated and are assigned a pore pressure equal to atmospheric: 1.01325E+05 Pa. The water table in four wells lies close to 980 m above mean sea level within the Dewey Lake. No pore pressure is assigned to the lower portion of this unit. An initial constant pore pressure of 9.17E+05 Pa was assigned to Magenta; 8.22E+05 Pa to the Culebra.

6.2.1. Adequacy of Requirements and Criteria

An objective of the analysis was to provide initial pore pressures for input to BRAGFLO. No written requirements or criteria were found in the relevant documents. However, the data must satisfy this objective.

The measurements required for obtaining these data are:

- ☐ The elevations of the tops and bottoms of the formations in several boreholes must be known with sufficient accuracy.
- ☐ The elevation of the static water table in these holes must be adequately known. This stand of water must approximate the undisturbed pre-drilling state sufficiently well.
- ☐ The density of the water must be well known and uniform throughout the well.
- ☐ The water in the well must come predominantly from the formation under investigation.

Details of how the elevations of the formation boundaries were determined were not apparent from the relevant documents. Presumably, considering the date of the investigation, they were determined from core logging. Because cores are never continuous, errors of a few feet may occur owing to uncertainty in the footage of core lost in unrecovered intervals. To some degree this can be corrected by comparing against measures of core recovery. Examination of relevant documents revealed small to rather considerable discrepancies between early reports of depths to formation boundaries, e.g., U. S. Geological Survey Water-Resources Investigation Reports (WRIR) 81-36 and 82-19, and in the primary data source, WRIR 83-4016. These discrepancies possibly arose from relogging of the core; otherwise, the depths should be accurate to within several centimeters. In any event, the first requirement must have been addressed by measurements of depths.

The second requirement was addressed by allowing water to enter the borehole over long time periods with the expectation that it would eventually stabilize at or close to the undisturbed pre-drilling state. Again, early measurements may have been superseded by later ones, giving rise to discrepancies noted between data in WRIR 81-36 and 82-19 as compared to WRIR 83-4016.

The third requirement was addressed by taking samples of the water, either by swabbing or by use of a bailer. These techniques would allow some change of density owing to loss of gases and evaporation; however, these effects should be small. Subsequently, the density was presumably measured by accurate laboratory methods. Thus, little error is expected from this source.

The fourth was often addressed by boring separate boreholes to each of the regions of greatest importance. Thus, "H" wells, whose designation ends in A, were finished just below the Magenta Member, the portion of the hole above this member having previously been cased and cemented. Thus, water flowing into the borehole would come only, or very predominantly, from the Magenta Member. The Culebra Member was similarly isolated in separate "B" wells located 100 feet distant. These measures provide reasonable assurance that the fourth requirement was met and that the uniformity aspect of the third requirement was met.

6.2.2. Validity of Assumptions

One assumption is that the measurements are sufficiently accurate for the intended use. Because only single, rather than multiple, determinations of density and of depths to formation boundaries and water levels were reported, it was not possible to evaluate this implicit assumption. A second assumption is that the pore pressure in the unsaturated zone is atmospheric. This seems very reasonable.

6.2.3. Alternate Interpretation

Because of the requirements of BRAGFLO to use constant values of the initial pore pressure in units above the Salado, the various measurements of pore pressure were averaged for both the Magenta and Culebra Members. An alternative interpretation might well have been that the pore pressures were not sufficiently constant regionally and that instead, a distribution of values would be more appropriate.

6.2.4. Uncertainty and Consequences

Uncertainty is difficult to assess. However, if one assumes for individual wells that the differences between data in WRIR 81-36 and 83-4016 represent uncertainty associated with the determinations, then the uncertainty can be as much as 10%. On the other hand, if the variability shown in measuring the depth to water shown in figures 5-17 , -18, -19 , -21, and -22 in SAND86-2311 is used instead, the uncertainty becomes much less. In any case, 10% uncertainty seems acceptable for the intended application.

The standard deviations of the data sets for the Magenta and Culebra, calculated by the reviewer from data in the accompanying Parameter Package, WPO 30713, dated 3/20/96, provide some measure of the uncertainty regionally. The standard deviation of the six determinations of initial pressure in the Magenta, 2.79E+05, seems large compared to the mean (9.17E+05) for the intended use. A similar large standard deviation, 2.94E+05, compared to the mean (8.22E+05) exists for the nine measurements for the Culebra. Because the initial pressure of these units is an important parameter in BRAGFLO, it is somewhat questionable whether designation as a constant adequately represents the parameter distribution. No sensitivity analyses of the effects of varying this parameter are known to the reviewer. Whereas the number of data points is small, it appears to be enough to provide a reasonable average and spread of the pressures. As noted above, the assumption of atmospheric pressure in the unsaturated zone is considered acceptable. The elevation of the water table was measured in four boreholes within the Dewey Lake and found to be very consistent, 980m ± about 1 m above mean sea level.

6.2.5. Appropriateness and Limitations of Methodology and Procedures

The method of calculating initial pore pressure appears adequate. It was calculated for the mid-point of the formation in each of the boreholes used and employed elementary physical concepts. The only obvious limitation is that the level of water in the borehole at the time of measurement may not have recovered to pre-drilling levels.

6.2.6. Adequacy of Application

Demonstration of adequacy would require examination of BRAGFLO results, such as might show sensitivity to different choices of initial pressure over the range of variability identified. None were provided. However, use of a constant for this parameter seems questionable, at least for the Culebra.

Because there is expected to be no flow into the Magenta, the use of a constant initial pore pressure is not a concern for this Member.

6.2.7. Accuracy of Calculations

The only calculations were those reported in spreadsheets. These were checked by hand calculation and found to be accurate.

6.2.8. Validity of Conclusions

The review of the data permits the following conclusions to be drawn. The average value of the parameter in each of the units considered is judged acceptable for the intended use. Specifically, a constant value of 1.01325E+05 Pa is judged suitable for the Santa Rosa Formation and that portion of the Dewey Lake Red Beds that lies above the water table. The values of 9.17E+05 Pa and 8.22E+05 Pa are deemed acceptable for the average initial far-field brine pore pressure in the Magenta Member and the Culebra Member, respectively. The elevation of the water table at 980 m above mean sea level is also found to be acceptable. These conclusions apply to WPO numbers 32539, 32539, 33544, and 33544, as noted at the beginning of this section. The choice of a constant instead of a distribution to be sampled for the Culebra Member, however, is questionable. This is not of concern for the Magenta because no flow is expected into this member.

6.2.9. Dissenting Views

None.

6.3. Non-Salado Permeability

The permeability values for Non-Salado formations were estimated for the WIPP site for input used in BRAGFLO. The package only includes permeability estimation for two units: Magenta and Dewey Lake. For other Non-Salado units, the values of permeability were assumed to be 1.0E-35 m^2 for the purposes of the PA, according to the memorandum from L. Dotson (Feb. 1, 1996). The information included in the Form 464s for Magenta and Dewey Lake is as follows:

MAGENTA

Parameter:	Log of intrinsic permeability
ID#:	2102, 2103, 2104
Form 464:	WPO 32545, entered 2/16/96
Parameter Package:	WPO 30607
Distribution Type:	Constant
Parameter Value:	-15.2 log(m^2) (6.3E-16 m^2)

DEWEY LAKE

Parameter:	Log of intrinsic permeability
ID#:	161, 162, 162
Form 464:	WPO 32734, entered 2/22/96
Parameter Package:	WPO 30607
Distribution Type:	Constant
Parameter Value:	-16.3 log(m^2) (5.0E-17m^2)

Definition: Intrinsic permeability is a physical property of a medium alone, which represents the conductive capability of a medium. It is often defined as $k = K\mu/\rho g$

where:

K = hydraulic conductivity

μ = fluid viscosity

ρ = fluid density

g = gravitational constant.

Intended Use: The estimated values of the intrinsic permeability for the Non-Salado units are used as input parameters in BRAGFLO in simulation of the hypothetical breach of the repository room.

Derivation: Permeability for the Magenta was derived from one of the transmissivity test results obtained from the USGS report (USGS 83-4016). For the Dewey Lake, laboratory permeability data on core samples from Borehole H-19b1 were by provided Terra Tek.

6.3.1. Adequacy of Requirements and Criteria

The requirements and criteria for the estimation of the Non-Salado permeability were not documented in the related package. According to the intended use in BRAGFLO, permeability of Non-Salado formations will be used as a constant for each unit in the vicinity of the WIPP site. As long as the parameter is representative for the formation in the area of the WIPP site, it should be considered adequate in the PA. Since the purpose of BRAGFLO is to estimate the potential breach flow rate into the Culebra, estimation of permeability of other Non-Salado units is considered less important.

6.3.2. Validity of Assumptions

The intrinsic permeability was assumed to be 1.0E-35 m^2 for the Forty-niner, Tamarisk, and Unnamed Lower Members of the Rustler Formation according to the memorandum from L. Dotson (Feb. 1, 1996). This simply assumes that these units are impermeable. This treatment is conservative because allowing flow from a breach borehole or shaft into these units would reduce the flow into the Culebra.

Assumptions for estimation of permeability for the Magenta and Dewey Lake were not given explicitly. In the USGS report (USGS 83-4016), there are 12 transmissivity data available (p. 105). Only the value for H-1, which is located within the WIPP site, was used to convert to the value of permeability. The reason for selection of this value was not given. Since this value is the smallest value among the values of the other test boreholes located in the vicinity of the WIPP site, the underlying assumption for the Magenta appears to be that the lowest permeability in the available data is representative and most conservative for the purpose of the PA.

6.3.3. Alternate Interpretation

Since the permeability of these formations is substantially lower than that in the Culebra, the effect of these formations in BRAGFLO is less important. Alternate interpretations do not need to be considered.

6.3.4. Uncertainty and Consequences

On the basis of the limited data base, the estimations of the permeabilities of the Magenta and Dewey Lake are very uncertain. However, the potential consequences associated with the uncertainties in the PA may be insignificant based on the roles of these formations in BRAGFLO.

6.3.5. Appropriateness and Limitations of Methodology and Procedures

Descriptions for the methodology and procedures for both tests on Magenta transmissivity and on Dewey Lake core analyses were not available. According to the Parameter Package, the core analyses for samples of H-19b1 were conducted under a qualified assurance plan in general accordance with ASTM 5084-90. The samples for the Magenta from H-19b1 were found to be contaminated by oil, according to the memorandum attached with the Parameter Package. This may be the reason for converting Magenta transmissivity from the USGS report to permeability.

6.3.6. Adequacy of Application

Adequacy of application of these parameters should be acceptable based on the limited effect of these parameters in BRAGFLO.

6.3.7. Accuracy of Calculations

The calculations were checked for permeability values for both the Magenta and the Dewey Lake. The conversion from transmissivity to permeability for Magenta is correct. The calculation of the average horizontal permeability for Dewey Lake is correct.

6.3.8. Validity of Conclusions

The estimated values of average intrinsic permeability for the Magenta and Dewey Lake are considered adequate for their intended use in BRAGFLO.

6.3.9. *Dissenting Views*

None.

6.4. Culebra Permeability

This section reviews the Culebra permeability presented in the Form 464 as follows:

Parameter:	Log of intrinsic permeability
ID#:	143, 144, 145
Form 464:	WPO 32775, entered 2/16/96
Parameter Package:	WPO 31167
Distribution:	Constant
Parameter value:	-13.678 log(m^2) (2.1E-14 m^2)
Definition:	The intrinsic permeability is defined as $k = K\mu/\rho g$,

where:

K = hydraulic conductivity

μ = fluid viscosity

ρ = fluid mass density

g = gravitational constant.

Intended Use: The intrinsic permeability is required by BRAGFLO for modeling the flow of ground water in and near the repository.

Derivation: The data package associated with this Form 464 does not encompass any derivations of parameters from measured data. Instead it simply states how the equation given under the definition calculates the intrinsic permeability from data provided from other sources.

Discussion: This package simply takes a value for the hydraulic conductivity, K, and converts it to intrinsic permeability, as required by BRAGFLO. Other data required to effect this conversion are the density, ρ, the dynamic viscosity, μ, and gravitational constant, g. K was derived from

70 transmissivity fields used in the 1992 PA analyses (SAND92-0700/3). The density was taken from SAND92-0700/3, Table 4.1-1, p. 4-1, which in turn cites SAND89-7068/2. The dynamic viscosity is taken from the same table, citing SAND86-7167. The gravitational constant for earth conditions is well known.

6.4.1. Adequacy of Requirements and Criteria

The only requirement is that an adequate value for intrinsic permeability be provided for use in BRAGFLO. On the assumption that the input data are adequate, the value entered on Form 464 is acceptable. The value used should represent adequately the average K of the Culebra in the region modeled.

6.4.2. Validity of Assumptions

The only stated assumption is that the median areal weighted average value of the hydraulic conductivity, derived from the 70 transmissivity fields used in the 1992 PA, is acceptable for use in the 1996 PA. This assumption is accepted because there is no expectation that new data will result in a major change in the data base for the Culebra transmissivity. The derivation of hydraulic conductivity from reported transmissivity involves a simple calculation; for the purposes of this review it is accepted that this calculation was done correctly. Implicit assumptions are that the values used for the fluid viscosity and density are also adequate.

6.4.3. Alternate Interpretation

This data package merely records the conversion of one parameter to another using well recognized equations found in hydrology reference books. There is no other interpretation.

6.4.4. Uncertainty and Consequences

The only (rather minor) uncertainties are for the data used as input to the conversion equation. These have been addressed under Section 6.5.2. The uncertainty for the viscosity seems moderate. This parameter was calculated according to an equation proposed by SAND81-0557. The equation starts with the viscosity of pure water at the appropriate temperature. Any uncertainty in the temperature transfers to an uncertainty in this value. The equation then adds corrections, using temperature dependent coefficients, for the effect of each of the dissolved ions in the solution. The simplifying assumption that the fluid contains only NaCl, therefore, adds some unquantified uncertainty by not taking into account the effects of, for example, magnesium and sulfate. Divalent cations, such as Mg^{++}, have a greater effect on density than univalent ones, which suggests that uncertainties of the order of magnitude of the apparent calculational error noted in Section 6.5.7 will be present.

6.4.5. Appropriateness and Limitations of Methodology and Procedures

The methodology used for the conversion is appropriate.

6.4.6. Adequacy of Application

The conversion is adequate for the intended application. The value of the parameter and its distribution, as a constant, are judged adequate; BRAGFLO requires only an average value in addressing the intended use, even though individual determinations show a variability of at least two orders of magnitude.

6.4.7. Accuracy of Calculations

The conversion of K to k, using the values provided for K, μ, ρ, and g, was calculated by hand and found to be correct.

In respect to the calculation of the fluid viscosity, it is here assumed that the equation and the temperature dependent coefficients proposed by SAND81-0557 are sufficiently accurate for the purpose at hand. SAND86-7167, p. 3-19, states that "a mean fluid density of 1.05 g/cm^3 was considered to be representative of the formation fluid within the model area." It is here noted that the fluid density used in the calculation of the intrinsic permeability was 1.090 g/cm^3. The implications of this difference are noted below. Another statement in SAND86-7167 (p. 3-19) is "Thus, a density of 1.05 g/cm^3 corresponds to a NaCl concentration of about 0.86 mol/l." This appears to be somewhat in error. Table 6.4.7-1, below, shows some of the data from Hodgman (1959) together with conversions of g/L to mol/L done by the Panel.

Linear interpolation between densities of 1.0413 and 1.0559 indicates that a density of 1.05 g/cm^3 corresponds approximately to 1.29 mol/L, not 0.86 mol/L as stated in SAND86-7167. On the other hand, if a liter of the fluid (e.g., 1050 g) is taken and it is assumed that this consists of 1000 g of water and 50 g of NaCl, then one does obtain about 0.86 mol of NaCl. Apparently this is what was done, but it ignores the fact that the total volume of most aqueous electrolyte solutions does not equal the volumes of the constituent salts plus water before mixing. Normally, the volume is less, owing to the disruptive effect of the ions on the structure of water, causing a partial collapse. Correspondingly, if the representative density is instead 1.09 g/cm^3, the molarity is about 2.23. Use of these data in an equation cited in

SAND81-0557 yields a value of μ equal to 1.027 Pa-s for a density of 1.05 g/cm^3, and equal to 1.105 Pa-s for a density of 1.09 g/cm^3. This discrepancy from the value actually used seems to be of very minor significance for the intended use; the uncertainty in other parameters (such as permeability) may be orders of magnitude and would dominate the aggregate uncertainty in the flow calculation.

Table 6.4.7-1 g/L to mol/L Conversions

	Concentration		
Specific Gravity	**%NaCl**	**g/L**	**mol/L**
1.0053	1	10.05	0.1719
1.0125	2	20.25	0.3464
1.0268	4	41.07	0.7027
1.0413	6	62.48	1.0689
1.0559	8	84.47	1.4453
1.0707	10	107.1	1.8323
1.0857	12	130.3	2.2293
1.1009	14	154.1	2.6364
1.1162	16	178.6	3.0556

6.4.8. Validity of Conclusions

The conversion is valid. The value of 2.1E-14 m^2 (of which the logarithm is -13.678) is judged adequate for the intended application. This value is entered on the Form 464, as noted at the beginning of this section. The adequacy of the values input to the conversion is also considered to be sufficient.

