Impact of Proposed Disturbed Rock Zone Conceptual Model Modifications to the Waste Isolation Pilot Plant Performance Assessment—8090

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ABSTRACT

The United States Department of Energy (DOE) and Sandia National Laboratories (SNL) have recently proposed a set of updates that integrate data from recent site characterization studies to two conceptual models for the Waste Isolation Pilot Plant's Performance Assessment (WIPP PA) program. This paper discusses the changes to the Disturbed Rock Zone (DRZ) model, which describes the macroscopic manifestation of grain-scale microcracks and larger macrocracks that are created by induced stresses in the salt surrounding excavations. The DRZ, as modeled in WIPP PA, is an important component of the repository system because its properties affect the quantity of available brine and its ability to enter the waste areas as well as the connectivity of panels after closure. The DOE and SNL have proposed decreasing the region that represents the DRZ in WIPP PA. Additionally, it has been proposed to make the permeability of DRZ a time-dependent quantity to reflect the long-term behavior.

In this paper, the implementation of the proposed DRZ model changes is outlined, and the impact of the DRZ modifications on the long-term performance of the WIPP is discussed. The DRZ modifications generally reduced the amount of brine that entered into the repository, as well as reduced the pressure in the repository, except for scenarios in which a pressurized brine pocket was encountered. Overall, the saturation and pressure changes affected the frequency and magnitude of the direct brine and spallings volumes.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is located in southeastern New Mexico and operated by the U.S. Department of Energy (DOE) as a disposal facility for transuranic (TRU) waste. The WIPP must comply with various environmental regulations, including 40 CFR 191, Subpart B, *Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, and 40 CFR 268.6, *Petitions to Allow Land Disposal of a Waste Prohibited Under Subpart C of Part* 268. These regulations require a risk analysis of releases of WIPP waste due to inadvertent human intrusion into the repository during the 10,000-year regulatory period. Sandia National Laboratories (SNL) conducts performance assessments (PAs) of the WIPP using a system of computer codes in order to demonstrate compliance with these regulations. The current WIPP PA technical baseline consists of twenty-four peer-reviewed conceptual models that were developed and selected by DOE through its scientific advisor, SNL.

One of the conceptual models in the WIPP PA is the Disturbed Rock Zone (DRZ) model, which describes the macroscopic properties resulting from the manifestation of microcracks and larger macrocracks that are created by induced stresses in the salt surrounding excavations and by redistribution of stresses around the opening. The DRZ is the region of the halite in the Salado Formation surrounding the WIPP repository that has been damaged by excavation. As a result of the damage, the permeability and porosity of the DRZ is greater than that of the surrounding intact halite. This leads to greater availability of brine within the repository, which can lead to increased dissolution of radionuclides into the brine, and elevated probabilities of releases to the environment through direct brine releases (DBR).

The method for the DRZ currently implemented in WIPP PA accounts for the initial change in DRZ properties as a result of excavation. However, no further evolution of the DRZ is incorporated, although it is well-known that the damaged halite will continue to change over the 10,000 year period analyzed by WIPP PA. The halite will eventually reach a post-damage steady-state with a permeability in between the permeabilities of the original halite and the elevated permeabilities associated with the damaged state. A new model for the permeabilities which accounts for this long-term steady state in WIPP PA is introduced.

This paper is one of a series of papers describing proposed changes for Waste Isolation Pilot Plant performance assessment calculations as summarized in Nemer et al. [1]. In the present paper, the impact of the proposed changes on the permeability of damaged halite in the Disturbed Rock Zone around the WIPP repository is discussed. The following section briefly outlines the history and current implementation of the permeability in WIPP PA, as well as the proposed model linking permeability to dilatant strains. Details of its implementation in WIPP PA are then presented. Finally, its effect on major output parameters in the brine and gas flow (BRAGFLO) models used to characterize repository performance as well as the DBR and spallings model results is shown.

PERMEABILITY

History of the DRZ Permeability Parameter in WIPP PA

The Compliance Certification Application (CCA) submitted by US DOE, in which DOE demonstrates that the radionuclide releases from the WIPP repository are below thresholds stated in 40 CFR 191, defined two different distributions for the permeability of intact and disturbed halite in the Salado Formation. The permeability of intact halite was selected from a log-uniform distribution with minimum 10^{-24} m^2 and maximum 10^{-21} m^2; the median of this distribution was $10^{-22.5}$ m^2. Disturbed halite was assumed to have a constant permeability of 10^{-15} m^2.

Between the submission of the CCA and the completion of the Performance Assessment Verification Test (PAVT), a later set of PA calculations whose results were used to establish the baseline for WIPP performance assessment, the U. S. Environmental Protection Agency (EPA) instructed that the values of several parameters, including the permeability, be changed [2]. The range chosen by the EPA is the model found in both the PAVT and the 2004 Compliance Recertification Application (CRA-2004) Performance Assessment Baseline Calculations (PABC). Following repository closure, the disturbed halite permeability is now represented by a randomly-sampled parameter, whose value is drawn from a log-uniform distribution with a minimum value of $10^{-19.4}$ m^2 and a maximum value of $10^{-12.5}$ m^2, derived from in situ permeability measurement.