6.4.9. Dissenting Views

None.

6.5. Climate Index

This section reviews the data and procedures from which the climate index was derived.

Parameter:	Climate index
ID#:	223
Form 464:	WPO 33031, entered 5/3/96
Parameter Package:	WPO 36425
Distribution:	Cumulative
	1.0 1.25 1.50 2.25 Value
	0.0 0.75 0.75 1.00 Prob
Parameter values:	Mean: 1.31
	Median: 1.17
	Std. Dev.: 0.348

Definition: The climate index provides a multiplier for the increases in the lateral ground water flow in the Culebra Member compared to that which exists at the present and that which may be caused by future climatic changes. It does not provide an indication in any direct manner of the corresponding increase in precipitation or infiltration responsible for producing this increase. Thus, the index relates to changes in ground water fluxes caused by climate change, not directly to climate change itself. It is applied uniformly to PA realizations as a sampled factor by which lateral flow in the Culebra may be altered by climatic changes.

Intended Use: The climate index is needed as a sampled parameter for input to SECOFL2D to simulate the effects of potentially increased precipitation in the future.

Derivation: The climate index is derived from numerous computer runs that use different values of infiltration and different values (three choices for each) for hydraulic conductivities in the disrupted zone, anhydrite, and Dewey Lake Red Beds. For each of these simulations the rate at which ground water flows out of the Culebra Member at the side boundaries is calculated. Two types of scenarios are examined. In one the assumption is that precipitation rapidly increases to the point where the water table is raised to near the ground surface, such that many seeps are formed, but no standing bodies of water. The lateral flow ratio, or climate index, was calculated from the lateral flow out the sides of the modeled area at steady state for a recharge rate of 2.0 mm/yr, which is sufficient to raise the water table to or close to the surface divided by the lateral flow out the sides of the modeled area at steady state for a recharge rate of 0.2 mm/yr, which resembles the present day situation. Some of the combinations of the parameters mentioned at the beginning of this section lead to unrealistic results, which are rejected. In the other scenario it is assumed that the pattern of alternating wet and dry periods deduced for the Holocene continues for 10,000 more years. For this case, the lateral flow out at 10,000 years in the future is divided by the lateral flow out now for simulations that start in both cases at the end of the last glacial maximum. These calculations yield the bimodal distribution reported on the Form 464. The first case is thought to be unlikely and is assigned an overall probability of occurrence of 0.25. Different simulations indicate a climate index for this case varying from about 1.50 to 2.25. The Holocene case is assigned an overall probability of 0.75; the lateral flow ratio varied from somewhat less than one to about 1.25. Those simulations which resulted in lateral flow ratios less than one were rejected as being non-conservative. Thus, the range for this scenario is from 1.00 to 1.25, as indicated above and on the Form 464.

Discussion: Documentation supplied with this parameter consists of Parameter Package SWCF-A:WBS1.2.07.1:PDD:QA. As stated in this package, the Climate Index increases flow magnitudes by the same factor at all locations within the flow fields used in the PA calculations. It was evaluated by running 54 steady-state and 17 transient SECOFL3D simulations in the Culebra, with input parameters thought to represent the range of likely future climates over the next 10,000 years. The Parameter Package describes the concepts, rationale, assumptions, and objectives in considerable detail. Existing data on past climates derived, for example, from plant and animal remains (sometimes fossilized) and radioisotope dating, are reviewed. Essentially, the conclusion is drawn that climate may vary between present day conditions and those present at the last glacial maximum during the Pleistocene (the Wisconsin). Two approaches were considered: 1) Oscillating climates in which 1000-year-long spikes of higher recharge occur at 500, 2000, 4000, 6000, 8000, and 10000 years in the future, with recharge rates of 0.2, 0.4, and 0.6 mm/yr; and 2) A sudden step to higher recharge which thereafter remains constant. The first concept resembles the historical pattern since the Wisconsin glaciation, and the second the onset of another continental glaciation. The probability of the first was assessed at 75%, and the latter at 25%. This leads to a bimodal distribution.

6.5.1. Adequacy of Requirements and Criteria

The requirement is to provide a parameter for SECOFL2D that may be sampled by PA for evaluating the effect of changing future climate. The numerous runs noted above, however, were run on SECOFL3D, which lends credence to the probability of meeting the requirement.

6.5.2. Validity of Assumptions

The main assumptions are:

1. The ground water basin conceptual model applies.
2. The lateral boundaries are flow divides (i.e., no-flow boundaries) during the period simulated.
3. Flow in the unsaturated zone can be neglected.
4. The flow system was in equilibrium with a recharge rate sufficient to maintain the water table near the land surface at the start of the simulations.

The first assumption is widely accepted for regional ground water flow studies.

The lateral boundaries coincide with topographic depressions and highs on the land surface that surround the site. It is assumed that these boundaries represent ground water divides, i.e., no flow boundaries, whose position remains fixed over the range of past and future climates. The boundary of the region modeled, in general, is several kilometers from the WIPP site. Figure 2 in the Parameter Package includes a topographic map showing the boundary, but it does not include a distance scale. Comparison with Figure 2-1 in SAND78-1596 suggests that where the boundary is closest to the site, toward Nash Draw to the west, the distance is 5 to 6 km. (The site boundaries for WIPP differ between the two figures, and the topographic contours in the Parameter Package are generalized, making comparison difficult.) In any case the separation of the model boundary from the site is large enough that a moderate error in the location of the hydrologic divides from the positions assumed should make little difference in the modeling.

The third assumption, negligible flow in the unsaturated zone, is acceptable. In this region of very low precipitation there will be very little lateral migration of ground water in the unsaturated zone.

Moreover, many of the simulations show rise of the water table to the surface, such that in those cases most of the rock will be saturated.

The fourth assumption applies only to transient simulations which began at the last glacial maximum. At that time it is reasonable that the water table would be at or close to the ground surface.

6.5.3. Alternate Interpretation

Interpretations are of two kinds. The first is how to view the knowledge of the paleoclimatological observations. Numerous investigators have concluded that the climate has varied since the Wisconsin glaciation. Therefore, the only doubts or alternative interpretations would be by how much and over what time frames. The evidence does not indicate that large bodies of standing water were present during the Holocene; therefore, the assumption that precipitation and infiltration were at most sufficient to produce seeps, but not lakes, represents a conservatively high value. In other words, an alternative assumption would be less conservative. In practice, three different recharge rates were assumed for transient conditions and two for a single step to glacial conditions; these are in keeping with the conservatism just noted and provide an indication of the effect of lower values. No other alternatives seem needed in respect to magnitude of recharge. In respect to transient conditions, the frequency and duration of spikes of higher recharge need to be specified. The approach taken was to assume that the future will resemble the past. The simulations show relatively little sensitivity to various choices of recharge rate, suggesting that sensitivity to changes in frequency and duration is similarly small. Although such scenarios were not tested, there appears to be little need to do so in view of other uncertainties.

The second type of interpretation deals with how to derive appropriate values and a distribution function from the computer results. Full details of the logic are presented in the Parameter Package. Briefly, for six of the simulations that did not yield unrealistic results and address the uncertainty in Holocene recharge rate, the lateral flow rate ratio varied from 1.6 to 2.1. This range was increased somewhat to account for uncertainty of the results to 1.5 to 2.25. Examination and consideration of the remaining acceptable runs did not provide sufficient reason for changing these choices. Thus, the climate index (the lateral flow ratio, defined as well as possible as the rate of lateral flow under wet conditions divided by present day conditions) for steady-state (glacial) conditions was determined to be 1.5 to 2.25. However, the probability of recurrence of full glacial conditions within the next 10,000 years was deemed to be low, in keeping with most thinking found in the literature. Therefore, the overall probability of such conditions was taken at 0.25, a rather speculative value and perhaps conservatively on the high side. For transient conditions, the results of the modeling of which are shown in figure 10 in the Parameter Package, the lateral flow ratio varies between 1.0 and about 1.25. With time these ratios decrease, i.e., future lateral flows sometimes are simulated as less than at present. These were rejected as being non-conservative, and the range taken instead as 1.0 to 1.25. The overall probability of these conditions was taken as 0.75. Other interpretations could be made, but little advantage is seen in doing so.

6.5.4. *Uncertainty and Consequences*

Obviously, there is a great deal of uncertainty, and even speculation, about what future climates will be. These are discussed in some detail above, but overall, the distribution presented on the Form 464 seems very reasonable.

6.5.5. *Appropriateness and Limitations of Methodology and Procedures*

The approach used strikes the Panel as being much more appropriate than attempting to do actual future climate modeling by use of complicated computer codes. The modeling of flow rates under various assumed conditions appears to capture the main elements and variability of what can be reasonably be expected and takes these limitations into account in the distribution function selected.

6.5.6. *Adequacy of Application*

The adequacy of application cannot really be addressed without having knowledge of future climates. From what can be deduced from present knowledge, the application in PA will be reasonable and adequate.

6.5.7. *Accuracy of Calculations*

All calculations were performed with SECOFL3D. The scope of this review does not include evaluating the adequacy or accuracy of computer results. It is assumed that the results are sufficiently accurate.

6.5.8. *Validity of Conclusions*

The review of the data and models used to derive the values and distribution of the climate index permits the following conclusion to be drawn, namely that the cumulative distribution of the climate index is judged adequate for the intended use because it is conservative. Specifically, the climate index consists of values 1.0, 1.25, 1.50, and 2.25, with corresponding cumulative probabilities of 0.0, 0.75, 0.75, and 1.00, as indicated on Form 464, WPO number 33031 and at the beginning of Section 6.6.

6.5.9. *Dissenting Views*

None.

6.6. Culebra Transmissivity Fields

Culebra Transmissivity Fields, based on 43 measurements in test wells spread over an area roughly 22 by 32 km, is used as input to GRASP-INV code suite. Taking the field values and using iterative solutions, GRASP-INV generates a set of fields that define transmissivity values at every node in the model of ground water flow in the Culebra Dolomite throughout the 22 by 32 km area. These transmissivity fields are then used by the two-dimensional SECOFL2D to calculate the ground water flow field in the Culebra Dolomite in the vicinity of the WIPP site. These transmissivity fields are randomly selected from numbers 1 through 100 to represent the transmissivity fields ranked according to travel times from the repository to the accessible environment.

Parameter:	Culebra Transmissivity Field Indices
ID #:	TRANSIDX
Form 464:	There is no Form 464 for Culebra Transmissivity Fields
Parameter Package:	WPO 35406
Distribution:	TRANSIDX has integers from 1 to 100

6.6.1. Culebra Transmissivity Data

Culebra transmissivity data are transmissivity values obtained from the analysis and interpretation of hydraulic tests in the 43 wells mentioned in Section 6.6.

Values: Range: 0.00007 to 830 ft^2/day (see attached Table 6.7.8 - 1)

Definition: Culebra Transmissivity quantitatively describes the ability of the water-bearing portion (aquifer) of the Culebra Dolomite to transmit ground water (fluid). Transmissivity is expressed as the rate of ground water (fluid) flow, in $feet^2$ /day (m^2/second), through a vertical strip of the aquifer 1 foot (1 m) wide, extending the full saturated thickness of the water-bearing zone (aquifer), under a unit decline in potentiometric surface (hydraulic gradient of 100%) at prevailing water (fluid) temperature.

Intended Use: The intended use of the transmissivity values is for entry into GRASP-INV for the purpose of creating a set of calibrated transmissivity fields for use by SECOFL2D to calculate ground water flow fields within the Culebra.

Derivation: The Culebra transmissivity values were obtained from the hydraulic testing of wells.

Discussion: Since the value of transmissivity is the product of hydraulic conductivity times aquifer thickness, it is apparent that the values of Culebra transmissivity can differ by approximately 300% just due to the change in thickness (5 to 13 m) from one location to another in the Culebra Dolomite over the WIPP site. However, this difference is small compared to the several orders of magnitude variation in Culebra transmissivity values interpreted from hydraulic testing of wells at the WIPP site. These variations in transmissivity appear to be due largely to the influence (presence) of open fractures within the Culebra and their density and degree of interconnectivity at any particular well site.

Numerous interpretations of the results of well hydraulic testing across the WIPP site have demonstrated that at many locations, the Culebra Dolomite behaves as a double-porosity medium with unrestricted interporosity flow. In this type of aquifer system, the fractures are believed to have higher permeability and provide lower storage, while the primary matrix porosity has less permeability, but a much higher storage capacity.

The Culebra Transmissivity data package provides Culebra transmissivity values to be used as input to GRASP-INV calculations. The data are based on 43 field hydraulic tests, of which the data from 21 wells require qualification. These wells are H2c, H3b2, H3b3, H4b, H4c, H5b, H6b, H7b1, H8b, H9, H10b, H16, H17, H18, DOE1, P18, WIPP-27, WIPP-28, WIPP-30, ENGLE, and USGS-1.

The data requiring qualification are essentially those collected from constant- or multi-rate pumping tests, slug tests, shut-in tests, and DSTs performed on individual wells, as conducted by the USGS from 1978 to 1981 and by SNL between 1983 and 1987. A list of the wells and transmissivity values is shown in the attached Table 6.6.1.8-1.

6.6.1.1. Adequacy of Requirements and Criteria

The data used to obtain values of Culebra transmissivity were collected from hydraulic testing of the Culebra Dolomite by conducting pumping tests, slug tests, bailing tests, and DSTs in boreholes that penetrated the formation. These methods of testing formations for hydraulic properties are appropriate, and indeed, are about the only known method of obtaining the hydraulic properties of the formations.

The earlier hydraulic tests (1978 to 1981) conducted at the WIPP site by the USGS were the first attempt at hydrogeological characterization of the Culebra. These tests, for the most part, were bailing tests, slug tests, or short-term pumping tests. Frequent equipment problems complicated the data interpretation or rendered the data useless. The interpretation of the data, while accurate for the most part, was limited dominantly to the manual curve matching methods of Cooper et al. (1967).

Later (1983 to 1987) hydraulic testing of the Culebra was conducted by SNL, or its subcontractors, under stricter quality assurance programs, and with the benefit of increased knowledge of the Culebra as a result of the previous work. Thus, the newer pumping tests were much longer in duration, used multiple observation wells and electronic pressure transducers with a DAS to record many more measurements. The data from the tests were simulated by sophisticated technical software programs that can differentiate between single and double porosity permeability in an aquifer to provide more enlightened interpretation. In addition, some of the boreholes were retested and reinterpreted using the newer software programs to obtain an improved understanding of transmissivity values.

Thus, the requirements and criteria for the hydraulic testing and data interpretation for transmissivity values are adequate for the intended use.

6.6.1.2. Validity of Assumptions

Many estimates of transmissivity of the Culebra Dolomite have been obtained by fitting observation well data, from pumping tests of other wells, to the analytical line-source solution of Theis (1935). There are several implicit assumptions for the use of the line-source solution to simulate observation well response. The first is that the aquifer is areally homogeneous because the ground water supplying the pumping well is derived equally from all directions (i.e., the hydraulic conductivity is everywhere the same in the aquifer).

The results of the 1984 pumping test No 1. of H-3b3, as shown in the drawdown data (Fig. 6-3 and 6-4, SAND86-2311) for two nearby observation wells (H-3b1 & H-3b2), suggest that the Culebra Dolomite aquifer acts as a double-porosity medium with unrestricted interporosity flow in the vicinity of the pumping well. That is, fractures provide the bulk of the aquifer's permeability, while the matrix pores provide the majority of the storage capacity. In addition, the permeability of fractures varies from location to location. Thus, it appears that the first Theis assumption of a homogeneous aquifer is invalid.

The second assumption is that, on the areal scale of the observations, the aquifer behaves like a single-porosity medium. [This assumption is said to be justified in a double-porosity medium if the observation well is far enough away from the pumping well that only the total-system response is observed (SAND86-2311, p. 60).] With respect to DOE-1, used as an observation well (approximately 5200 feet away) during the pump testing of H-3b3, the plot of pressure vs lapsed time (SAND86-2311, Fig. 6-5, p. 61) does not exhibit a double-porosity effect. Thus, this second assumption appears to be valid in the case of DOE-1 and H-3b3.

6.6.1.3. Alternative Interpretations

Observation-well responses to pumping tests were interpreted by fitting to the line-source solution derived by Theis (1935). With regard to the 1985 pump test of H-3b2 and the use of observation wells including DOE-1 (5200 feet away), there were pre-test pressure/water level trends in the Culebra Dolomite that needed to be taken into consideration by modifying the observed data. Thus, there are two possible interpretations: the best fit to the observed data with no modifications and the best fit including a linear compensation for the pretest trend. In the first case, there is no compensation for the rising pressure/water level, so the data show less drawdown and more rapid recovery than if the trend had been absent. This results in a transmissivity that is too high and a slightly erroneous storativity in order to simulate a fit for these data. Applying a linear correction derived from the pretest behavior to the observed test data probably results in overcompensation, particularly in late time. The simulated fit to these data uses a transmissivity that is probably a minimum, as well as a slightly erroneous, storativity. According to SAND86-2311, p. 72, the two interpretations should provide limits to the apparent transmissivity value.