After emplacement of waste in a panel has been completed, a panel closure system (PCS) will be installed as a mechanism to isolate the waste panels from one another and from the environment. The original model for the PCS, proposed by the DOE in the CCA, is shown in Fig. 1. Moving away from the waste panel, the PCS consists of an explosion-isolation wall, an isolation zone, and a concrete barrier (or monolith). In the PA model, these are treated as additional materials with their own properties, including permeability. The disturbed rock zone over the PCS, which is expected to heal with time, is treated as a separate material, DRZ_PCS, with a permeability range of $10^{-20.7}$ to $10^{-17.0}$ m^2. The proposed changes to the DRZ model do not affect the properties of the panel closure system, specifically the permeability of the DRZ above the PCS.

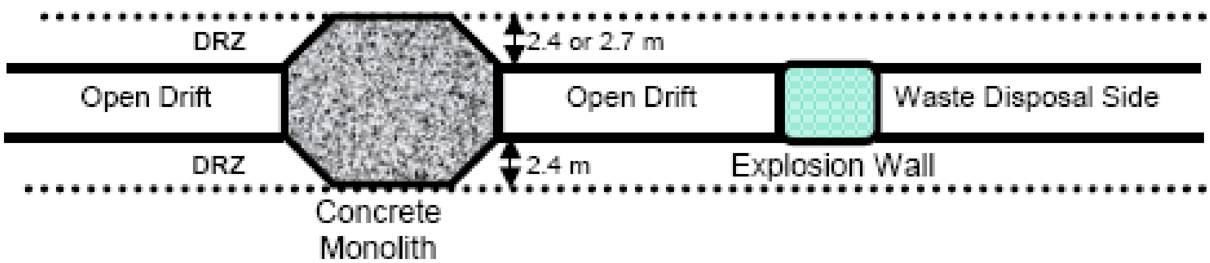

Fig. 1. Panel Closure System (PCS) proposed by the DOE in the CCA for use in the WIPP repository.

It should be noted that the PCS illustrated in Figure 1 may be substantially different from the PCS that will actually be installed in the WIPP repository. DOE is currently implementing a program which will monitor the concentration of hydrogen and methane gases in the repository. Provided that the concentrations of these gases remain well below their respective flammability limits, it may not be necessary to construct explosion walls. Instead, it may be possible to replace the PCS shown in Fig. 1 with a steel bulkhead and 100 feet of mined salt. The data obtained from the monitoring program will be used to determine which system will be used.

Peach Model for Permeabilities

One of the goals of the proposed revisions to the DRZ is to define a new relationship for the permeability as a function of dilatant strain, and to make the permeability more time-dependent. Chan and co-workers [3] created a model relating permeability both to strain and to networked porosity. The Chan model is a combination of the Carman-Kozeny model of porosity-based permeability [4] and the theoretical work of Peach on the permeability of damaged salt [5]. Peach uses percolation theory arguments to define the dilatant strain ε as

$$\varepsilon = \frac{2\pi \langle c \rangle^2 \langle w \rangle \alpha}{\langle l \rangle^3} \qquad \text{(Eq. 1)}$$

where $\langle c \rangle$ is the mean crack radius, $\langle w \rangle$ is the mean crack half-width, α is a volumetric shape factor, and $\langle l \rangle$ is the mean crack spacing. The overall expression for the permeability is given by

$$k = \frac{2}{15}\langle w\rangle^2 \varepsilon \alpha p^* \qquad \text{(Eq. 2)}$$

where p^* is the fraction of cracks that are part of a connected network. Using the linear relationship between dilatant strain ε and mean crack half-width $\langle w \rangle$, the relationship between permeability and strain can be written as

$$k = \frac{p^* \langle l\rangle^6}{30\pi^2 \alpha \langle c\rangle^4} \varepsilon^3 \qquad \text{(Eq. 3)}$$

Rather than attempting to evaluate the prefactors in the above expression, Chan and co-workers [3] treat the prefactor as a fitting parameter C_p to be estimated using nonlinear regression of experimental data, so that the permeability can be written as

$$k = C_p \varepsilon^3 \qquad \text{(Eq. 4)}$$

Thus, dilatant strain rates can be compared with permeabilities by determining the parameter C_p, which will vary between materials. Several studies carried out on WIPP salt have evaluated C_p; the resulting value is found to be 2.13×10^{-8} m^2 [6]. It should be noted that the Peach model for permeabilities has a phenomenological derivation; there have been few *in situ* studies to measure the relationship between strains and permeabilities.

IMPLEMENTATION

DRZ Extent

Field measurements, laboratory observations, numerical modeling, and operational experience since the CCA show that the extent and permeability of the DRZ can be better represented in WIPP PA. Still, DOE and SNL acknowledge that there are uncertainties that affect the extent of the DRZ and the rate at which healing will occur, so the scoping calculations will continue to model the DRZ in a conservative manner.

Sonic velocity data was used to define the onset of healing in the DRZ, which was then incorporated into PA fluid flow simulations. The details of this procedure are discussed by Park and Herrick [7]; the resulting analysis indicates that the DRZ extends below the room to Marker Bed 139, above the room up to anhydrite “a,” and roughly 2 m from either side of the room. The DRZ extent is implemented in WIPP PA in the BRAGFLO code, which is a numerical model that simulates the simultaneous flow of immiscible fluids through porous media in one, two or three dimensions. BRAGFLO calculates brine and gas flow within and surrounding the repository incorporating the effects of disposal room closure, gas generation, brine consumption and inter-bed fracturing in response to gas pressure. The grid in the BRAGFLO calculations includes the DRZ extent.

Stratigraphy varies by location around the repository, so Ismail and Park [8] considered more than one option. Munson et al. [9] indicate that the location of anhydrite “a” is 4.74 m above the roof of the waste room, while Christian-Frear and Webb [10][1] estimate that the distance from the roof through anhydrite "a" is 5.03 m. In keeping with the CCA Conceptual Model Peer Review Panel's recommendation to model the DRZ in a conservative manner, the upper DRZ was assigned to extend 5.03 m above the waste room in the BRAGFLO grid (Fig. 2).[2] No changes are recommended for modeling the extent of the lower DRZ. Table I summarizes the DRZ extent modeling changes for the scoping calculations, and Fig. 2 shows the BRAGFLO grid that includes the revised DRZ dimensions and was used for the scoping calculations described in Nemer et al. [1] compared with the CRA-2004 PABC grid.

Table I. DRZ extent in the BRAGFLO grid.

	Analysis	Location
Upper DRZ	CRA-2004 PABC	0 to 11.95 m above the panel roof
	Scoping Calculations	0 to 5.03 m above the panel roof
Lower DRZ	CRA-2004 PABC	0 to 2.23 m below the panel floor
	Scoping Calculations	0 to 2.23 m below the panel floor

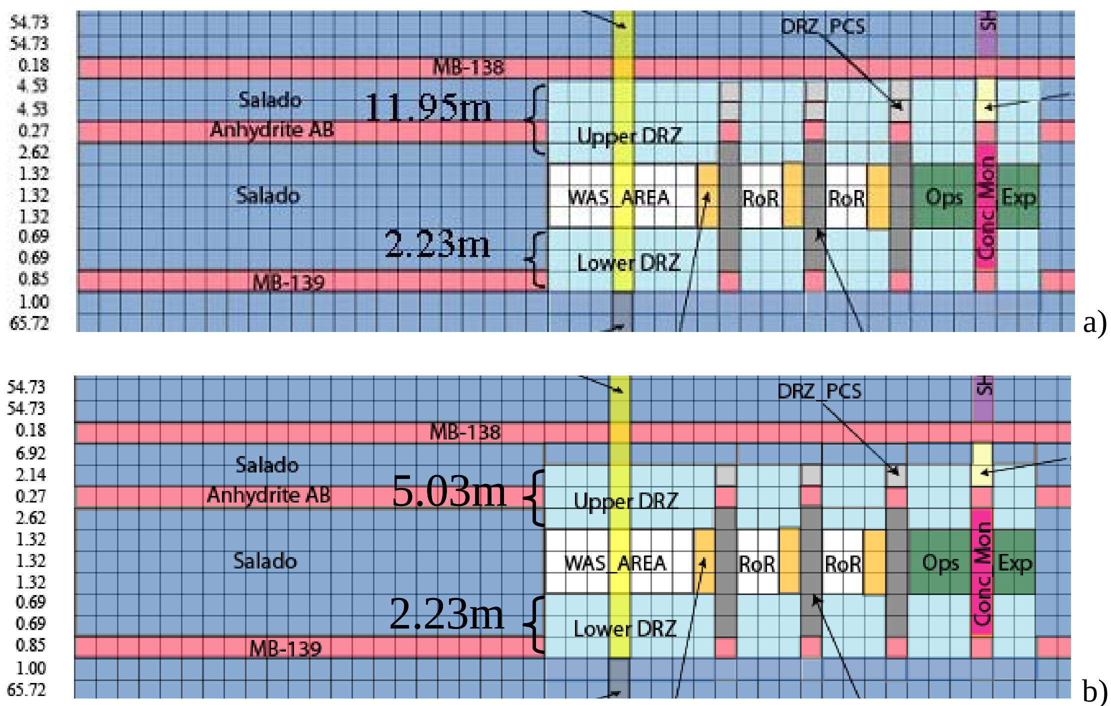

Fig. 2. DRZ modeling for the a) CRA-2004 PABC and the b) scoping calculations, DRZ extent in the BRAGFLO grid. (Scale on left side indicates cell height in meters.)

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[1] The figure in Appendix A of Christian-Frear [10] indicates that anhydrite "a" lies 5.03 m about Clay Seam F. Christian-Frear and Webb [10] use Clay F to approximate the roof of the waste rooms (Table 1 and Appendix C).

[2] The DRZ extends past anhydrite "a" in the BRAGFLO grid because the simplified startigraphy model that the grid uses models anhydrite layers "a" and "b" as a single anhydrite bed and centers the composite bed on the anhydrite "b" location.

Changes to the Permeability Model

The current WIPP PA models assume that the permeability within the DRZ around the disposal rooms takes on a single, constant value for the entire 10,000-year time period studied in WIPP PA. However, it is known that healing will occur, changing a number of physical properties in the DRZ. This behavior in the PA models is accommodated by defining a new material, DRZ_2, which more accurately reflects the long-term behavior of the DRZ.