The transmissivity value of 7.0E-05 ft^2/day for well P-18 was obtained from interpretation of late time match parameters (after 600 hours since test inception) by using semi-log slug test type curves on the semi-log plot of H/H_o vs elapsed time (SAND87-0039, p. 99). Use of the late time curve match for the transmissivity value seems questionable in this case, as the early time (first 600 hours) data represent the aquifer characteristics in the vicinity of the well, before boundary effects. Furthermore, the late time data might reflect packer leakage that might have occurred after the pressure across the packer reached a critical value. Thus, use of the late time data, after boundary effects, seems inappropriate and slightly speculative to obtain a transmissivity value for the well and its immediate environs. Further, the early time (first 600 hours) interpreted value of 4.3E-03 ft^2/day is fairly close to the 1.0E-03 ft^2/day value provided by the interpretation of a previous bailing test by the USGS (USGS 83-4016)

6.6.1.4. Uncertainty and Consequences

With any science involving interpretation of natural phenomena, there always will be uncertainties. Thus, as is to be expected, there are uncertainties about some of the results of the hydraulic testing at the WIPP site and the estimated values of transmissivity. However, for the most part, the degree of uncertainty about the transmissivity values is not so much as to limit the intended use.

As an example, the following is a discussion of the uncertainty about the results of the ENGLE well pumping test. Interpretation of the data from the 1983 hydraulic testing of the ENGLE well provides a transmissivity value of 43 ft^2/day based on a single porosity medium interpretation using INTERPRET simulation of the drawdown data. [*Note: The recovery data for the well was stopped after one hour and not used in the interpretation. Due to a decrease in the pumping rate during the latter part of the test, the drawdown had actually decreased to approximately 46% of its maximum by the time the pump was stopped and water level recovery recorded. After only one hour the recovery pressure exceeded the initial pressure by 10.44 psi and measurements were stopped. No explanation in SAND87-7125 or SAND87-0039 was provided for the reason for the difference between final and initial water levels.*]

The INTERPRET simulated curves (SAND87-0039, p. 107) of the drawdown data for the ENGLE well match very closely except for the very late time data, implying that the single porosity model is appropriate for the analysis. The uncertainty about the 43 ft^2/day transmissivity value is related to the fact that the pumping tests for a number of other wells (DOE-1, DOE-2, H-3, H-8, H-11 and WIPP-13) with a transmissivity greater than 1.0 ft^2/day, as analyzed with INTERPRET, have shown a double porosity effect and negative skin factors; whereas, the ENGLE well is interpreted as having a relatively high transmissivity, but also a positive skin factor (Assuming a Culebra porosity of 20%, a total system compressibility of 1.0E-05 psi^{-1}, a fluid viscosity of 1.0 cp, the skin factor for the simulation can be calculated as 4.2.) and single-porosity behavior, which appears to be anomalous. It is reported (SAND87-0039, p. 108) that a possible explanation may be that the low volume windmill pump at the ENGLE well never stressed the aquifer. The relatively high pumping rate of 10 gpm for sustained periods of time, during the pumping test and the preceding step drawdown tests, may have developed the well. The acidizing and developing of well DOE-2, as well as its subsequent change from single porosity to double porosity hydraulic response, is cited as an example of this phenomenon. This well development theory might also partly explain why the post recovery water levels (pressures) were greater than the initial water level. The well also may have still been recovering from the nearly three hours of step-drawdown testing the day before the test.

6.6.1.5. Appropriateness and Limitations of Methodology and Procedures

For the most part, the data requiring qualification were collected from hydraulic testing (constant- or multi-rate pumping tests, slug tests, shut-in tests, and DSTs) performed on individual wells, as conducted by the USGS from 1978 to 1981 and by SNL between 1983 and 1987. Although, at the time, there was no national certifying organization for these types of tests, there were published references by the USGS, the Bureau of Reclamation, EPA and the American Petroleum Institute.

The testing conducted by both the USGS and SNL were performed in accordance with specially developed internal test procedures for slug-tests and pumping tests, while the DST procedures had been developed and used for a number of years by the petroleum industry. As a matter of administrative procedure, all USGS testing and reporting on projects generally required approval by cognizant authorities within the organization. The SNL testing programs also were generally evaluated by internal review teams and authorized by cognizant management authorities.

The general procedures for the pumping tests and slug tests are documented in enough detail to be repeatable, although specific details are lacking in the SAND reports referenced. Some of the very specific test details are probably only available in old project data files and may be difficult to locate.

Many types of reports were reviewed as part of the evaluation of transmissivity values. The SNL HDRs contained substantial amounts of data which were largely reduced from the enormous amount of raw data accumulated by the DAS for the numerous hydraulic tests conducted at a number of wells. These data were sorted by borehole number, recording time, and measurement type, converting all measurements to a time interval using Julian days and converting electrical voltage inputs from the recording instruments into pressure, while converting all measurements from English to metric, as well as filtering out redundant data. Some of the older USGS reports on earlier phases of testing presented all the raw data as well as the interpretations in the same report. At that time, it was standard policy to provide the raw data in the reports. This also was at a time when automated data collection systems were just being developed. It was not yet obvious, as it later became, that data reduction would be necessary in order to minimize the tremendous quantities of data that could be supplied by the DAS and the use of electronic transducers providing data points every few seconds/minutes for days, weeks, months, or even years at a time.

In those cases where the data have been reduced (mostly the SAND reports where the field data were collected with a DAS using electronic pressure transducers), the reduced data accurately portray the raw data except for extraneous data, which sometimes have been purposely omitted. For instance, a spot check of the reduced pump test data in Table II.B.11 (SAND85-7206, pp. 89-94) for pumped well H-6b for test H6008, compared to the original data in Appendix C (SAND85-7206, pp. 471-500), shows a reasonably close correlation, as does the comparison of the reduced data points of drawdown and time with the graphs of drawdown vs time for the three wells at the H-6 hydropad (SAND85-7206, pp. 471-473).

The quality of the data reviewed is essentially sufficient to provide data plots with enough data points that reasonable interpretations can be made of the hydraulic characteristics of the Culebra Dolomite in order to calculate representative transmissivity values.

Many of the slug test (and DST) results in the USGS and SAND reports were interpreted by using type curve-matching techniques on semi-log plots of pressure (drawdown) vs time based on the classic work of Cooper et al (1967). This analytical technique is a well qualified, time-proven method for determining aquifer transmissivity and storativity.

During the hydraulic testing, the water levels (pressure) were measured to the nearest 1/100 of a psi (0.023 feet) which, for this type of testing, is satisfactory. The measurements of pressure (water levels) were generally recorded on a logarithmic basis such that, as a minimum, five or more data points would fall within each log cycle on the semi-log plot, which is adequate for analysis and interpretation. The hydraulic testing completed with a DAS and pressure transducers literally produced thousands of data points, which then required data reduction techniques to produce manageable quantities of data for automatic plotting and analysis/interpretation techniques through computer simulation.

In the beginning phases of the WIPP site characterization of the hydrogeology, the initial testing was completed by the USGS using standard hydraulic testing techniques, such as slug tests and well shut-in tests, and measuring water levels before, during, and after the testing.

As more was learned about the complexities of the site, the testing by the USGS and SNL became more sophisticated to deal with the need for more site-specific and stratigraphic horizon-specific hydrological information. In the early phases of investigation many of the Culebra wells indicated low permeability and slug tests were determined as the appropriate testing mechanism for the low yield wells. In some cases, however, the flows from the formation into the wells were higher than expected and the slug tests could not be completed satisfactorily (e.g., the H-6b testing by the USGS [Dennehy 1982, p. 18]). In this case, SNL contracted for additional testing of H-6b and later performed more testing at the H-6 hydropad (SAND85-7206, p. 43, 106-7, and 410+) and were able to obtain values for transmissivity.

Later phases of testing at other wells either contracted by or conducted by SNL (SAND86-2311) used downhole strain-gage transducers and automated DAS to store raw millivolt output from the transducers and calculate pressures. Analyses of hydraulic test data were performed with INTERPRET well-test interpretation code. These later tests were certainly appropriate for the task and had few, if any limitations of methodology and procedures.

Review of the various source documents for the transmissivity values indicates that the assumptions, calculations, extrapolations, methods, and conclusions pertinent to the data were appropriate for the development of the parameters used as input to the WIPP PA, except as noted in Section 6.6.1.8.

6.6.1.6. Adequacy of Application

Analysis of the results of the 1985 pumping test of H-3b2 indicate that at late time, a significant portion of the well recovery was related to additional stresses other than the pumping test (SAND86-2311, p. 62). For example, it is known that the wells at the H-3 hydropad were still recovering from the step-drawdown test and three other pumping episodes related to pump testing before the start of the 62-day pump test of H-3b2. Figure 6-7 (SAND86-2311, p. 62) showing the linear-linear plot of both drawdown and recovery data of H-3b2 and the INTERPRET simulation of the test data, indicates the static formation pressure specified for the simulation is several psi higher than the pressure measured at the beginning of the step-drawdown test. Toward the end of the recovery period, the simulation predicts increasingly less recovery than was observed. This late time difference in pressure recovery data shown in the simulation plot would seem to demonstrate the possible additive effect of sealing of the Exhaust Shaft in July 1985. The additive effects of the multiple pre-test pumping were included in the simulation.

In a review of the reports on all these wells, it appears that the test procedures were correctly implemented, except as discussed in Section 6.6.1.8.

In order to calculate the transmissivity of well H-5B from the water level recovery data measured during Shut-in Test #1 (USGS WRI 82-19), using the Theis recovery method, the average discharge (or recharge) of water (Q) to the test zone is required. As described in USGS WRI 82-19, the Q value was obtained by placing a pressure transmitter into the well after the bailing had ceased and measuring the rate of change in pressure (water level) as the well gradually filled back up with water from the formation to the level before the well was shut-in. Because of the well depth, the time needed to install and set the packer assembly into the well before the shut-in period amounted to several hours, during which time there were no measurements. The pressure measurements made during the brief open hole recovery period of continually decreasing discharge, represented flow rates that would have been larger than discharge rates, as measured later in the shut-in period. Consequently, the calculated value of Q is undoubtedly larger than the actual average discharge for the entire flow period. Therefore, the computed transmissivity, using Theis's Equation, probably is larger than the actual value for the Culebra Dolomite at well H-5B.

At well P-18, (SAND87-0039, p. 99) during the withdrawal slug test, it was noted that when the packer in the tubing was deflated the pressure recorded did not match the water level as estimated using the measured density correction factor of 1.05. Because more confidence was placed in the specific gravity measurements made when the tubing was last bailed, than in trying to match initial water level by changing the density to 1.14, it was assumed that the transducer depth was incorrect and the depth was increased by 7.5 feet. These changes in the initial depth to water and the static depth of water were used in the final interpretation of the transmissivity from the P-18 slug test.

The parameters (water levels, water pressures, density, discharge volumes) that were measured during the hydraulic testing of the Culebra Dolomite are dependent on the natural physical properties of the water-bearing formation, such as permeability and effective porosity, which are not expected to change much in the next 10,000 years. The values of the measured parameters, however, may change over time, but the age of the data (or date collected) does not materially affect the quality of the data or the results of the interpretation of the data.

SAND86-2311 (p. 32) states that, "because of data noise, a degree of subjectivity is involved in defining response times for the various wells (i.e., H-6 and others). Also, for wells exhibiting rising water-level trends before the test, drawdown was considered to begin when water levels actually started declining, even though the effects of pumping must have been felt sooner to reverse the upward trend. Consequently, the response times presented in Table 5-1 should be considered approximations, and are most likely overestimates."

For much of the hydraulic testing, there were multiple tests of the Culebra Dolomite at the same hydropad using one of the three wells first as a pumping well and then in the next test of another well at the pad, using the former test pump well as the observation well. An example of this was the pump test of H-3b3, using H-3b1 and H-3b2 as observation wells, and then further use of H-3b3 as an observation well while pump testing H-3b2, as reported in SAND86-2311.

The numerous graphs of the drawdown and recovery data from the pumping/slug/DST tests of the wells show that an adequate number of data points were collected to make accurate representations of the changes in the measured parameters during the testing and recovery periods.

As reported in SAND86-2311 (p. 54-61), for the H-3 pumping test, the interpreted transmissivity values from the three wells for the two pumping tests (first test with H-3b3 pumping and H-3b1 and H3b2 as observation wells, and second test with H-3b2 pumping and H-3b1 and H-3b3 as observation wells) varied among the three wells only 3.3% for the first test and 5.5% for the second test, although the transmissivity value for the second test was approximately 60% of the first test.

The intended use of the data is for input into GRASP-INV code to provide a distribution of transmissivity values of the Culebra Dolomite across the WIPP site. Thus, the values of transmissivity provided by the 43 well locations provides a fairly reliable indication of the variation in transmissivity within the Culebra Dolomite at and near the WIPP site.

The analysis of pumping tests of the H-3 pad (SAND86-2311, pp. 54-59) provides reasonable interpretations of the Culebra transmissivity from numerical simulations of the data from the H-3b3 well. This demonstrates that the test measurements follow a predictable pattern which indicates the adequacy of the application.

6.6.1.7. Accuracy of Calculations

No calculations are shown in the reports reviewed by the panel.

6.6.1.8. Validity of Conclusions

The data used in the interpretations of pumping tests of H-4c, H-8b. H-16, H-17, H-18, DOE-1, ENGLE, P-18, and WIPP-30 (as reported in SAND87-0039) are the same as those shown in the HDRs and other referenced reports. In other cases, such as the USGS slug testing of well H-6b in 1978 (USGS WRI 82-8,

p. 18), it has been duly reported that the data are inadequate or incomplete and no interpretations were attempted.

The range of uncertainty for each measurement is not stated within the reports reviewed, although it seems apparent from the numerous graphs of drawdown vs time and the simulated curve matching that reliable estimations of transmissivity can be made using those data.

The general conclusions regarding the Culebra transmissivity values gleaned from the interpretation of hydraulic test results of selected wells as reported in various reports reviewed can be summarized as: 1) a wide range (several orders of magnitude) of transmissivity values is apparent which demonstrates the areal heterogeneity of the Culebra Dolomite over the WIPP site, 2) the Culebra behaves as a double porosity medium with unrestricted interporosity flow in several wells, while other wells clearly demonstrate only single porosity flow. This suggests that fractures may provide the bulk of the permeability within the Culebra Dolomite, while the rock matrix pores provide the majority of storage. The reliability of these conclusions is demonstrated by the results of a large number of repetitive tests and retests of numerous wells over the WIPP site which yield very similar values.

The sources of the data were the hydraulic tests (e.g., slug tests, bailing tests, DSTs and pumping tests) conducted on single wells, the effects of which were measured in other single observation wells. Thus, to some extent, the wide range in Culebra transmissivity values reflects not only the heterogeneous nature of the Culebra Dolomite, but also the volume of rock that was stressed during the specific hydraulic testing as a result of the type and length of test and the location. At a single location, the transmissivity value can differ, depending on the type of test, because the volume of rock hydraulically stressed during a pumping test would be much larger than that stressed during a slug test and would represent conditions of a different spatial scale within the Culebra Dolomite radially outward from the borehole tested.

The processes used to produce the transmissivity values involved the collection of the field data (measurements of water levels, and flow discharge rates over time), the filtering, reduction, cataloging, and presentation of the data in data plots, and the interpretation of the data through the use of analytical and numerical techniques. These processes are appropriate to produce the transmissivity values for their intended use in GRASP-INV.

It is concluded that the transmissivity values, as listed in Table 6.6.1.8-1, are adequate and appropriate for their intended use in GRASP-INV, with the exception of the well P-18 value discussed below.

Table 6.6.1.8-1 Summary of Transmissivity Data Review

	Reported Culebra Transmissivity Values			
Well No.	**ft^2/day**	**m^2/sec**	**log m^2/sec**	**Status**
H-2c	0.79	8.5E-07	-6.07	A
H-3b2	2.3	2.5E-06	-5.62	A
H-3b3	2.3	2.5E-06	-5.62	A
H-4b	0.77	8.3E-07	-6.08	A
H-4c	0.77	8.3E-07	-6.08	A
H-5b	0.2	2.2E-07	-6.67	A
H-6b	37	4.0E-05	-4.40	A
H-7b1	830	8.9E-04	-3.05	A
H-8b	8.2	8.8E-06	-5.05	A
H-9	100	1.1E-04	-3.97	A
H-10b	0.73	7.8E-07	-6.11	A
H-16	0.79	8.6E-07	-6.07	A
H-17	0.21	2.3E-07	-6.63	A
H-18	1.85	2.0E-06	-5.54	A
DOE-1	11.0	1.2E-05	-4.93	A
P-18	0.00007	7.5E-11	-10.12	I
WIPP-27	200	2.2E-04	-3.67	A
WIPP-28	240	2.6E-04	-3.59	A
WIPP-30	0.175	1.9E-07	-6.73	A
ENGLE	43.0	4.6E-05	-4.34	A
USGS-1	514.0	5.5E-04	-3.26	A

Explanation:

A = Adequate
I = Inadequate

Well P-18 - the transmissivity of 7.0E-05 ft^2/day for well P-18, as reported in the Draft Culebra Transmissivity Database (July 1,1996), represents a value obtained from interpretation of late time match parameters (after 600 hours since test inception) rather than early time data using semi-log slug test type curves on the semi-log plot of H/H_o vs elapsed time (SAND87-0039, p. 99). Use of the late time semi-log curve match for the transmissivity value seems questionable in this case, as the late time data do not represent the aquifer characteristics in the vicinity of the well, before boundary effects. Use of the late time data, after boundary effects, appear inappropriate since the theory presented by Cooper et al. (1967) does not include boundary effects. Further, the early time (first 600 hours) interpreted transmissivity value of 4.3E-03 ft^2/day (SAND87-0039, p. 99) is in fairly close agreement with the 1.0E-03 ft^2/day value provided by the interpretation of a preceding bailing test by the USGS (USGS 83-4016).

6.6.1.9. Dissenting Views

None.

6.6.2. Culebra Thickness

Culebra thickness is a parameter that supports the development of the Culebra transmissivity fields. The parameter description follows:

***Parameter*:**	Culebra dolomite thickness
ID#:	2071
***Form 464*:**	WPO 32790, entered 5/3/96
Parameter Package:	WPO 36445
Distribution:	Constant
***Value*:**	7.75 m
***Definition*:**	Representative thickness of the Culebra dolomite.

***Intended use*:** This parameter has been used in a particle tracking program to calculate travel time from the repository to the accessible environment (SAND92-0700/3, p. 2-91). Travel time is calculated for each transmissivity field, and the transmissivity fields are ranked by travel time. Transmissivity field index numbers are assigned according to this ranking. These index numbers are integers from 1 to 100. During PA modeling, transmissivity fields are selected by sampling the index numbers. The transmissivity fields are treated as equally likely.

***Derivation*:** The constant 7.75 m is an average of 68 thickness values. Each value is either a thickness from an individual borehole or the average thickness from boreholes at a hydropad. A table of these thicknesses was provided with the Parameter Package (Table B.1a-d, SAND89-7068/2). The individual thicknesses in this table ranged from 5.49 m in H-2c near the repository, to 11.3 m at the H-7 hydropad and in well FFG-165. These last two wells are located over 4 km southwest of the WIPP site.

6.6.2.1. Adequacy of Requirements and Criteria

The mean value for Culebra thickness is in the data base primarily for use in ranking transmissivity fields. Consequently, the value should be sufficiently representative to support this use. This requirement is satisfied by using a large number of boreholes scattered throughout the regional flow modeling domain. The locations of the boreholes are somewhat concentrated in the vicinity of the repository, which will not adversely affect the use of the average, since the repository area is relatively important.

6.6.2.2. Validity of Assumptions

No assumptions are involved in the derivation of the Culebra thickness parameter.

6.6.2.3. Alternate Interpretation

The CCA (p. 2-41) mentions an alternate interpretation of the thickness of the Culebra in which a thin organic upper interval was not included in thickness calculations. When this alternate interpretation was used, the average thickness was about a meter less than the thickness calculated by other investigators (CCA, Table 2-3, p. 2-42). This alternate interpretation was not followed in the calculation of the average thickness of 7.75 m given on the Form 464. The existence of the alternate interpretation has no effect on the adequacy of the average thickness for use in the development of the transmissivity field index. A smaller thickness value would decrease travel times but not change the relative travel times. Consequently, the ordering of the transmissivity fields would not be changed.

6.6.2.4. Uncertainty and Consequences

Minor uncertainties are associated with the Culebra thickness. Choosing the depth to the top and bottom of the Culebra involves uncertainties in interpretation of core recovery (intervals represented by missing core), borehole samples, and borehole geophysical logs. Errors in depth measurement are possible, but no evidence for such error was seen. Such uncertainties will not have a significant effect on PA modeling. Where the thickness is used to rank the transmissivity fields, the rank is related to relative travel times and would not be sensitive to uncertainty in average thickness. A high average thickness would increase travel times and a low value would decrease travel times, but the ranking of the travel times would not be affected.

6.6.2.5. Appropriateness and Limitations of Methodology and Procedures

The best method for determining depth to top and bottom of Culebra would be using core descriptions where core recovery was complete and the entire Culebra was cored. Less accurate methods involve combinations of interpretation of geophysical borehole logs, drill cuttings, and drilling time. It is beyond the needs of this review to determine the method used for each of the boreholes. All of these commonly used methods are appropriate.

The Parameter Package indicated that where gamma ray logs are used to support the determination of the depths to the top and bottom of the Culebra, the top is indicated by an increase in natural gamma radiation above that in the lower Tamarisk, and the bottom is indicated by a further increase in gamma radiation reflecting clay in the unnamed lower member of the Rustler formation. The gamma ray log for H-8c (USGS WRI 82-4118, in pocket) was inspected to see whether these inflections are present. They were, indeed, identifiable. Other gamma ray logs also exhibit these deflections at the top and bottom of the Culebra (Mercer and Orr 1979).

The lack of anomalies in the thickness data of Table B.1a-d suggests that their adequacy was not adversely affected by limitations of the various methods.

6.6.2.6. Adequacy of Application

The application of the Culebra thickness is given as input to SECOFL2D on the Form 464. Details of the uses of the parameter are not provided, but it has been used along with effective porosity for particle tracking to rank the transmissivity field indices according to travel time to the accessible environment. The thickness is judged to be adequate for this purpose. The ranking of the transmissivity indices is based on relative travel time, so any error in the Culebra thickness used would have little effect.

6.6.2.7. Accuracy of Calculations

Calculations were not included in the parameter data package. The calculations are very simple and, as a spot check, the thickness of the Culebra in H-8c was investigated by examining the core description and geophysical logs. This thickness was found to be adequately determined.

6.6.2.8. Validity of Conclusions

The value of 7.75 m for Culebra thickness (treated as a constant) is an adequate representation of this parameter for PA modeling. This value is a mean, which is a measure of central value that is commonly and correctly used to represent a variable quantity. The fact that reported thicknesses have deviated as much as 3.65 m from this value will not have any significant effect on PA calculations, because the selection of index numbers is a random process that would not be adversely affected by any minor variation in ranking of transmissivity fields.

6.6.2.9. Dissenting Views

None.

6.6.3. Culebra Storativity

Culebra Storativity is a parameter that supports the development of the Culebra transmissivity fields. The parameter description follows:

Parameter:	Measured storativity
ID#:	3418
Form 464:	WPO 37664, entered 5/3/96 However, the storativity value is from recent reinterpretation of pumping test data from the H-2 and H-11 hydropads. This reinterpretation was under a qualified QA program. Furthermore, the H-11 pumping test was conducted in 1996 under a qualified QA program. Consequently, the present peer review covers data collected at the H-2 hydropad in 1981, which are reported in field notes covering the period 4/29/81 to 5/15/81. The review does not cover any other data or analyses that support the parameter value on the Form 464.
Parameter Package:	WPO 37664
Distribution:	Constant
Value:	1E-05
Definition:	Representative Storativity for Culebra Dolomite.
Intended use:	Input to GRASP-INV for generation of transmissivity fields.

Derivation: This parameter is based on analysis of data from pumping tests at the H-2 and H-11 Hydropads, which were performed in 1981 and 1996, respectively. The data from the H-2 test have been reanalyzed under a qualified QA program (Ruskauff and Beauheim, WPO 38487), and the data from H-11 were collected during a 1996 pumping test. The H-2 pumping test data have not been qualified.

6.6.3.1. Adequacy of Requirements and Criteria

The value for Culebra storativity is used in GRASP-INV to calculate transient head data for producing calibrated transmissivity fields. Consequently, the data used to estimate the storativity should be adequate for this use. This requirement is satisfied by the H-2 1981 pumping test data. The field notes show that the pumping rate was held constant and the pressure in the observation well was measured at acceptable time intervals and to acceptable accuracy. The drawdown values obtained from the test adequately fit a theoretical curve, which supports the adequacy of the requirements imposed for the pumping test.

6.6.3.2. Validity of Assumptions

No significant assumptions are involved in the pumping test data being reviewed. The assumptions in the subsequent analysis of the data include aquifer homogeneity and isotropy, which are not strictly valid, but are adequate for the purpose of estimating storativity. The test is conventional, and the resulting storativity is reasonable. For example, see Freeze and Cherry (1979, p. 60), where the typical range for storativity is given as 5.0E-03 to 5.0E-05. The pore volume compressibility, and hence the storativity of a fractured dolomite aquifer, would tend to be near the lower end of this range. The relatively good fit of the data to the theoretical curve supports the reasonableness of using the simplifying assumptions to analyze the data.

6.6.3.3. Alternate Interpretation

The pumping test data represent the response of the Culebra near the hydropad to the hydraulic stress imposed by the pumping, and no alternate interpretation of the hydraulic significance of the data is apparent. The subsequent interpretation of the H-2 test data by fitting to analytical drawdown curves appears to be adequate. (Interpretation is qualified under recent SNL QAPD.)

6.6.3.4. Uncertainty and Consequences

Very little uncertainty is associated with the pressure and pumping rate values obtained from the pumping test. However, no pre-test water level data were recorded with the pumping test data to help evaluate the effects of any rising or falling water level trends on the test analysis. The following information indicates that no significant trend existed. This pumping test preceded shaft construction and most other WIPP activities that might affect it, and the test data indicate there was sufficient time for recovery from the hydraulic effects of previous pumping for tracer testing at the H-2 hydropad, which stopped on 4/7/81, leaving 21 days for recovery. Recovery from the test reviewed (pumping from 4/29 to 5/2) approaches initial static water level within 13 days after pumping stopped, suggesting no significant rising trend from the previous testing.

6.6.3.5. Appropriateness and Limitations of Methodology and Procedures

The methodology for collecting the pumping test data involved using pressure transducers for measuring pressure (which may be converted to hydraulic head). This procedure is adequate, and produces accurate data measured at adequate time intervals. The method of measuring pumping rate is not explicitly given, but it is recorded in milliliters per minute, suggesting a container and stop-watch. This procedure would be appropriate for such a small discharge rate. The pumping rate was recorded in the field notes often enough to establish that it was sufficiently constant, varying from 0.246 to 0.257 gallons per minute.

6.6.3.6. Adequacy of Application

The application of the Culebra storativity value obtained from H-2 is as input to GRASP-INV to develop calibrated transmissivity fields for the PA modeling. This storativity is adequate for this purpose. It is obtained from an adequate data set, in which the recovery data are consistent with the drawdown data. The fit to the Theis curve is good, and the H-2 hydropad is near the upstream end of the simulated critical path of flow to the accessible environment. The storativity value obtained from H-2 is representative for this flow path.

6.6.3.7. Accuracy of Calculations

The important calculations related to the acquisition of the data were done using the DAS software. Conversion of discharge rates in the field notebook were checked and found to be correct. Calculations related to the analysis of the data to obtain storativity were performed by INTERPRET/2 software, which is not part of this review.

6.6.3.8. Validity of Conclusions

The pumping test data from the 1981 H-2 hydropad test are adequate to support the analysis that yielded a value of 1.0-E05 for storativity. The pumping rate was held constant, pressure was measured accurately and at adequate time intervals, and no conditions were found that would prevent the data from yielding an acceptable storativity. The data fit a theoretical drawdown curve. Type-curve matching is appropriate and conforms to conventional practice for estimating storativity. Furthermore, the storativity obtained is reasonable. It is near the lower end of the range of published storativities where the storativity of fractured dolomite would be expected.

6.6.3.9. Dissenting Views

None.

6.6.4. Culebra Fluid Density

Culebra formation fluid density is a parameter that supports the development of the Culebra transmissivity fields. The parameter description follows:

***Parameter*:**	Culebra Fluid Density
ID#:	N/A
***Form 464*:**	There is no Form 464 for Culebra fluid density. Culebra formation fluid density is used under Analysis Plan AP-018, Version 00, "Ground Water Modeling Analysis Plan for the Generation of Transmissivity Fields for the Culebra Flow and Transport Calculations," which references data package WPO 35843. This data package contains a table of Culebra fluid density. Fluid density data in the table were reviewed for this peer review package.
Parameter Package:	WPO 35843
Distribution:	Not applicable. See the section on intended use below.
***Value*:**	Formation fluid density values are in Table II of WPO 35843.
***Definition*:**	*In situ* Culebra fluid density (g/cm^3).

***Intended use*:** The Culebra fluid densities are input data for GRASP-INV in accordance with a memorandum from March LaVenue to AP-018 dated 5/3/96. These data are kriged to determine the fluid density values at each of the model grid blocks (cells). The density at a cell enters into the code's calculation of hydraulic potential for the cell. Density is held constant in each cell while GRASP-INV is calculating transmissivity fields.

***Derivation*:** The density values in Table II of WPO 35843 are from SAND89-7068/2, Table E.1, except the density from H-19, which was obtained under an approved QA plan. The water quality sampling that was performed to get the values in Table E.1 is described in Appendix F of SAND89-7068/2.

6.6.4.1. Adequacy of Requirements and Criteria

The table of values for Culebra formation fluid density (except the value for WIPP-27, which is outside of the model area) is in the data base for use in GRASP-INV as dens.dat (Attachment G of the memo of 5/3/96 cited above). Consequently, the values in the table should be sufficiently representative to support this use. This requirement is satisfied by sampling wells scattered throughout the regional flow modeling domain. The wells were adequately purged before collecting the sample used for the determination of density.

6.6.4.2. Validity of Assumptions

No significant assumptions are involved in the derivation of the Culebra formation fluid density parameter. Approximations involved in calculating density from chemical composition might result in insignificant errors (SAND86-7167, Appendix E).

6.6.4.3. Alternate Interpretation

Fluid density for most wells is a direct measurement and no alternate interpretations are involved. A few densities were calculated based on chemical composition of water samples (from SAND89-7068/2, Table E.1). Calculated densities correlate well with directly measured densities (SAND86-7167, p. E-6).

6.6.4.4. Uncertainty and Consequences

Annual density data reported on Table E.1 generally varies 0.002 g/cm^3 or less for an individual well, due either to natural variation or measurement error (by inspection). This amount is typically equivalent to about 0.2 m difference in hydraulic head. The variation will not affect transmissivity fields because it is small. Furthermore, the model is calibrated to freshwater hydraulic head, and head gradients will be similar in all runs regardless of any such variations in fluid densities.

6.6.4.5. Appropriateness and Limitations of Methodology and Procedures

The methodology and procedures for measuring the formation fluid densities were appropriate. Pumping a well until the well is purged and water quality parameters stabilize will result in reliable measurement of the *in situ* fluid density. Calculation of density from the chemical composition of the water is also appropriate. Limitations in the accuracy of the density measurements are discussed in the previous section.

6.6.4.6. Adequacy of Application

The application of the Culebra formation fluid density to GRASP-INV is an adequate way to satisfy the input requirement of the code. The densities are a reasonable representation of densities in the ground water system because they are accurately derived and scattered throughout the model area.

6.6.4.7. Accuracy of Calculations

Peer review calculations of formation fluid density at Culebra pressure and temperature for a few wells showed that the densities were calculated accurately.

6.6.4.8. Validity of Conclusions

The Culebra formation fluid density values contained in the Culebra Fluid Density Data table of the Culebra Fluid-Density Data Parameter Package (WPO 35843) are adequate for the intended use in GRASP-INV. They are sufficiently accurate and are adequately distributed over the model area.

6.6.4.9. Dissenting Views

None.

6.6.5. Culebra Steady-State Freshwater Heads

Culebra steady-state heads is a distributed parameter that supports the development of the Culebra transmissivity fields. The parameter description follows:

***Parameter*:** Culebra Steady-State Heads

***ID#*:** N/A

***Form 464*:** There is no Form 464 for Culebra steady-state heads. Culebra steady-state heads (undisturbed fresh-water heads) is used under Analysis Plan AP-018, Version 00, "Ground Water Modeling Analysis Plan for the Generation of Transmissivity Fields for the Culebra Flow and Transport Calculations," which references SAND89-7068/2. This report contains estimated heads that were reviewed and reselected for use in the steady-state calibration. The heads used in the calibration are in Section II of the Parameter Package: Culebra Steady-State Freshwater Heads, Date of Record, April 25, 1996. The Parameter Package is identified as WPO 37288 in a memo from Al Lappin to Karen Schmiege, dated June 3, 1996, Head data in Section II of the Parameter Package were reviewed for this peer review package.

Parameter Package: WPO 37288

Distribution: Not applicable. See the section on intended use below.

***Value*:** Undisturbed freshwater heads for Culebra are in the table titled "1996 Culebra Undisturbed Head Values and Uncertainties" in the Parameter Package identified above.

***Definition*:** Representative values for undisturbed Culebra freshwater head during the period from 1977 to 1989. Undisturbed means not affected by WIPP activities.

***Intended use*:** The undisturbed Culebra freshwater heads are input to GRASP-INV as pressure for the steady-state calibration phase of developing transmissivity fields.