In addition to the extent of the DRZ, the range of permeabilities which will be used for DRZ_2, as well as the onset of steady-state behavior was determined. The first step of the analysis was to find the time at which no further dilatancy of the DRZ is expected. Park and Herrick [7] show the evolution of the dilatancy with time, where at $t > 200$ years, the dilatancy damage criterion no longer predicts a disturbed zone. This indicates very little change takes place after that time. Therefore $t = 200$ years is taken to be the point at which DRZ_1 is replaced by DRZ_2.

To calculate the permeability range, the strain distributions around the room were computed using the quasistatic, large-deformation finite element code SANTOS. Although SANTOS is nominally a two-dimensional code, we do not expect there to be significant differences between the two-dimensional and three-dimensional results, because of the large ratio between the room dimensions in the *z*-direction compared to the modeled *x*- and *y*-directions. Also, SANTOS currently implements the simpler MD model for calculating stresses as opposed to the more accurate MDCF model, which adds fracture growth to the MD model; however for stresses above 5 MPa, the discrepancies in the results obtained from the two models is only on the order of 3 percent [11]. The volumetric dilatant strains were then converted to permeabilities using the Peach model in Eq. 4, where the regression constant determined by Pfeifle et al. [6] is 2.13 x 10^{-8} m^2. The calculations were carried out for the minimum and maximum gas generation rates. The results were analyzed to determine the minimum and maximum permeabilities within the cells identified as DRZ.

Examining the permeability range obtained for the minimum and maximum gas generation rates, shown in Fig. 3, the maximum permeability in the DRZ at time $t = 200$ years after completion of excavation is 2.09 x 10^{-18} m^2, while the minimum permeability is 3.24 x 10^{-23} m^2. In practice, however, it is difficult to measure permeabilities below about 10^{-21} m^2; additionally, the permeability of intact halite, as currently implemented is from 10^{-24} m^2 to 10^{-21} m^2. Consequently, we assigned the maximum permeability of intact halite, 10^{-21} m^2, as the minimum value for the permeability of DRZ_2. (Although at 10,000 years after closure, the maximum observed permeability in the DRZ has decreased to $10^{-18.53}$ m^2, the maximum value at 200 years after closure is used to establish the overall range.) Since permeability is entered into the PA parameter database as a logarithmic quantity, the log of the permeability is treated as a uniform quantity, with maximum log (2.09 x 10^{-18}) = –17.68, and minimum log (10^{-21}) = –21.00. The resulting parameters are provided in Table II. The permeability range for DRZ_2 corresponds closely with the range used for the DRZ above the PCS ($10^{-20.7}$ to $10^{-17.0}$ m^2), with the main difference being the 200 year delay before the permeability of the DRZ is changed to the values for DRZ_2.

Table II. Properties of the DRZ_2 permeability parameter used in the scoping calculations.

Distribution	Loguniform
Units	m^2
Mean	$10^{-19.34}$
Median	$10^{-19.34}$
Minimum	$10^{-21.00}$
Maximum	$10^{-17.68}$