***Derivation*:** The undisturbed heads are interpreted from hydrographs of water level measurements in observation wells from 1977 through 1989.

6.6.5.1. Adequacy of Requirements and Criteria

The table of values for undisturbed Culebra freshwater heads (except the value for WIPP-27, which is outside the model area) is in the data base for use in GRASP-INV (Attachment I of the memo of 5/3/96 from Marsh LaVenue to AP-018). Consequently, the values in the table should be sufficiently representative to provide an initial steady-state calibration target during calculation of the transmissivity fields. This requirement is satisfied by measuring water levels and borehole fluid density in wells scattered throughout the regional flow modeling domain.

6.6.5.2. Validity of Assumptions

No significant assumptions are involved in the measurement of the water levels. Judgment and logic must be used to interpret which parts of the hydrographs represent undisturbed head and what value from the hydrograph should be picked as representative.

6.6.5.3. Alternate Interpretation

Interpretation of the undisturbed heads could vary. In fact the same set of data originally interpreted in SAND89-7068/2 has been reinterpreted to get the 1996 values. However, the interpretations differ only slightly. Difference in interpretation will not significantly affect the transmissivity fields because they do not significantly affect the head contour surface. Since some of the hydrographs have been variously affected by WIPP shaft activities and hydrologic testing, quantitative methods of calculating representative head (averaging, integrating) would not be appropriate.

6.6.5.4. Uncertainty and Consequences

Most uncertainty in the measurements is due to uncertainty in borehole fluid density. Measures of this uncertainty are presented in a table in the Parameter Package that augments Table G.2 of SAND89-7068/2. The uncertainty ranges up to 2 m and may average about 1 m. Inspection of head contour maps, such as Figure 2.12 of SAND89-7068/2, indicates that this level of uncertainty will not change the general character of the potentiometric surface. Consequently, it will not adversely affect the representativeness of the transmissivity fields.

6.6.5.5. Appropriateness and Limitations of Methodology and Procedures

Borehole fluid density was adequately addressed in calculating freshwater head. The procedure for picking undisturbed head involved choosing an average head where long-term data were unaffected by WIPP activities, and correlating to disturbed hydrographs to find relatively unaffected sections. This procedure is appropriate because the hydrographs of most wells are affected by WIPP shaft activities and hydrologic testing, and these effects preclude the use of quantitative methods, such as averaging heads or integrating areas between hydrographs and the best-fit line.

6.6.5.6. Adequacy of Application

The application of the representative undisturbed freshwater heads to GRASP-INV is an adequate way to proceed with calibration to produce a transmissivity field. It will improve the kriged transmissivity field and provide a starting point for further improvement by calibration to transient features on the hydrographs.

6.6.5.7. Accuracy of Calculations

Calculations involved in measuring water levels and converting them to freshwater heads are relatively simple, and the consistency of the data points on the hydrographs indicates that they were done accurately. A spot check of the value for pressure for H-1 in the GRASP-INV input file referenced above demonstrated that the pressure was correctly calculated from freshwater head, borehole fluid density, acceleration of gravity, and height of the water column.

6.6.5.8. Validity of Conclusions

The Culebra undisturbed freshwater head values contained in the Section II of the Parameter Package Culebra Steady-State Freshwater Heads dated April 25, 1996, are reasonable and are adequate for the intended use in GRASP-INV. They are sufficiently representative and are adequately distributed over the model area.

6.6.5.9. Dissenting Views

None.

6.7. Culebra Physical Transport

6.7.1. Culebra Dolomite Grain Density

This section reviews the data from which the grain density in the Culebra Dolomite were derived and the value obtained.

Parameter:	Culebra Dolomite Grain Density
ID#:	843
Form 464:	WPO 32689, entered 6/11/96
Parameter Package:	WPO 37232
Distribution:	Constant
Parameter values:	2.82 g/cm^3

Definition: The grain density is the average density of solids in the formation. In this case this means mostly dolomite with small percentages of gypsum, halite, and clays.

Intended Use: A parameter needed for calculation of solute retardation.

Derivation: This parameter was derived from the bulk and pore volumes measured for numerous core samples.

Discussion: The calculation is straightforward, but requires, in addition, either a bulk density of the sample or the weight of the sample. Presumably such data exist in the archives of INTERA Technologies who made the determinations. There is no reason to doubt the measurements inasmuch as they are quite simple and are covered under the INTERA QA plan.

6.7.1.1. Adequacy of Requirements and Criteria

An objective of the analysis was to provide data on the grain density in the Culebra Dolomite needed for calculation of solute retardation, as stated in SAND89-7079, p. 2-50. The measurements required for obtaining these data are two out of three of bulk volume, pore volume, and volume of solids, together with some measure of the weight of either the bulk volume or the volume of solids. The bulk volume was determined in most instances by taking caliper measurements of core samples. However, in some instances the core was deeply striated and in those cases the volume was measured by an Archimedes technique using toluene in order to avoid affecting the volume of expandable clays. The pore volume was determined most reliably by helium porosimetry and also, in some cases, by resaturation of dry samples with distilled water or brine. From these data, and presumably the weight of the bulk sample, the grain density was calculated.

The largest potential measurement error is probably that for the pore volume. An approximate confirmatory measurement was made by measuring the pore volume via saturation with distilled water, or in one instance with brine. These measurements agreed on average to within ±0.4% porosity as compared with an average porosity of 14.9%. Thus, the least certain measurement is adequate for the intended application.

6.7.1.2. Validity of Assumptions

The only assumption was that a constant value for grain density is adequate. The data indicate that this assumption is sufficiently reliable for the intended use.

6.7.1.3. Alternate Interpretation

The interpretation is based on very simple analysis of the raw data and simple statistics. There is no need for an alternative interpretation, even though a distribution could be constructed and sampled.

6.7.1.4. Uncertainty and Consequences

Uncertainties were presented in the form of statistics and by a comparison between two alternative methods of measuring porosity. Consequences for the intended application were implicitly discussed in the rationale for selecting a constant value for the parameter.

6.7.1.5. Appropriateness and Limitations of Methodology and Procedures

The measurement techniques were appropriate. The limitation of reduced precision at low porosities was evidently taken into consideration in rejecting a single anomalous value.

6.7.1.6. Adequacy of Application

Results of the application were not presented in the documentation provided. However, on the assumption that the manner in which this parameter is used in performance assessment is correct, there is no reason to suspect anything other than adequacy for the intended use. Presumably, solute retardation is calculated through use of surface area of adsorbing solids, notably the surface density of sorbing sites. Thus, density is related to both grain size and grain density.

6.7.1.7. Accuracy of Calculations

Visual examination of the data indicated little variability, with the exception of one value, which evidently was excluded from the calculation of the statistics. This examination provided reasonable assurance that the mean was reliable.

A single value grain density of 2.33 g/cm^3 reported in Appendix B of SAND90-7011 does not appear in the recalculation of the statistics reported in the data record. However, this sample was clearly anomalous because it had a much lower pore volume, which would mean that it could not have been measured with comparable precision. Exclusion of this value for this reason is appropriate, even though no explanation such as given in this paragraph was found in the relevant documents.

6.7.1.8. Validity of Conclusions

The conclusion is that the constant value of grain density, 2.82g/cm^3, may be used for the intended application.

6.7.1.9. Dissenting Views

None.

6.7.2. Effective Culebra Thickness

Effective Culebra thickness is a parameter that supports Culebra Physical Transport modeling. The parameter description follows:

***Parameter*:** Effective Culebra Thickness

***ID#*:** 3462

***Form 464*:** WPO 37727, entered 5/7/96

Parameter Package: WPO 37727

***Distribution type*:** Constant

***Value*:** 4.0 m

Definition: Effective Culebra Thickness represents the median Culebra total thickness within the land withdrawal boundary minus the thickness of Unit 1 (upper Culebra) as defined by Robert Holt (Memo from Lucy Meigs to Jim Ramsey dated May 6, 1996).

Intended use: The Effective Culebra Thickness is used for PA transport simulations using SECOTP2D.

Derivation: The thickness (3.0 m) of Unit 1 was calculated as the median of 12 thicknesses measured in nine wells located within the land withdrawal boundary and in the waste handling, exhaust, and air intake shafts. This thickness was subtracted from the total thickness. The total thickness (7.0 m) is from the Meigs Memo, May 6, 1996.

6.7.2.1. Adequacy of Requirements and Criteria

The Effective Culebra Thickness is used for PA transport simulations via SECOTP2D. The parameter is used to calculate ground water velocity from volumetric flux, so it affects the rate of movement of contaminants in the transport model. Consequently, the value should be sufficiently representative to provide a realistic estimate of the ground water velocity. The rationale for the value selected is that the Culebra may be divided into four hydrostratigraphic units that are recognizable in cores, and the upper unit (Unit 1) conducts much less water than the other three. The median thickness of this unit measured in representative wells and the three shafts is subtracted from the median total thickness of the Culebra to obtain the representative thickness of the more permeable lower part of the Culebra that conducts most of the water. The requirement is, then, that Unit 1 be recognizable and measured with reasonable accuracy. Inspection of core logs and shaft wall descriptions indicates that Unit 1 is indeed recognizable as a relatively massive unit with significantly fewer vugs and fractures that are not filled with gypsum and anhydrite.

6.7.2.2. Validity of Assumptions

The assumption that the more massive upper part of the Culebra contributes little to ground water flow is supported by injection testing described in USGS WRI 79-98. This testing was completed on wells H-1, H-2c, H-3 and P-14. In these tests, interpretation of tracer and temperature logs indicates no fluid loss in the upper 3 to 4.3 m. Furthermore, data from recent tests at the H-19 hydropad are said to indicate that the upper Culebra does not play a significant role in solute transport (Culebra Effective Thickness Parameter Package, Attachment 1, WPO 37223). H-19 testing is not included in this peer review because it was conducted under the SNL QA program (Parameter Package WPO 37223).

6.7.2.3. Alternate Interpretation

The effective thickness actually varies from well to well. In some wells, most of the flow probably comes from a thickness that is less than 4.0 m. For example, in H-3 injection testing, over half of the fluid was lost in the lower two feet (0.6 m) of the formation (Mercer and Orr 1979, pp. 45 to 46). At some locations, especially where permeability throughout the Culebra is low, the flow may be distributed more uniformly over the entire thickness of the Culebra. In the Waste Handling Shaft, the entire Culebra section was wet, but no obvious local source for the water was observed (Holt and Powers 1984, p. 4-11).

Basing the effective thickness on stratigraphic units is supported by the data, but is a matter of judgment. It represents a compromise between using more than the lower unit, which is appropriate in some places, and less than the lower unit, which is appropriate where a very small interval conducts most of the water. At most locations, there is adequate information on the thickness of the hydrostratigraphic units, but no direct hydraulic data on which interval is the most permeable.

6.7.2.4. Uncertainty and Consequences

Uncertainty in Effective Culebra Thickness is caused by (1) uncertainty in how adequately the median thickness of the lower units derived from 11 data points represents the actual thickness of these units, and

(2) how adequately the permeability is correlated with the lower units. The consequence of the uncertainty is that if the effective thickness is under-estimated, the effect on solute transport modeling is conservative, but if it is over-estimated the effect is non-conservative. The effect on solute transport rates would be roughly proportional to the degree of under- or over-estimation.

6.7.2.5. Appropriateness and Limitations of Methodology and Procedures

The methodology is appropriate. As mentioned in Section 6.7.2.3, it strikes a balance between using the entire thickness of the Culebra and using a very small value for effective thickness. The entire thickness would be inappropriate because the evidence strongly indicates that much of the thickness does not contribute significantly to flow at most localities. A very small value would be inappropriate because core descriptions, shaft descriptions, and tracer testing indicate it is not the general condition. Using the median thickness of the hydrostratigraphic units that contain most of the permeable material is appropriate. The thickness of the Culebra and its hydrostratigraphic units is fairly constant in the land withdrawal area, and the quality of the core descriptions is adequate. Furthermore, injection tracer testing and temperature logging in wells not used to calculate the effective thickness support the interpretation that most of the ground water movement is in the lower part of the Culebra.

6.7.2.6. Adequacy of Application

The application of effective thickness to simulating solute transport is an adequate way to account for the low permeability of the upper part of the Culebra. If the entire Culebra thickness were used in solute transport modeling, the simulated rate of movement of contaminants would tend to be too slow. Using the thickness of the more permeable part of the Culebra, and assuming all the fluid moves through this unit, will tend to increase the simulated rate of movement of contaminants and is, therefore, more conservative. Not using an effective thickness that is less than the thickness of lower permeable part of the Culebra is reasonable because the data do not indicate that a single, thinner unit in the lower Culebra has widespread excess permeability.

The wells used to calculate the effective thickness are areally distributed to provide representative information on Culebra stratigraphy and permeable intervals. The core descriptions and shaft wall descriptions are good enough to establish the presence of an upper, less permeable layer in the Culebra. Intervals where core was not recovered suggest the presence of fracture porosity.

6.7.2.7. Accuracy of Calculations

Calculations involved in developing the value for effective thickness are relatively simple, and documents reviewed contained nothing that indicated any thicknesses were miscalculated.

6.7.2.8. Validity of Conclusions

The Effective Culebra Thickness of 4.0 m on Form 464, WPO 37727 dated 5/7/96, is reasonable and is adequate for the intended use in solute transport modeling by SECOTP2D in the land withdrawal area. Inspection of core descriptions and descriptions of shaft walls indicates that the upper part of the Culebra is more massive than the lower part and that the vugs and fractures tend to be filled with gypsum and anhydrite. The value of 4.0 m is sufficiently representative of the thickness of the part of the Culebra that conducts most of the ground water. It will provide adequate representative ground water velocities for simulating the rate of movement of contaminants.

6.7.2.9. Dissenting Views

None.

6.7.3. Advective Porosity

This section reviews the estimation of the advective porosity used in model SECOTP to simulate potential contaminant transport in the Culebra in the PA. The information about this parameter provided in the Form 464 is as follows:

Parameter:	Culebra advective porosity
ID#:	3487
Form 464:	WPO 38358, entered 6/14/96
Parameter Package:	WPO 37227
Distribution Type:	Log-uniform
Parameter Values:	Minimum = 1.0E-04
	Maximum = 1.0E-02

Definition: Advective porosity is defined to be fracture porosity of a fractured porous medium. The physical concept of advective porosity is the pore volume of total fractures divided by the bulk volume in a fractured porous medium at a given scale.

Intended Use: The Culebra advective porosity is used in model SECOTP as one of the input parameters to simulate contaminant transport in the Culebra under the hypothetical case of borehole intrusion. Specifically, advective porosity is used to calculate velocity of advective transport that is supposed to occur only in fractures (SAND92-1579).

Derivation: Since the Culebra advective porosity and matrix block length (Section 6.7.4) were derived from the same process, the discussion of the derivation covers both parameters. Derivation of the Culebra advective porosity and the half matrix block length involves three major steps: (1) tracer tests in the field, (2) numerical simulations to fit the observed breakthrough curves obtained from the tracer tests, and (3) integration of simulation results to generate a parameter value for input to SECOTP. A brief description of the three steps follows.

Numerous hydraulic tests including tracer tests were conducted at the WIPP site in order to identify the hydraulic and solute transport properties of the Culebra. Among those, the tracer tests conducted at hydropad H-3, H-11, and H-19 were selected as the main basis for development of the Culebra advective porosity and matrix block length for the PA. These hydropads are located along the identified flow pathway within the Culebra dolomite from the waste-storage area to the accessible environment.

Numerical simulations using SWIFT II and THEMM have been performed to fit the breakthrough curves obtained from the tracer tests and to identify the possible ranges of the solute transport parameters, including the advective porosity and matrix-block length. Results of the numerical simulations are provided in Table 1 of the memorandum by Meigs dated July 2, 1996.

The solute transport parameters generated from the simulations of the tracer tests at the local hydropad scale were integrated and analyzed further to derive the transport parameters and their statistical distributions for model SECOTP at the PA model scale.

Discussion: Because the distribution of fractures is discontinuous and scale-dependent, advective porosity is scale-dependent. Advective porosity is a fitting parameter which can be obtained by simulation of field tracer test. It characterizes the feature of a fractured porous flow system in conjunction with matrix-block length and other parameters based on a double-porosity solute transport conceptual model. Advective porosity is generated based on an idealized conceptual model. This parameter is model-dependent. Different conceptualizations, different numerical codes, or different values of other parameters in the model, may result in different values for this parameter.

6.7.3.1. Adequacy of Requirements and Criteria

Since the Culebra advective porosity and matrix block length were derived from the same process, the discussion of adequacy of requirements includes both parameters. The requirements for estimation of the Culebra transport properties were clearly stated in the related documents (McCord and Meigs, 1996; Beauheim et al. 1995). The objective of estimation of the transport parameters of the Culebra was to provide reasonable input parameters for the PA model to simulate potential radionuclide transport in the Culebra from the disposal facility to the accessible environment.

The tracer tests were designed and conducted under specific requirements in order to characterize the transport properties of the Culebra. Specific requirements designed for the tracer tests at H-19 and H-11 were discussed in detail in Beauheim et al. (1995).