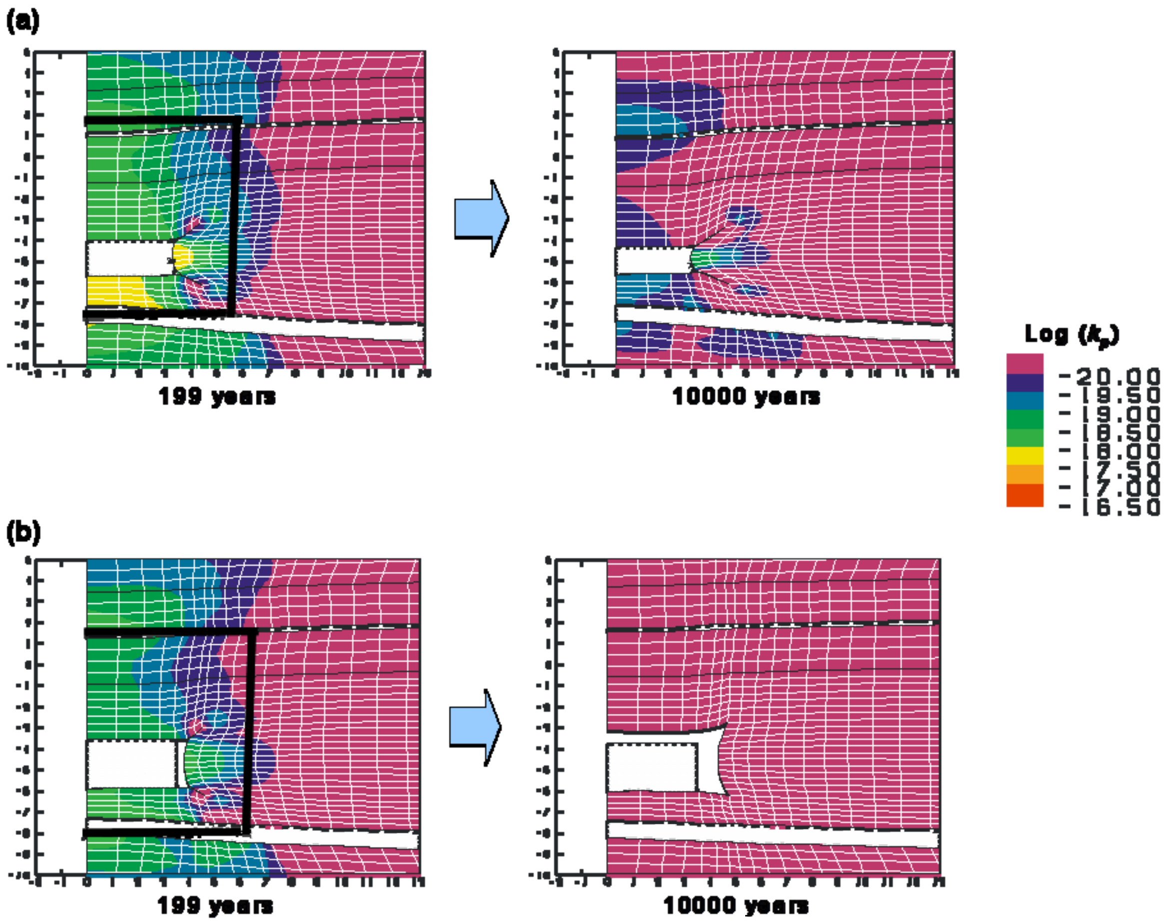

Fig. 3. Permeability of damaged halite in the Disturbed Rock Zone (DRZ) around the WIPP repository as a function of time for the (a) minimum and (b) maximum gas generation rates. Permeability represented on a logarithmic scale. Taken from Park et al. [12].

PA RESULTS

This section includes the results from the scoping calculations described in Nemer et al. [1]. The results from three sets of code calculations are compared with those from the CRA-2004 PABC. The DRZ modifications affect the calculation of the brine and gas flow in and surrounding the repository by the BRAGFLO code. The pressures and saturations calculated by BRAGFLO affect two release mechanisms, direct brine and spallings, which are described in Nemer et al. [1]. The results for the DBR and spallings release are discussed below.

Brine and Gas Flow

A full set of compliance calculations were completed for the scoping calculations, including BRAGFLO calculations with the DRZ modifications. The BRAGFLO results for scoping calculations are compared with the BRAGFLO results from the CRA-2004 PABC [13].

Five scenarios (S1-S5) considered in the BRAGFLO modeling, are used to calculate DBRs and spallings releases in the WIPP PA. These scenarios are the same as those used for the CCA, the PAVT, the CRA-2004 and the CRA-2004 PABC. The scenarios include one undisturbed scenario (S1) and four scenarios with a single drilling intrusion into the repository (S2-S5). Two types of intrusion are modeled: an E1 intrusion, which assumes the intrusion passes through both a waste panel and a pressurized brine pocket under the repository; and an E2 intrusion, which assumes the intrusion only passes through the waste panel. Scenarios S2 and S4 model the effect of an E1 and E2 intrusion at 350 years, respectively, while scenarios S3 and S5 model the effect of an E1 and E2 intrusion at 1,000 years, respectively. This is shown below in Table III.

Table III. Scenarios used in BRAGFLO calculations.

Scenario	# of Drilling Intrusions	Time of Intrusion (years)	Castile Brine Pocket Encountered	Intrusion Type
S1	0 (Undisturbed)	-	-	-
S2	1	350	Yes	E1
S3	1	1,000	Yes	E1
S4	1	350	No	E2
S5	1	1,000	No	E2

The BRAGFLO results are generally compared on a scenario basis. Three of the five BRAGFLO scenarios were selected for comparison in this paper to reduce the discussion and comparison while covering the main differences between scoping calculations and CRA-2004 PABC analyses. Analysis of the S1, S3, and S5 scenarios are sufficient to determine the effects on repository performance since the S2 and S4 scenarios repeat the S3 and S5 scenarios, but place the drilling intrusion at 350 years after repository closure. Thus, discussion and analysis of results presented herein focuses on the S1, S3, and S5 scenarios.

BRAGFLO calculates many quantities involving the brine and gas flow in and around the repository, incorporating the effects of disposal room closure, gas generation, brine consumption and inter-bed fracturing in response to gas pressure. The results of BRAGFLO are used as an input of the repository conditions for the DBR and spallings models, and the radionuclide transport into the marker beds or up the borehole to the Culebra, which all are sensitive to the waste panel saturation and pressure. The cellulose, plastic and rubber (CPR) degradation is a function of the waste panel saturation, and a major contributor for the waste panel pressure calculations. The waste panel saturation and pressure and the fraction of CPR consumed in the waste panel were chosen for comparison between scoping calculations and CRA-2004 PABC analyses, as these quantities determine DBR and spallings volumes.

Brine flow into the repository is a function of the surrounding material properties, such as permeability, porosity, pressure and saturation. The higher the permeability and pressure of the surrounding material, the faster the rate of brine inflow will be. A high porosity and saturation will provide more brine available for transport into the repository. The DRZ is one of the modeled features surrounding the waste area. Decreasing the extent of the DRZ will decrease the amount of brine available for transport into the repository, while the decrease in the DRZ permeability will slow the rate of brine flow from the DRZ into the repository. The DRZ modifications are expected to decrease the total amount of brine that flows into the repository from the DRZ. Realizations in which the majority of the brine enters the repository from the DRZ will have lower saturation levels, decreasing CPR degradation and pressure. Realizations where the majority of the brine enters the repository from sources other than the DRZ should not be greatly effected.