The simulations to match the tracer test results were also designed and conducted under specific requirements in order to characterize the transport properties of the Culebra and to improve the conceptual models. Specific requirements for the simulations of the tracer tests were discussed in detail in McCord and Meigs (1995).

The rationale for integration and conversion of the parameters to the PA model SECOTP was discussed in the two memorandums (Meigs 1996; McCord 1996).

It should be noted that model simulations have not been completed at this time (as of July 2, 1996). The current estimations of advective porosity and matrix block length were based on part of the curve fitting results of the tracer test at H-3, H-11, and H-19. The results have provided upper and lower bounds of the parameters at those hydropads. The current work has indicated that the estimation of advective porosity and matrix block length may further be improved, but they will lie within the upper and lower bounds estimated based on the completed simulations.

In general, the requirements for the derivation of the parameters are adequate. Even though the model simulations have not been completed, using the currently estimated bounds will not adversely affect the PA calculation. The completion of the tracer test simulations may better identify the distribution of the parameter at the hydropad scale. It is not expected to change the upper and lower bounds of the distribution of the parameters.

6.7.3.2. Validity of Assumptions

There are many assumptions associated with all processes involved in the derivation of the parameter. The assumptions related to step 1 and step 2 of the parameter derivation are not discussed here, since they are considered appropriate. This section focuses on the evaluation of the assumptions used in conversion of the parameter at the hydropad scale (10-30 m) to the PA model scale (2.5 km). Some assumptions evaluated here may not be explicitly discussed in the related document, but they are implied in the derivation processes.

Assumption 1 -- The Culebra is assumed to be a double-porosity medium for the entire area of the WIPP site in terms of transport property.

The Culebra, in general, is characterized as a fractured dolomite with non-uniformly distributed fractures and vugs based on the field data, including borehole logs, shaft logs, hydraulic tests, and tracer tests. It has been recognized that the hydraulic and transport properties of the fractures at any location depend on such features as whether the fractures are open or filled with gypsum, their frequency, and the degree of interconnection between fractures and vugs over distances (Beauheim et al. 1995). The dominant transport processes may vary due to the spatial variation of the distribution of fractures and their features. In areas where fractures are not open, transport may occur slowly in the matrix. In areas where open fractures with large apertures exist, advective flow may primarily occur in the fractures, while the matrix only acts as storage for diffusive transport in accordance with concentration gradient. In cases where both fractures and matrix allow ground water to flow, advective transport may occur in both. In summary, the degree of double-porosity behavior varies spatially at the site.

Even though the double-porosity behavior varies in space, it is reasonable to generalize the entire dolomite at the WIPP site as a double-porosity medium. Such an assumption may allow model results to be more flexible when parameters vary, and also allow model results to be more conservative.

Assumption 2 -- Transport properties observed from the tracer tests at H-3, H-11, and H-19 are assumed to be representative of the entire PA model.

This is a reasonable assumption because H-3, H-11, and H-19 are located along the flow pathway from the repository area to the boundary of the PA model. The transport properties along the flow path are the most important concern.

Assumption 3 -- The advective porosity is assumed to be uniform for the entire PA model with an uncertainty approximately equal to the range of values derived from the simulation results of the tracer tests.

This is a highly simplified assumption. It is inconsistent with the field data, and inconsistent with the heterogeneous flow model used in the PA. The tracer tests conducted at H-3, H-11, and H-19 indicated that there is great spatial variability of the transport properties along the flow path. The variability does exist between the hydropads, and between the boreholes at each hydropad. The estimated advective porosity for H-3, H-11, and H-19 are approximately 1.0E-03, 5.0E-05, and 5.0E-02, respectively (Table 1, Meigs 1996), with three orders of magnitude difference.

With such an assumption, spatial variability observed from the three tracer tests was converted to the uncertainty of an average advective porosity over the entire flow pathway of 2.5 km. This means that any value randomly selected from the estimated range is assumed to be a possible average advective porosity for the Culebra for the entire PA model. The simulation result of using this value constitutes one of the realizations of possible contaminant transport.

It should be noted that the advective porosity is a scale-dependent fitting parameter. Spatial variability at different locations at a small scale is not equivalent to the uncertainties of the average advective porosity at a large scale. Simply applying this assumption may cause the PA model to result in an unrealistically large range of simulation results.

Some results may represent the average conditions of transport. Some may not be realistic for the actual conditions. Advective velocity is determined by dividing the Darcy velocity by advective porosity. The smaller the advective porosity, the faster the peak concentration of solute occurs and the greater the peak concentration, when the other parameters are fixed. The migration of contaminant may be either too slow when the average advective porosity is equal to the high end of the estimation or too fast when the low end of the estimation, is used for the entire area.

Assumption 4 -- The estimated range of advective porosity at hydropad scale using SWIFT II and THEMM is truncated based on the professional judgment, and is assumed to be representative at the PA model scale using SECOTP.

The range of advective porosity values obtained from SWIFT II and THEMM simulations based on the tracer test results at small scale of 10-30 m is from 4E-05 to 9E-02 (Table 1 in Memorandum from Meigs July 2, 1996). Based on professional judgment at SNL, the range of advective porosity in the Form 464 is reduced to 1.0E-04 to 1.0E-02 for the PA model, at a scale of 2.5 km. As stated in the memo (Meigs 1996), "We strongly feel that the extreme values of advective porosity less than 1.0E-04 and greater than 1.0E-02 will not occur over regions as large as the existing pathway, and thus aerial averages lie between these two end points."

The reduction of the range of estimation is considered reasonable by the peer review panel. The spatial variability demonstrated at H-11, H-3, and H-19 indicates that the average advective porosity along the entire pathway should lie between the extreme values obtained from the individual hydropads. However, the quantitative analysis of how much the range should be truncated was not given in the related document.

Assumption 5 -- A log-uniform distribution is assumed to represent the probability of the uncertainty of the average advective porosity in the PA model.

Due to lack of sufficient data, a meaningful distribution based on three tracer test results is not possible. Based on orders of magnitude difference in the advective porosity obtained at H-3, H-11, and H-19, a log-uniform distribution is a close solution. It is also a conservative solution, since a log-uniform distribution tends to have high probability for the low values than for the high values of advective porosity. The low value of advective porosity will lead to fast transport.

6.7.3.3. Alternate Interpretation

Alternate interpretations exist in several ways. Three alternate interpretations are evaluated here, including (1) alternate approaches for applying the double-porosity model to curve fitting the tracer test results, (2) alternate approaches for converting local scale parameters to regional scale model, and (3) alternate conceptual models for simulation of a fractured porous medium system.

1. Two approaches have been used by SNL to simulate the tracer test results. One is designated as a homogeneous layer approach using SWIFT II, and the other is designated as a heterogeneous approach used in code THEMM. Both models were used to fit the breakthrough curves from the tracer tests. The fitted advective porosity values from the two models deviate somewhat (Table 1 in the Memorandum by Meigs July 2, 1996). The differences are within one order of magnitude. The differences are expected because the advective porosity is a model dependent parameter as discussed in the definition. However, in terms of estimation of the range of the parameter, both models yielded consistent results. Therefore, alternate interpretations yielded essentially similar estimations.

2. An alternate representation of transport parameters in the PA model was investigated by SNL. Possibility of zonation of transport parameters associated with hydraulic parameters, which are the distributed transmissivity in the PA flow model, was evaluated, as discussed in the memorandum by McCord (1996). The scatter plots between advective porosity (or matrix block length) and transmissivity in Figure 1 (McCord 1996) do not indicate obvious correlation between transport parameters and hydraulic parameters. Therefore, zonation approach was not considered in the PA. However, it should be noted that the presented scatter plots may not represent the real correlation between transmissivity and the actual transport properties. The physical evidence does exist that both hydraulic and transport properties are related to the distribution of fractures, including the degree of opening, degree of interconnection, and their frequency.

3. An alternate conceptual model has been investigated by SNL (McCord 1996). A multirate/multiporosity model was found to be able to better simulate the physical transport processes of the Culebra.

6.7.3.4. Uncertainty and Consequences

The primary uncertainties of the estimated advective porosity are due to the lack of knowledge of the actual transport properties along the flow path in the PA model. Using average advectivity porosity in the PA model with a much greater scale than the tracer test scale will unavoidably introduce great uncertainty.

The consequences of the uncertainty of the average advective porosity may result in an unrealistic large range of the PA simulation results. Given a fixed Darcy's velocity, two orders of magnitude difference in advective porosity may result in two orders of magnitude difference in fracture flow velocity. Therefore, the uncertainty of advective porosity may have a strong impact on the travel time of peak concentration and on the magnitude of peak concentration at the boundary of the accessible environment.

Another concern of the uncertainty is how much is the appropriate amount for truncation of the range of the parameter. It certainly has impact on the results. Quantitative evaluation is not available.

However, since log-uniform distribution is assigned to the parameter, the chances of random selection of the small values are greater than the changes of random selection of large values. Therefore, it is expected that the uncertainties of the PA results due to the uncertainty of the Culebra advective porosity are on the conservative side.

6.7.3.5. Appropriateness and Limitations of Methodology and Procedures

The tracer test at H-3 was performed in 1984. The tracer test at H-11 was performed twice, in 1988 and in 1996. The tracer test at H-19 was performed in 1995 and in 1996. The tracer tests done after 1988 were conducted under a qualified QA program.

The methodology and procedures used for the past tracer tests at H-3 and H-11 were not designed as rigorously as for the recent tests. Evaluation was done of the test conditions and test results (Lappin and Chocas 1996; SAND85-7206; SAND89-7065; SAND92-1579) for these two hydropad tests.

The repeated tracer tests at H-11 were conducted twice (in 1988 and in 1996) under similar conditions. Comparisons between the testing conditions and breakthrough curves between the two tests indicate that the H-11 test result of 1988 is not significantly different from the results obtained in 1996. The peak concentrations occur at the same time, about a half day for H-11b3, and about 5 days for H-11b2. The peak concentrations for H-11b3 (12.5 mg/l) in 1996 is somewhat higher than the peak concentration in 1988 (8 mg/l). For H-11b2, the peak concentrations are identical. From this point of view, the test results obtained in 1988 are considered adequate.

The observed breakthrough curves at H-3 obtained from the 1984 tests are not as smooth as expected. This may be due to the limitations of the equipment and procedures applied in 1984. However, the unexpected non-smoothness does not appear to change the general shape of the curves; therefore, it should not affect the interpretation results of the parameters.

6.7.3.6. Adequacy of Application

Application of the advective porosity in SECOTP is based on the assumptions discussed in Section 6.7.3.2. Given the conceptual model and approach designed for simulations of the Culebra transport in the PA, the application of the estimated advective porosity with a log-uniform distribution is expected to be conservative.

6.7.3.7. Accuracy of Calculations

All the simulations and calculations were performed under a qualified QA program. Therefore, calculations were judged to be accurate.

6.7.3.8. Validity of Conclusions

The tracer test results from H-3 (1984) and H-11 (1988) were reviewed and are considered adequate for the derivations of the transport parameters at those hydropads. The estimated range (1.0E-04 to 1.0E-02) and distribution (Log-uniform) of the Culebra advective porosity provided in Form 464 (WPO 38358, entered 6/14/96) is acceptable for the intended use.

6.7.3.9. Dissenting Views

None.

6.7.4. Half Matrix Block Length

This section reviews the estimation of the half matrix block length used in model SECOTP to simulate potential contaminant transport in the Culebra in the PA. The information about this parameter provided in the Form 464 is as follows:

Parameter: Culebra half matrix-block length

ID#: 3485

Form 464: WPO 38356, entered 6/13/96

Parameter Package: WPO 37225

Distribution Type: Uniform

Parameter Values: Minimum = 0.05 m

Maximum = 0.5 m

Definition: Matrix block length defined in a double-porosity fractured porous medium model represents effective fracture spacings (SAND92-1579). Half matrix block length is effective distance from fracture to center of the matrix block.

Intended Use: The Culebra matrix block length is one of the input parameters in model SECOTP which simulates contaminant transport in the Culebra under the hypothetical case for a breach of the repository. Specifically, matrix block length is used to simulate physical retardation of transport due to diffusion between fractures and matrix and within matrix in response to concentration gradient (SAND92-1579).

Derivation: See "Derivation" in Section 6.7.3.

Discussion: Similar to advective porosity, matrix block length is a fitting parameter, rather than a measured one. It is scale-dependent, model-dependent, and dependent on variation of other parameters in a double-porosity model.

Matrix block length has a clear physical meaning. It describes the amount of surface area available for matrix diffusion along a given flow path (SAND92-1579). However, matrix block length does not describe the actual geometry of a fracture system. It only represents the effective fracture spacings, not actual structure spacings. Since matrix block length is a fitting parameter, it unavoidably involves model errors, computational errors, and possibly uncertainty of the other parameters.

Given the flow pathway length and the effective layer thickness, the larger the matrix block length, the smaller the surface area available for matrix diffusion. If matrix block length is very small, diffusion occurs as soon as flow occurs through fractures. Then transport behavior approaches that in a porous medium of single porosity. If the matrix block length is large, diffusion takes longer, acting as a physical retardation of solute transport. Then the medium is considered to have significant double-porosity behavior. The direct effect of matrix block length on solute transport is that the larger the parameter, the greater the peak concentration, and the sooner peak concentration occurs.

6.7.4.1. Adequacy of Requirements and Criteria

See Section 6.7.3.1.

6.7.4.2. Validity of Assumptions

There are many assumptions associated with all processes involved in the derivation of the parameter. The assumptions related to step 1 and step 2 of the parameter derivation are not discussed here, since they are considered appropriate. This section focuses on the evaluation of the assumptions used in conversion of the parameters at the local scale hydropad to the one used in the PA model. Some assumptions evaluated here may not be explicitly discussed in the related document, but they are implied in the derivation processes.

<u>Assumption 1</u> -- The Culebra is assumed to be a double-porosity medium for the entire area of the WIPP site in terms of its transport properties.

The Culebra, in general, is characterized as a fractured dolomite with non-uniformly distributed fractures and vugs based on the field data, including borehole logs, shaft logs, hydraulic tests and tracer tests. It has been recognized that the hydraulic and transport properties of the fractures at any location depend on such features as whether the fractures are open or filled with gypsum, their frequency, and the degree of interconnection between fractures and vugs over distances (Beauheim et al. 1995). The dominant transport processes may vary due to the spatial variation of the distribution of fractures and their features. In areas where fractures are not open, transport may occur slowly in the matrix. In areas where open fractures with large aperture exist, advective flow may primarily occur in fractures, while the matrix only acts as storage for diffusive transport in response to concentration gradient. In cases where both fractures and matrix allow ground water to flow, advective transport may occur in both. In summary, the degree of double-porosity behavior varies spatially over the site.

Even though the double-porosity behavior varies spatially, it is reasonable to generalize the entire Culebra dolomite at the WIPP site as a double-porosity medium. The double-porosity model allows great flexibility through varying parameters that control the degree of interaction between fractures and matrix.

Assumption 2 -- *The transport properties observed from the tracer test results at hydropads* H-3, H-11, and H-19 are assumed to represent the transport properties of the entire PA model.

This is a reasonable assumption because H-3, H-11, and H-19 are located along the flow pathway from the repository area to the boundary of the WIPP site. The transport properties along the flow pathway are the most important concern.

Assumption 3 -- The matrix block length is assumed to be uniform for the entire area of the PA model, with an uncertainty value approximately equal to the range of values derived from the simulation results of the tracer tests.

This is a highly simplified assumption. It is inconsistent with the field data, and inconsistent with the heterogeneous flow model used in the PA. The tracer tests conducted at H-3, H-11, and H-19 indicated that there is great spatial variability of the transport properties along the flow path. The variability does exist between the hydropads, and between the boreholes at each hydropad. The estimated matrix block length from the tracer test analysis results in a range of 0.015 m to 1.76 m (Table 1, Meigs 1996), with two orders of magnitude difference.

With such an assumption, the spatial variability observed from the three tracer tests was converted to the uncertainty of an average matrix block length over the entire flow pathway of 2.5 km. This means that any value randomly selected from the estimated range is assumed to be a possible representative matrix block length for the Culebra of the entire model area. The simulation result of using this value constitutes one of the realizations of possible contaminant transport.

It should be noted that the spatial variation of the parameter at local scales is not equivalent to the estimate of the uncertainty of the average parameter over large distance. Simply applying this assumption may cause the PA calculations to cover an unrealistic, large range of results. Some results may represent the average conditions of physical retardation of transport. Some may not be realistic for the actual conditions (i.e., the matrix diffusion along with transport is overestimated when the average matrix block length is equal to the low end, or the contaminant release is overestimated when the high end is used as the average matrix block length for the entire area).

<u>Assumption 4</u> -- The estimated range of matrix block length at hydropad scale using SWIFT II and THEMM is truncated based on professional judgment, and is assumed to represent a conservative estimation at the PA model scale using SECOTP.

The range of the half matrix block length obtained from SWIFT II and THEMM simulations, based on the tracer test results at hydropad scale of about 20 m, is from 0.0075 m to 0.88 m (Table 1 in Memorandum from Meigs July 2, 1996). The range of the half block length in the Form 464 is reduced to 0.05 m to 0.5 m for the PA model at a scale of 2.5 km. The low end was truncated (increased) by more than half order of magnitude, while the high end is only truncated by less than a factor of 2. Based on the concept of the matrix block length, the larger the value, the smaller the surface area, and the less the physical retardation. Therefore, more truncation at the low end and less truncation at the higher end provides a conservative range of estimation.

The reduction of the range of estimation is reasonable and conservative as explained by Meigs (1996).

First, as demonstrated at H-11, H-3 and H-19, the spatial variability of the matrix block length has two orders magnitude difference (Table 1, Meigs 1996). Along such a variable flow path, the actual average over the entire flow path is expected to lie between the extreme values obtained from the individual hydropads of a local scale. The decision to truncate the low end and high end was based on the professional judgment. As stated in Meigs (1966), "We strongly feel that the extreme values of matrix block length greater than 1.0 m will not occur over regions as large as the exit pathway." This statement is well accepted under the condition that assumption 2 is true. The extreme value observed at a local scale is not possible to represent an average value over the entire flow pathway, which has a spatial variability of two orders of magnitude. However, quantitative analysis about the amount of truncation was not performed to support the estimation of the range of the parameter.

The second reason is that there is a difference in conceptualization of fractured systems in SWIFT II and SECOTP. The simulations of the tracer tests were based on the conceptualization of a fractured porous medium using a 3D intersecting fracture sets approach. The SECOTP is developed based on a 2D parallel plates concept. This means that if the same matrix block length is used in both models, the surface area in the 3D model is three times the one in the 2D model. The effect of matrix diffusion therefore will be three times greater in a 3D model than in a 2D model, under the condition that matrix block has not been completely saturated. As discussed in the memorandum by Meigs (1996), if matrix blocks become saturated, a double porosity model will approach a single porosity model. The total porosity (matrix porosity + fracture porosity) will be immediately accessible by solutes. Model results using 3D or 2D configurations under saturated conditions will be equivalent. Therefore, applying the matrix block length identified from SWIFT II to SECOTP should lead to conservative results, (i.e., shorter travel time for peak and higher concentration for peak).

Assumption 5 -- A uniform distribution is assumed to represent the probability of uncertainty of the average matrix block length in the PA model.

Based on assumptions 3 and 4, a uniform distribution was assigned to the Culebra matrix block length in the Form 464. Due to lack of sufficient data, a meaningful distribution based on three tracer test results is not possible. Based on professional judgment, a uniform distribution is assumed. This distribution implies that equal probability is assigned to any value within the range. Based on the discussion in assumption 4, a uniform distribution is considered appropriate.

6.7.4.3. Alternate Interpretation

Alternate interpretations of the double-porosity conceptual model exist. Two approaches were used by SNL to simulate the tracer test results. One is designated as a homogeneous layer approach using SWIFT II, and the other is designated as a heterogeneous approach used in code THEMM. Both models were used to fit the breakthrough curves from the tracer tests. The fitted matrix block length values from the two models are very close (Table 1 in the Memorandum by Meigs July 2, 1996). Alternate interpretations yielded essentially similar estimates.

Another alternate interpretation of transport parameters was investigated by SNL. The possibility of zonation of transport parameters associated with hydraulic parameters, which is the distributed transmissivity in the flow model in the PA, was evaluated in the Memo from McCord to Meigs (1996). The scatter plots between advective porosity or matrix block length with transmissivity shown in Figure 1, do not indicate correlation between transmissivity and transport parameters. Therefore, zonation was not considered in the 1996 PA. However, poor correlation presented in the scatter plots does not mean there is no correlation between hydraulic and transport properties. The physical evidence supports that both hydraulic and transport properties are strongly related to the distribution of fractures.

6.7.4.4. Uncertainty and Consequences

Matrix block length is probably the most import parameter in the double-porosity transport model. In the 1992 PA report, it is ranked as the sixth most important parameter in the overall PA (SAND92-0700/4 pp. 9-8). Uncertainty in the estimation of the matrix block length will have significant impact on the PA results.

The consequences of applying average matrix block length over the entire PA model may result in an unrealistic, large range of the PA simulation. Since the range of matrix block length covers one order of magnitude, the difference in the characteristic diffusion time will be two orders of magnitude, as expressed in Equation (5-13) in SAND92-1579 (p. 5-47). Therefore, the uncertainty of matrix block length may have a strong impact on the time for peak concentration to occur and on the magnitude of peak concentration at the boundary of the accessible environment. As illustrated in the example in Attachment 1 of the memorandum by McCord (1996), one order of magnitude difference in matrix block length yields about 1.5 orders of magnitude difference in peak concentration and 1.5 orders of magnitude difference in peak travel time.

Based on the discussion in assumption 4, the uncertainties of the Culebra matrix block length are expected to result in a conservative consequence in the PA calculation.

6.7.4.5. Appropriateness and Limitations of Methodology and Procedures

See Section 6.7.3.5

6.7.4.6. Adequacy of Application

Application of the matrix block length in SECOTP is based on the assumptions discussed in Section 6.7.4.2. Given the conceptual model and approach designed for simulations of the Culebra transport in the PA, the application of the estimated matrix block length is considered conservative.

6.7.4.7. Accuracy of Calculations

All the simulations and calculations were performed under a qualified QA program. Therefore, the calculations are judged to be accurate.

6.7.4.8. Validity of Conclusions

The tracer test results from H-3 (1984) and H-11 (1988) were reviewed and are considered adequate for the derivation of the transport parameters at those hydropads. The estimated range of the Culebra half matrix block length (0.05 m to 0.5 m) and its distribution (uniform) provided in Form 464 (WPO 38356, entered 6/13/96) is acceptable for the intended use.

6.7.4.9. Dissenting Views

While I agree that the log-uniform distribution with minimum and maximum values of 0.05 and 0.5 m is adequate for use in the PA, and realistically represents the uncertainty in this parameter, I do not agree that this range should be described as conservative, as it is stated at various places in this section. I do not think the use of this range of values is so cautious as to be described as conservative in the sense of a tendency to cause containment concentrations or transport rate to be overestimated.

Darrel E. Dunn

Paul L. Cloke

David A. Sommers

6.7.5. Diffusive Porosity

This section reviews the estimation of the diffusive porosity used in model SECOTP to simulate the potential contaminant transport in the Culebra in the PA. The information about this parameter provided in the Form 464 is as follows:

Parameter: Diffusive Porosity for Culebra Dolomite

ID#: 3486

Form 464: WPO 38357, entered 6/13/96

Parameter Package: WPO 37228

Distribution Type: Cumulative

Parameter Values:

Value	Probability
0.10	0.0
0.11	0.10
0.12	0.25
0.16	0.50
0.18	0.75
0.19	0.90
0.25	1.00

Definition: Diffusive porosity is defined as matrix porosity that allows diffusion to occur according to the concentration gradient in the matrix. This porosity is the interconnected porosity of a medium, which is equal to the interconnected pore volume divided by the bulk volume.

Intended Use: The Culebra diffusive porosity is used in model SECOTP as one of the input parameters to simulate contaminant transport in the Culebra under the hypothetical borehole intrusion case. Specifically, diffusive porosity is part of the storage of a double porosity model. Diffusion into the storage contributes to retardation of solutes.

Derivation: The Culebra diffusive porosity was derived based on the laboratory measurements of more than 100 core samples from 21 boreholes (Parameter Package, WPO 37228). The core analyses for H-19b4 and AIS were conducted recently by Terra Tek under a qualified QA program. The rest of the core analyses were conducted in two periods, 1985 to 1986 and 1987 to 1988, and are documented in SAND90-7011.

6.7.5.1. Adequacy of Requirements and Criteria

Porosity is a basic physical property of a medium. The measurement of the Culebra porosity based on core samples was designed carefully and conducted by several approaches. The objectives of the core analyses, clearly stated in SAND90-7011, were to better understand the physical properties of the pore structure of the Culebra, and to augment the Culebra data base for site characterization and performance assessment studies. The sampling and analyses processes documented in the report (SAND90-7011) have demonstrated that the requirements to meet the objectives were adequate. The adequacy of the requirements can be summarized as following:

More than 100 samples, including whole-core and core-plug samples, from 21 different boreholes located in the WIPP area were measured.

Some of the samples were measured using both the helium approach and the water resaturation approach.

Results from different phases and from different laboratories were consistent.

Tests were performed under a quality assurance plan.

6.7.5.2. Validity of Assumptions

The assumptions related to the estimation of porosity of the Culebra include the assumption that the selected samples are a reasonable representation of the Culebra dolomite, which statistically represents the porosity distribution of the Culebra physical textures. This appears to be a reasonable assumption based on large number of samples collected.

Another assumption implied in the derivation of the range of porosity is that the average porosity of core samples from a borehole was used as a representation of the porosity of the Culebra at the borehole location. This is a reasonable assumption because in the model the porosity represents the average porosity of the Culebra layer of 4 m. Due to this data reduction, the range of porosity was reduced to 0.10 to 0.25 from the range of 0.03 to 0.30, which is based on core sample results.

In SAND90-7011, it was mentioned that the selected core samples were based on the availability of samples. Since a lot of core samples that were in apparently porous and fractured parts of the Culebra have been destroyed and not recovered during coring, the measured samples may not be a complete representation of the physical characterization of the Culebra. This is true in general; however, for the intended use of the diffusive porosity in SECOTP, the measured porosity from core analyses can be considered representative because the fracture porosity is addressed by another parameter separately in model SECOTP.

6.7.5.3. Alternate Interpretation

Porosity measurement by the helium method is a standard and well known process. An alternate measurement approach is the water saturation method. Both methods resulted in almost identical results. Detailed discussion of both approaches is presented in Section 6.7.5.5.

6.7.5.4. Uncertainty and Consequences

The estimated Culebra porosity and its distribution are considered reasonable and not associated with significant uncertainties.

6.7.5.5. Appropriateness and Limitations of Methodology and Procedures

The methodology and processes for the measurement of the Culebra porosity were documented in detail in SAND90-7011. They are considered appropriate for characterization of the physical properties of the formation.

The basic approach used for measurement of porosity is the helium method based on Boyle's Law. Helium is a non-adsorbing gas and has a minimum deviation in behavior from an ideal gas. The helium method is supposed to provide an approximation of total interconnected porosity. Advantages of Boyle's Law helium method are: (1) it is very accurate, (2) it is fairly rapid except for extremely low-permeability (less than 1.0E-18 m^2) samples, and (3) it is non-destructive, allowing the samples to be reused for other analyses (SAND90-7011).

Water-resaturation approach was also used to measure the porosity of cores. The resaturation method is supposed to provide an estimate of the interconnected porosity for ground water flow and solute transport modeling, and also have the advantage of determining the void volume when the mineral samples are wet, as is the case *in situ*. The resaturation method using deionized water was applied on part of the samples that had been used to measure porosity using the helium method. Results of applying both methods show good agreement.

The core analyses documented in SAND90-7011 were performed by two phases, 1985 to 1986 and 1987 to 1988, and were conducted by two laboratories, Terra Tek, and K&A Laboratories. Results from two phases and two laboratories were checked for consistency by duplicate analyses on the same samples. The results were consistent.

Based on the description in SAND90-7011, the methodology and procedures used for measurement of porosity are considered appropriate.

6.7.5.6. Adequacy of Application

Application of the Culebra matrix porosity in SECOTP, based on the estimated range and its distribution, appears to be adequate. The matrix porosity plays a role of storage for physical retardation of a transport process. Since the estimation of porosity is representative, its application in the model is considered adequate.

6.7.5.7. Accuracy of Calculations

All the calculations to estimate the borehole average porosity and its distribution were performed under a qualified QA program. Therefore, the calculations are judged to be accurate.

6.7.5.8. Validity of Conclusions

The estimated Culebra diffusive porosity ranging from 0.1 to 0.25 with a cumulative distribution provided in the Form 464 is adequate for the intended use.

6.7.5.9. Dissenting Views

None.

6.7.6. Diffusive Tortuosity

This section reviews the estimation of the diffusive (matrix) tortuosity used in model SECOTP to simulate potential contaminant transport in the Culebra in the PA. The information about this parameter provided in the Form 464 is as follows:

Parameter:	Diffusive tortuosity
ID#:	3474
Form 464:	WPO 38345, entered 6/11/96
Parameter Package:	WPO 37226
Distribution Type:	Constant
Parameter Value:	0.11

Definition: Tortuosity is conceptually defined as a measure of the effect of the shape of the flowpath followed by water molecules in a porous medium (Fetter 1993). It can be represented by the ratio between a straight-line length and the length of the actual pathway between the ends of a tortuous flowpath.

Intended Use: The Culebra tortuosity is one of the input parameters in model SECOTP, which simulates contaminant transport in the Culebra under the hypothetical case for a breach of the repository. Specifically, tortuosity is used in the calculation of the coefficient of molecular diffusion in the model. It contributes to matrix diffusion and partially contributes to hydrodynamic dispersion. In general, the smaller the tortuosity value, the slower the rate of matrix diffusion.

Derivation: The estimation of the Culebra tortuosity was based on the results of 36 core samples from the core analyses reported in SAND90-7011 and from the core analyses on H-19b4 recently conducted by Terra Tek. The constant parameter value provided in the Form 464 is the median of the 13 borehole average tortuosity values.

Tortuosity for each sample was calculated based on the formation factor and porosity using the following equation (SAND90-7011):

$$\tau = 1 / (F \phi) \qquad (1)$$

where:

F = Formation factor

ϕ = Matrix porosity

Formation factor is a standard parameter used by the petroleum industry (Archie 1942). It is determined by $F = R_b/R_w$, where R_b is the measured electrical resistivity of the porous medium saturated with fluid of electrical resistivity R_w. The greater the formation factor, the greater the electrical resistance of the formation, which indicates the flow path is more tortuous.

6.7.6.1. Adequacy of Requirements and Criteria

Tortuosity is a basic physical property of a porous medium. However, methods of direct measurement of tortuosity are not available. The indirect measurements of the Culebra tortuosity, as reported in SAND90-7011, were based on the formation factor concept for core sample analysis. The results of the various approaches were compared with each other for a quality control check. The sampling and analyses methodologies are documented in SAND90-7011 and have demonstrated that the requirements were adequate to meet the objectives.

6.7.6.2. Validity of Assumptions

No assumption is explicitly given in the Parameter Package. The parameter value of 0.11 is the median value based on the borehole average values from the 13 boreholes. The reason for using a constant rather than a distribution, given in the Parameter Package (WPO 37226), is that "there is a relatively small range to the data with a few outliers."

Using the borehole average as the basis for development of the parameter is reasonable because the parameter used in SECOTP represents the tortuosity of the entire thickness of the Culebra. Particularly, there exists great vertical variability of tortuosity, as demonstrated by the 21 core samples from borehole H-19b4, ranging from 0.017 to 0.203. However, the borehole average tortuosity values from the other boreholes, except H-11, are based on single sample results. Thus, they may not be a reasonable representation of the borehole average at those locations.

Two borehole average values out of 13 are considered representative. One is borehole H-19b4, with 21 core samples, and the other is borehole H-11, with four core samples. The borehole average values are

0.11 and 0.09 for H-11 and H-19b4, respectively. By reviewing these two values, the selected parameter value of 0.11 is considered at least representative of the borehole average along the flow pathway from the repository to the WIPP boundary.

In summary, the assumption that the parameter was derived from the borehole average is a good intended assumption, but it was not supported by a sufficient data base. Nevertheless, through comparison of the selected value to the borehole average values along the pathway, the tortuosity of 0.11 is considered acceptable.

6.7.6.3. Alternate Interpretation

There are alternate interpretations of tortuosity. One of them is based on correlation analysis between tortuosity and matrix porosity. The correlation analysis between tortuosity and porosity is shown in Figure 4.16 (SAND90-7011). There is a general trend of increasing tortuosity with increasing porosity. The estimation of the formation factor uses Archie's equation

$$F = 1.0 / \phi^{2.13} \tag{2}$$

where the power of 2.13 represents the cementation factor, which is obtained based on the data. Figure 4.17 (SAND90-7011) plots the formation factor values determined from electrical-resistivity measurements and determined by using Eq. (2). It has an R^2 of 0.77 for the linear regression, which indicates that there is some correlation between porosity and tortuosity. Tortuosity is also related to the distribution of pores in the sample. If the porosity values of two samples are the same, but the distribution of the grain sizes are different, the tortuosity values may be different. The value of tortuosity should be smaller for the non-uniform grain size sample than for the uniform grain size sample.

If Eq. (2) is substituted into Eq. (1), an alternative approximation of the range of tortuosity of 0.07 to 0.21 will be obtained based on the range of porosity of 0.10 to 0.25 (Section 6.7.5). Since the number of samples for porosity is much larger, and the distribution of porosity is much more representative (Section 6.7.5), estimated tortuosity based on the data base of porosity may be an alternative interpretation, but not necessarily a better interpretation.