For the undisturbed S1 and the E2 intrusion S4 and S5 scenarios, the DRZ modifications were expected to decrease the saturation, pressure and CPR degradation in the waste panel, relative to CRA-2004 PABC levels. The average and 95th percentile of the waste panel saturation, fraction of CPR consumed and pressure at several times for the undisturbed scenario S1 and E2 intrusion scenario S5 are shown below in Table IV and Table V, respectively. As seen in Table IV and Table V, both the average and upper 95th percentile of the waste panel saturation decreased from the CRA-2004 PABC results to the scoping calculation results for all times. Table IV and Table V show both the average and upper 95th percentile of the fraction of CPR consumed in the waste panel decreased from the CRA-2004 PABC results to the scoping calculation results for both the S1 and S5 scenarios, except for the upper 95th percentile at 2,000 years for the S5 scenario. The decreased CPR degradation was caused by the lower saturations. The trend in CPR degradation is reflected in the waste panel pressure histories as well, since for the S1 and S5 scenarios, the pressure appears to be a function of the CPR degradation. As seen in Table IV and Table V, both the average and upper 95th percentile of the waste panel pressure decreased from the CRA-2004 PABC results to the scoping calculation results. The average pressure for the scoping calculation is lower than the CRA-2004 PABC results for the entire 10,000 years, while the upper 95th percentile pressure for the scoping calculation is higher than the CRA-2004 PABC at 2,000 years and lower or equal for the remaining times.

Table IV. Average and upper 95th percentile values of the waste panel saturation, fraction of CPR consumed and pressure for the scoping calculation and CRA-2004 PABC S1 (undisturbed) analyses [13].

		500 years		2,000 years		5,000 years		10,000 years	
		Average	95th	Average	95th	Average	95th	Average	95th
Saturation	Scoping	0.12	0.37	0.07	0.22	0.05	0.20	0.04	0.18
	PABC	0.17	0.49	0.11	0.45	0.08	0.35	0.08	0.32
Percent CPR Consumed	Scoping	3%	9%	8%	26%	14%	39%	18%	57%
	PABC	3%	10%	10%	31%	18%	62%	24%	69%
Pressure (MPa)	Scoping	4.3	6.9	7.9	12.7	8.9	14.0	9.3	13.8
	PABC	4.5	7.1	8.1	13.3	9.3	14.0	10.0	13.9

Table V. Average and upper 95th percentile values of the waste panel saturation, fraction of CPR consumed and pressure for the scoping calculation and CRA-2004 PABC S5 (E2 intrusion) analyses [13].

		500 years		2,000 years		5,000 years		10,000 years	
		Average	95th	Average	95th	Average	95th	Average	95th
Saturation	Scoping	0.12	0.37	0.17	0.76	0.19	0.82	0.23	0.83
	PABC	0.17	0.49	0.21	0.90	0.27	0.95	0.37	0.97
Percent CPR Consumed	Scoping	3%	9%	9%	36%	17%	52%	25%	84%
	PABC	3%	10%	10%	35%	20%	67%	29%	91%
Pressure (MPa)	Scoping	4.3	6.9	5.0	11.3	5.5	11.4	5.9	11.4
	PABC	4.5	7.1	5.2	10.8	5.9	11.3	6.4	11.9

For both the undisturbed scenario and the E2 intrusion scenarios, the DRZ modifications lowered the saturation in the repository, which decreased the CPR degradation and pressure. The lower saturation and pressure should decrease the amount of DBR and spallings releases. The DBR and spallings volumes are discussed below.

For the E1 intrusion scenarios S2 and S3, the DRZ modifications were expected to lower the saturation, pressure and CPR degradation before the intrusion and then have a small effect after the intrusion. The average and 95th percentile of the waste panel saturation, fraction of CPR consumed and pressure at several times for the E1 intrusion scenario S3 are shown below in Table VI.

Table VI. Average and upper 95th percentile values of the waste panel saturation, fraction of CPR consumed and pressure for the scoping calculation and CRA-2004 PABC S3 (E1 intrusion) analyses [13].

		500 years		2,000 years		5,000 years		10,000 years	
		Average	95th	Average	95th	Average	95th	Average	95th
Saturation	Scoping	0.12	0.37	0.58	0.92	0.52	0.87	0.54	0.88
	PABC	0.17	0.49	0.69	0.98	0.65	0.98	0.67	0.99
Percent CPR Consumed	Scoping	3%	9%	10%	39%	21%	61%	30%	88%
	PABC	3%	10%	11%	39%	24%	74%	35%	100%
Pressure (MPa)	Scoping	4.3	6.9	8.8	12.7	7.9	13.7	7.8	12.2
	PABC	4.5	7.1	8.5	12.2	8.0	12.4	8.1	12.4

As seen in Table VI, both the average and upper 95th percentile of the waste panel saturation decreased from the CRA-2004 PABC results to the scoping calculation results for all times. Table VI shows both the average and upper 95th percentile of the fraction of CPR consumed in the waste panel decreased from the CRA-2004 PABC to the scoping calculation analysis. The decreased CPR degradation for the scoping calculation results was caused by the lower saturations and can be seen throughout the entire 10,000 years. The average waste panel pressure is decreased from the CRA-2004 PABC results to the scoping calculation results except at 2,000 years, while the upper 95th percentile decreased from the CRA-2004 PABC results to the scoping calculation results at 500 and 10,000 years and increased at 2,000 and 5,000 years. The waste panel pressure is a strong function of the brine pocket pressure and with a decrease in available port space in the DRZ, due to the DRZ extent modification, the overall pressure of the system will increase once the brine pocket is intruded upon. This can be seen in the scoping calculation pressure results at 2,000 and 5,000 years. The lower CPR degradation for the scoping calculations allows the pressure to decrease below the CRA-2004 PABC levels by 10,000 years.

For the S3 scenario, the DRZ modifications lowered the saturation in the repository, which decreased the CPR degradation. The pressure is dominated by the pressurized brine pocket properties for the S3 scenario. The scoping calculation average DBR volumes for the E1 intrusion scenario should be similar to those calculated for the CRA-2004 PABC. As the spallings volumes are dominated by the upper 95th percentile pressures, the spallings volume should increase relative to those calculated for the CRA-2004 PABC. The DBR and spallings volumes are discussed below.

Direct Brine Release

DBR calculations were performed using the BRAGFLO results of the scoping calculation which incorporated the DRZ modifications. In this section, the DBR results of the scoping calculation analysis are compared with the CRA-2004 PABC analysis. Each analysis generated 7,800 separate results for all the vector, scenario, time, and location combinations. To compare the results, summary statistics for each analysis are shown in Table VII, including the number of non-zero, maximum and average DBR volumes for each scenario. Note that the scenario in Table VII represents the state of the repository when the intrusion occurs. That is, S1 indicates that there were no previous intrusions, and S2 indicates that there was a previous intrusion into a pressurized brine pocket at 350 years, etc. For consistency with the CRA-2004 PABC analysis, non-zero DBR volumes are defined as volumes that are greater than 10^{-7} m^3.

Table VII. Number of non-zero, maximum and average DBR volumes calculated by scenario for the scoping calculation and CRA-2004 PABC analyses [14]. The averages shown represent the average of the non-zero volumes.

Scenario	# of Non-Zero		Maximum (m^3)		Average (m^3)	
	Scoping	PABC	Scoping	PABC	Scoping	PABC
S1	34	57	3.76E–01	1.80E+01	2.46E–02	5.23E–01
S2	306	357	3.81E+01	6.89E+01	1.06E+01	1.26E+01
S3	212	237	3.34E+01	6.40E+01	6.49E+00	1.01E+01
S4	22	27	2.65E–01	1.41E+01	2.98E–02	8.02E–01
S5	33	43	1.01E–01	1.41E+01	1.43E–02	5.25E–01
Total/Max	607	721	3.81E+01	6.89E+01	1.06E+01	1.26E+01

As seen in Table VII, the number of non-zero DBR volumes in the scoping calculation in all scenarios decreased relative to the CRA-2004 PABC. The total number of non-zero DBR volumes for the scoping calculation analysis is approximately 84% of the CRA-2004 PABC total. The maximum DBR volume in the scoping calculation for scenarios S1, S4, and S5 decreased by approximately two orders of magnitude from the CRA-2004 PABC analysis (Table VII). For scenarios S2 and S3 the maximum DBR volume decreased from the CRA-2004 PABC levels by approximately 45% for the scoping calculation analysis. The maximum remained in the S2 scenario for all three analyses. Table VII shows that the average DBR volume in the scoping calculation decreased from the CRA-2004 PABC by an order of magnitude for the S1, S4 and S5 scenarios and by ~25% for scenarios S2 and S3.

The number of non-zero, maximum and average DBR volumes decreased in the scoping calculation analysis from the CRA-2004 PABC. The DRZ modifications decreased the DBR volumes, so normalized DBRs should decrease similarly.

Spallings Release

Using the BRAGFLO results of the scoping calculation which incorporated the DRZ modifications calculations of the spallings releases were performed. The spallings results of the scoping calculation analysis are compared with the CRA-2004 PABC analysis using summary statistics. Table VIII contains the number of non-zero spallings events, average of non-zero volumes, and maximum spallings volumes for each scenario. Note that the scenario in Table VIII represents the state of the repository when the intrusion occurs. That is, S1 indicates that there were no previous intrusions, and S2 indicates that there was a previous intrusion into a pressurized brine pocket at 350 years, etc.

The overall frequency of spallings events in the scoping calculation is quite similar to that observed the CRA-2004 PABC. Both analyses had approximately 450 non-zero spallings events (out of 7,800 calculations). Thirty-four of the CRA-2004 PABC vectors had spallings in at least one of the scenarios. That corresponds to thirty-nine of the scoping calculation vectors.