6.7.6.4. Uncertainty and Consequences

The estimation of the Culebra tortuosity appears to involve some uncertainties. This can be demonstrated by Figure 4.15 (SAND90-7011), the relative frequency histogram for calculated tortuosity values, which does not provide a continuous distribution. The uncertainties may be associated with many factors, including but not limited to the following: (1) the number of samples is not large enough, (2) measurement of electrical resistivity of porous medium may not be accurate enough, and (3) the indirect approaches involve approximations.

The associated uncertainty of the estimated tortuosity is not considered to have significant impact on model SECOTP in the PA. The importance of tortuosity is less significant than the other three parameters in model SECOTP. Particularly, tortuosity is used with matrix block length and free-water diffusion coefficient to calculate the characteristic diffusion time (SAND92-1579, p. 5-47). The effect of variation in matrix block length on diffusion time will be much greater than the effect of variation in tortuosity. Thus, the uncertainty associated with tortuosity is not critical.

6.7.6.5. Appropriateness and Limitations of Methodology and Procedures

The methodology and processes for the measurement of the Culebra tortuosity were documented in detail in SAND90-7011. They are considered appropriate in support of the characterization of the physical properties of the formation, and adequate for the intended use of the parameter.

Specifically, different approaches were used to cross-check the results. Three approaches were used to estimate tortuosity, including the electrical resistivity method using Eq. (1), Archie's equation using Eq. (2), and the diffusion studies. Evaluations for the results from these three approaches were conducted. Differences in the estimation of formation factor values from the electrical resistivity method and diffusion studies were attributed to dead-end pore space, constrictivity, and grain-to-fluid interface phenomena. Since the samples used in the diffusive studies are somewhat biased to the low porosity side, it was difficult to make meaningful conclusions. Results of the comparison indicate that the estimates of tortuosity involve some uncertainties, which appear to be due to the limitations of the approach.

6.7.6.6. Adequacy of Application

In model SECOTP, the Culebra tortuosity is treated as a constant, even though the measurement results of core samples indicate that tortuosity values vary significantly vertically and horizontally. The application of tortuosity as a constant is acceptable considering the relatively small impact of the variations of the parameter in the model simulations. However, treating tortuosity as a constant may potentially result in an increase of uncertainty in the matrix block length in simulations of tracer test breakthrough curves. An increase of matrix block length increases diffusion time, which resembles the effect of a decrease in tortuosity (not equivalent in magnitude).

6.7.6.7. Accuracy of Calculations

All the calculations to estimate the borehole average tortuosity and its distribution were performed under a qualified QA program. Therefore, the accuracy of calculations are judged to be assured.

6.7.6.8. Validity of Conclusions

The estimated average Culebra tortuosity of 0.11 provided in the Form 464 (WPO 38345, entered 6/11/96) is adequate for the intended use.

6.7.6.9. Dissenting Views

None.

7.0 CONCLUSIONS

The Panel carefully reviewed the 32 parameter packages and the related parameter values submitted for peer review. Each is considered in Sections 4 through 6. The reader is referred to the individual conclusions in the appropriate sections for details of qualification information on each parameter.

As an overall summary:

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

Salado

☐ DRZ Compressibility	(Section 4.1)
☐ Undisturbed Halite Pressure	(Section 4.2)
☐ Undisturbed Halite Compressibility	(Section 4.3)
☐ Undisturbed Halite Porosity	(Section 4.4)
☐ Undisturbed Halite Permeability	(Section 4.5)
☐ Undisturbed Anhydrite Pressure	(Section 4.6)
☐ Undisturbed Anhydrite Compressibility	(Section 4.7)
☐ Brine Salt Mass Fraction	(Section 4.8)
☐ Brine Viscosity	(Section 4.9)
☐ Brine Density	(Section 4.10)
☐ Brine Compressibility	(Section 4.11)

Castile

☐ Castile Brine Reservoir Rock Compressibility	(Section 5.1)
☐ Castile Brine Reservoir Porosity	(Section 5.2)
☐ Castile Brine Reservoir Pressure	(Section 5.3)
☐ Castile Brine Reservoir Permeability	(Section 5.4)
☐ Castile Brine Reservoir Volume	(Section 5.5)

Units Above the Salado

☐ Non-Salado Effective Porosity	(Section 6.1)
☐ Non-Salado Pressure	(Section 6.2)
☐ Non-Salado Permeability	(Section 6.3)
☐ Culebra Permeability	(Section 6.4)
☐ Climate Index	(Section 6.5)
☐ Culebra Thickness	(Section 6.6.2)
☐ Culebra Storativity	(Section 6.6.3)
☐ Culebra Fluid Density	(Section 6.6.4)
☐ Culebra Steady-State Freshwater Heads	(Section 6.6.5)
☐ Culebra Dolomite Grain Density	(Section 6.7.1)
☐ Effective Culebra Thickness	(Section 6.7.2)

☐ Advective Porosity (Section 6.7.3)
☐ Half Matrix Block Length (Section 6.7.4)
☐ Diffusive Porosity (Section 6.7.5)
☐ Diffusive Tortuosity (Section 6.7.6)

The conclusions with regard to the remaining parameters are:

☐ Culebra Transmissivity Data (Section 6.6.1)

The transmissivity value interpreted for one well (P-18) was found to be inadequate. This value is one of 43 values used to determine the transmissivity fields.

The interrelations among the many parameters involved with the natural barriers and the complexity of developing data packages and Forms 464 became very evident during the Panel's work. In view of the large number of parameters, and in some cases very limited data, the Panel concluded that SNL's investigators performed remarkably well. As noted above, nearly all parameters proved to be adequate for the intended use. This surely reflects the overall competence of the SNL staff, whether working under an approved QA plan or not. The Panel commends them for their work.

8.0 SIGNATURES

I, by signature, hereby affirm that to the best of my knowledge and belief the findings and conclusions of this Natural Barriers Peer Review Report presents a true and accurate evaluation of the parameters reviewed and I concur with these findings and conclusions within the areas of assignment and expertise.

Darrel E. Dunn Ph.D.
NB Panel Chairman
Hydrogeology

M

Florie Caporuscio, Ph.D.
NB Panel Member
Geology

Paul L. Cloke

Paul L. Cloke, Ph.D.
NB Panel Member
Geological Sciences

David A. Sommers, Ph.D.
NB Panel Member
Hydrogeology

Charlie A. Wilson

Charlie Wilson, Ph.D.
NB Panel Member
Hydrogeology

Chuan-Mian Zhang, Ph.D.
NB Panel Member
Ground Water Hydrology

9.0 PEER REVIEW MEMBERS AND ACCEPTABILITY

Darrel E. Dunn, Panel Chairman, is an independent consultant in hydrogeology with 38 years of experience. He has a Ph.D. in geology from the University of Illinois, Urbana; and is a registered professional geologist in Wyoming. Relevant education includes graduate credit in hydrogeology, petroleum reservoir engineering, engineering geology, stratigraphy, sedimentation, sedimentary petrology, clay mineralogy, mathematics, and statistics. Relevant experience includes five years of petroleum work involving supervision of oil well drilling, drill stem testing, coring, and borehole geophysical log interpretation. He has taught advanced hydrogeology courses at Montana State University, and the University of Toledo, Ohio. Dr. Dunn has been involved in finite-difference modeling of ground water and vadose systems since 1967 and has performed pumping tests and analyzed the data for a wide range of aquifer types and transmissivities. He has developed Fortran codes for finite-difference modeling and other hydrogeologic applications. He has been heavily involved in nuclear waste disposal since 1988. Nuclear work has included modeling uranium transport using SWIFT III at the DOE Feed Material Production Center, Fernald, Ohio; pumping tests and finite-difference ground water flow and transport modeling at the DOE Rocky Flats Site, Golden, Colorado; and analytical ground water solute transport modeling at Hanford and the Idaho National Engineering Laboratory.

Florie Caporuscio, Panel Member, majored in geology at the University of Massachusetts (Amhurst) where he graduated with a B.S. in 1977. He then completed his M.S. in geology/chemistry at Arizona State University in 1980. Following three years of work as a staff geologist at Los Alamos National Laboratory on the Yucca Mountain Project, he went to the University of Colorado for a doctorate. The Ph.D. was completed in 1988 in geology and a one-year post-doctoral fellowship in Italy followed. While at the Universite de Paris, Dr. Caporuscio pursued crystallographic studies to characterize trace radioactive element substitution in major mineral phases. He is a geochemist with 12 years of experience in high level and transuranic radioactive waste disposal, with primary responsibilities in the characterization of ash flow tuffs, their alteration products, and the technical analysis of bedded salt deposits. He has also worked in the fields of low level radioactive and mixed waste contamination, remediation and disposal. He has demonstrated efficient management of projects from inception to completion, and effective liaison with Federal, state, and local government agencies to enhance projects, inform the public, and meet environmental standards.

Paul L. Cloke, Panel Member, has 42 years of post-Ph.D. experience in geological science. Dr. Cloke majored in geological sciences, including most courses required of chemistry majors, at Harvard College, graduating with an A.B., Magna cum Laude, in 1954. He majored again in geological science at

Massachusetts Institute of Technology with a doctoral minor in mathematics to earn his Ph.D. in 1954. Following a few years working for the Anaconda Company, he returned as a post doctoral fellow in geochemistry at Harvard University from 1957 to 1959. Much of his experience has dealt with geochemistry and economic geology, but for the past eleven years has focused on problems in the disposal of nuclear wastes. This includes interfaces among hydrology, geochemistry, waste package design, climate modeling, and performance assessment. Frequent participation as a technical specialist on quality assurance audits involved most of those areas of investigation. For about five years he worked in performance assessment departments, first on the former U.S. Department of Energy Salt Repository Project and later on the Yucca Mountain Site Characterization Project. The former also involved significant interaction with the West German nuclear waste disposal program and to some extent with the Waste Isolation Pilot Plant program. For nearly three years he managed the Scientific Investigation Support Department under the Technical and Management Support Service Contract between Science Applications International Corporation and the U.S. Department of Energy. This Department dealt mostly with hydrology, geochemistry, and general geology (e.g., economic, field mapping). During the past two to three years, especially, he has had significant interactions with European nuclear waste programs (Germany, Switzerland, Sweden, Spain, Great Britain) as well as the Canadian and Japanese programs. Thus, he has had extensive experience in applying chemistry, computing, physics, and mathematics to solving geologic and nuclear waste management problems. Dr. Cloke has managed and overseen numerous projects ranging from neutron activation and gas chromatographic analyses to field sampling and analysis of lake sediments and modeling of evaporative lakes. He has wide knowledge of metallic and non-metallic commodities and how they are processed to manufacture end products. He also has considerable experience in designing and writing waste management plans.

David A. Sommers, Panel Member, is an independent consultant based in Newport Beach, California. Dr. Sommers has a Ph.D. in Geology from the University of Massachusetts, an M.S. in Geology from the University of Rochester, and a B.A. in Geology from the University of Cincinnati. He has over 30 years of experience as a professional hydrogeologist, with registration in several states, and certification by the European Federation of Geologists. His professional experience has involved hazardous waste site evaluations, soil and ground water remediation, industrial and municipal ground water supply development, mine dewatering and environmental site assessments/characterizations of industrial and commercial properties, and managing QA/QC functions spanning a broad range of investigative, engineering, and design efforts. Dr. Sommers served on the NRC/NAS Committee on Ground Water Resources and Coal Mining and is frequently retained as a technical expert to support litigation and provide expert testimony. Dr. Sommers has been involved in nuclear-related projects since 1971. He directed the hydrology studies for the PSARs for three planned nuclear power plants, was a member of a team completing the GEIS for planned nuclear waste repositories, completed the hydrology investigations for two uranium mills in Utah and Wyoming, conducted dewatering studies for a planned underground uranium mine in New Mexico and completed feasibility studies for *in situ* mining of uranium in Colorado and Washington. Since 1995, Dr. Sommers has been an independent reviewer for DOE/WIPP-IRT and DOE/WIPP-PRP.

Charles Wilson, Panel Member, is responsible for managing a broad range of projects involving hydrogeology and geotechnical engineering, water resources planning, and environmental contamination. Activities within these projects have addressed such specialized topics as designing and conducting large-scale hydrologic tests in very low permeability, fractured rock, design and regulatory permitting of large mixed radioactive/hazardous waste landfills; development of a national water resources planning agency for the Republic of the Philippines; and design of a sitewide ground water monitoring system for the U.S. Department of Energy's Idaho National Engineering Laboratory. His broad expertise and extensive experience combine to provide innovative solutions to difficult technical problems.

Chuan-Mian Zhang, Panel Member, has a Ph.D. from the Civil Engineering Department of Colorado *State University. She has more than 10 years of experience in surface water and ground water hydrology,* including hydrogeology and contaminant transport, ground water and watershed modeling, conjunctive use of surface water and ground water, water resources management, statistic applications in hydrology and soil and water quality assessment, and geochemical analysis. She has completed numerous surface water and ground water investigations under various conditions, using analytical or numerical models. She has developed innovative quantifiable numerical or analytical approaches or tools to address practical problems and meet specific project needs. Recent work has included extensive involvement at Rocky Flats, one of DOE's environmental investigation sites. The work at Rocky Flats includes ground water and contaminant transport modeling, surface water and sediment transport modeling, hydrogeologic analyses, statistical background comparison of chemical and geochemical data, and geochemical analyses.

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SAND96-0561, "Modeling Brine Inflow To Room Q: A Numerical Investigation of Flow Mechanisms," Abstract. G.A. Freeze, T.L. Christian-Frear. Sandia National Laboratories: Albuquerque, NM. 1996.

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Determination of Peer Review Member Independence Form

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

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

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

10/88 - 9/90; Fernald, Ohio; IT Corp; Hydrogeologist; Groundwater modeling

9/90 - 2/96; Denver, CO; AST; Hydrogeologist; Geology, hydrology, groundwater modeling, project management

1/93 - 7/93; Albuquerque, NM; AST; Hydrogeologist; Well Parameter Review, Technical Support Group QA

7/93 - 3/94; Richland, WA; AST; Hydrogeologist; Hanford Remedial Action EIS

2/95 - 9/95; Albuquerque; AST; Hydrogeologist; WIPP Independent Review Team QA

1/91 - 5/91; Idaho Falls, ID; AST; Hydrogeologist; Groundwater Modeling

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

If yes, describe involvement.

M

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: Daniel E Dunn

Date: 4/23/96

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

Determination of Peer Review Member Independence Form

Yes — Currently employed by DOE or DOE Contractor? Yes/No

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

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

4/96 Informatics, Albuquerque NM, staff consultant
Peer Review of WIPP

8/93 – 3/96 Advanced Sciences Inc, Los Alamos Office, Project
Manager and Senior technical Lead, Environmental Restoration
Project

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

If yes, describe involvement.

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

Signature: Florie A Caporuscio

Date: 4/1/96

Peer Review Manager Approval: John A. Thies — Date: 4-1-96

Paul Cloke

Determination of Peer Review Member Independence Form

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

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

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

1985 - 1988 Battelle Memorial Institute under contract to DOE Salt Repository Project (HLW). Advice to DOE + management of subcontracts, mostly for geochemistry

1988 - 1995 Science Applications International Corporation - similar to above. Numerous audits or (quality assurance) of contractor work. - See resume

1993 - Served as consultant on review panel for data used for performance assessment of WIPP site. Subcontract from ASI to SAIC.

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: Paul F. Cloke

Date: May 10 1996

Peer Review Manager Approval: John A. Thies   5/14/96 Date

Determination of Peer Review Member Independence Form

NO Currently employed by DOE or DOE Contractor? Yes/No

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

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

July & August 1995 Sandia Nat Labs in Albuquerque, NM as member of the Independent Review Team for Advanced Sciences, Inc. as expert hydrogeologist reviewing data packages for shaft hydrology studies

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: David A. Sommers (DAVID A. SOMMERS, Ph.D.)

Date: April 24, 1996

Peer Review Manager Approval: J A Thies
John A. Thies

4/25/96
Date

Determination of Peer Review Member Independence Form

____ Currently employed by DOE or DOE Contractor? Yes/No

x Employed by DOE or DOE Contractor previously? [✓ Yes]/No

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

1978 - 1983 U. of California Lawrence Berkeley Laboratory - Performed field hydrology study of Hanford Site

1983 - 1985 Hydrotechnique Inc, Berkeley CA - Performed consulting services to Hanford Site

1986 - 1996 Golder Associates Inc - Albuquerque NM - Performed consulting services to Hanford, INEL, Los Alamos Sites

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

If yes, describe involvement.

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

Signature: Charles R. Wilson

Date: 3/29/96

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

Chuan-Mian Zhang

Determination of Peer Review Member Independence Form

NO Currently employed by DOE or DOE Contractor? Yes/No

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

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

During 1993 – 1995. Work for Rocky Flats for EG&G.

Performed Groundwater modeling, Surface water modeling, Hydrogeologic analysis, and statistical analysis work for operable unit No. 2 and No 6.

Work was performed during my employment with WCFS at Denver.

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

If yes, describe involvement.

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

Signature:

Date: 5/11/96

Peer Review Manager Approval: John A. Thies 5/14/96

Date