The number of non-zero spallings events in the S1 scenario decreased by approximately 22% from the CRA-2004 PABC to the scoping calculation analysis. This decrease can be explained by the moderate decrease for average S1 pressures in the waste panel. The maximum S1 spallings volume is identical for both analyses, but the average non-zero spallings volume was larger for the scoping calculation analysis. The frequency of non-zero S2 and S3 spallings events increased from the CRA-2004 PABC to the scoping calculation analysis. While the average S3 pressures in the waste panel were very similar between analyses, the upper 95th percentile of pressures in the scoping calculation was higher for most times after the borehole intrusion than the CRA-2004 PABC pressures. The increase in the extreme pressures led not only to more spallings volumes, but the maximum S3 spallings volume for the scoping calculation is approximately 59 % larger than the maximum S3 volume from the CRA-2004 PABC. The maximum scoping calculation S2 spallings volume is almost 68% larger than the corresponding CRA-2004 PABC volume. Furthermore, the average non-zero spallings volumes in the scoping calculation exceeded the corresponding CRA-2004 PABC volumes by the greatest amount in these scenarios. The spallings volumes frequency and maxima for the S4 and S5 scenarios are very similar for both analyses. The moderate impact that the DRZ modifications had on pressures in the waste panel did not appreciably affect these statistics for the S4 and S5 scenarios, but the average non-zero spallings volume did increase.

Table VIII. Spallings summary statistics by scenario for the scoping calculations and the CRA-2004 PABC [15]. The averages shown represent the average of the non-zero volumes.

Scenario	Statistic	Scoping	CRA-2004 PABC
S1	Maximum [m^3]	1.67	1.67
	Average [m^3]	0.509	0.416
	# of non-zero volumes	90	115
S2	Maximum [m^3]	14.0	8.33
	Average [m^3]	0.907	0.612
	# of non-zero volumes	121	117
S3	Maximum [m^3]	12.8	8.04
	Average [m^3]	0.773	0.571
	# of non-zero volumes	118	103
S4	Maximum [m^3]	1.61	1.67
	Average [m^3]	0.497	0.364
	# of non-zero volumes	52	52
S5	Maximum [m^3]	1.52	1.67
	Average [m^3]	0.578	0.456
	# of non-zero volumes	70	68
All Scenarios	Maximum [m^3]	14.0	8.33
	Average [m^3]	0.694	0.502
	# of non-zero volumes	451	455

Table IX lists the summary spallings statistics by drilling location. Spallings volumes in the scoping calculation follow similar trends related to drilling location that were observed in the CRA-2004 PABC. That is, spallings are most likely to occur for a lower drilling intrusion, and the largest spallings volumes occur for the same location. Spallings are less likely for middle and upper intrusions, and the maximum volumes for these intrusion locations are significantly less than the maximum volume associated with a lower intrusion.

Table IX. Spallings summary statistics by location for the scoping calculations and the CRA-2004 PABC [15].

Location	Statistic	Scoping	CRA-2004 PABC
L	Maximum [m^3]	14.0	8.33
	# of nonzero volumes	198	180
M	Maximum [m^3]	2.04	2.36
	# of nonzero volumes	129	145
U	Maximum [m^3]	1.61	2.36
	# of nonzero volumes	124	130

SUMMARY AND CONCLUSIONS

WIPP PA consists of twenty-four conceptual models that describe various features of the repository system. Following the certification, continued experiments and analyses have furthered the understanding of the repository system. Several aspects of WIPP PA that could be refined by incorporating the results of some repository investigations into PA models have been identified. Inclusion of the results of these analyses in WIPP PA models will result in a more accurate representation of the repository and better but still conservative predictions of the long term performance of the repository.

The DRZ that is expected to initially surround excavated areas is currently modeled in WIPP PA simulations with a conservatively large size. Additionally, this region is currently assigned a relatively high permeability (in comparison to intact salt) for the entire 10,000 year regulatory period. The DRZ was modeled in this manner since there are several uncertainties related to how the DRZ will evolve. In recent years, field measurements, laboratory observations, numerical modeling and operational experience has led to a better understanding of the DRZ, and these have been incorporated into numerical simulations to reassess the DRZ. Based on the results of these analyses, the DRZ extends 5.03m above the waste rooms instead of the 11.95m that the PA simulations currently use. Furthermore, the permeability of the DRZ decreases after 200 years to simulate the reconsolidation of the salt in the DRZ that is expected to take place during the 10,000 year regulatory period.

Scoping calculations that include these modeling changes have been conducted to assess the impact on the long term performance of the WIPP repository. Based on the results of these changes, the following has been observed:

- In general, modifying the DRZ caused brine saturation levels in the waste panel to decrease from CRA-2004 PABC levels.
- In scenarios where no pressurized brine pocket was encountered, modifying the DRZ characteristics generally caused pressures in the waste panel to decrease by a modest amount. When a pressurized brine pocket was intersected, average pressures were similar between the two analyses, but extreme high pressures (the upper 95th percentile) exhibited a transient increase from CRA-2004 PABC levels.
- The changes in brine saturation and pressures caused direct brine volumes to decrease in the frequency, maximum and average relative to the CRA-2004 PABC volumes.
- Increases in the maximum and average spallings volumes were caused by pressure increases due to the interaction of the brine pocket and reduced pore space in the DRZ.

ACKNOWLEDGEMENTS

This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy National Nuclear Security Administration under Contract DE-AC04-94Al85000.

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