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Carlsbad Field Office
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APR 1 7 2012

Mr. Jonathan Edwards, Director
Office of Radiation and Indoor Air
Radiation Protection Division
U. S. Environmental Protection Agency
Washington, D.C. 20460

Subject: Response to EPA Letter Dated December 22, 2011

Dear Mr. Edwards:

This letter is in reply to the Environmental Protection Agency's (EPA) December 22, 2011 letter regarding the first set of review questions and comments related to the Planned Change Request (PCR) for replacing the current "Option D" Panel Closure System (PCS) with an alternative design. In Enclosure 1 to this letter, the U.S. Department of Energy (DOE) Carlsbad Field Office (CBFO) is providing responses to EPA's questions. In addition, the DOE/CBFO is providing the references on compact disc, used in the responses (Enclosure 2).

If you have any questions, please contact Mr. Russ Patterson at (575) 234-7457.

Sincerely,

Jose R. Franco, Manager
Carlsbad Field Office

Enclosures (2)

cc: w/o enclosures

R. Lee, EPA	*ED
K. Economy, EPA	ED
S. Ghose, EPA	ED
J. Walsh, EPA	ED
T. Peake, EPA	ED
N. Elkins, LANL-CO	ED
P. Shoemaker, SNL-CPG	ED
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Enclosure 1

Responses to U.S. EPA Letter dated Dec 22, 2011

Responses to the review questions and comments contained in the U.S. Environmental Protection Agency (EPA) letter dated 22 December 2011 on panel closure properties in the Panel Closure Redesign and Repository Reconfiguration (PC3R) Performance Assessment (PA) are documented in this memorandum. These concerns and questions are identified here in italics to clearly distinguish them from the responses generated by the U.S. Department of Energy (DOE).

1.1 Duration of Time Period T1

Parameter Name	PABC 2009 Value	Used in PC3R PA ERMS 555489	Units
Duration of Time Period T1	Not Applicable	100	years

EPA Concerns

DOE's justification for adopting 100 years as the time frame for the T1 time period is not clear, especially given the range of values given by different sources.

Hansen and Thompson (2002, p. 4) estimated that a reduction of ROM salt porosity from 0.33 to 0.10 would occur within a maximum of 100 years, and indicate that it would take more than 100 years for ROM salt porosity to drop to the target value of 0.05.

Numerical simulations conducted by Callahan and DeVries (1991, Figure 4-2 SAND91-7052) predicted the essentially total reduction in the void volume of a room filled with crushed salt within about 25 years. These predictions do not seem to be supported by the measured closure rates of Panel 1 access drifts used in Hansen and Thompson (2002).

In DOE's proposed 2006 panel closure redesign (which also used 100 feet of loosely placed ROM salt for the panel closure material), a value of 200 years was used for creep closure to reduce the porosity from an initial value of 0.33 (averaged to 0.27 when combined with the porosity of the concrete block explosion wall) to a final value of 0.05 (Vugrin and Dunagan 2006, Table 3 and p. 15 ERMS 543865). No reason is given for reducing the time required to reach a .05 porosity value from 200 years to 100 years in the PC3R PA.

Technical Question 1.1a: *Please clarify the justification of the 100 year duration for T1. Different documents have estimated different time periods for run of mine salt to reach steady state porosity. Specifically, the PC3R cites Callahan and DeVries (1991, SAND91-7052), who predict consolidation of ROM salt to a porosity of 0.05 in about 13 years, and Hansen and Thompson (2002, ERMS 523476), who predict consolidation of ROM salt to a higher porosity of 0.10 within 100 years.*

Technical Question 1.1b: *Please justify the assumption that loosely placed, ROM salt will consolidate to a porosity of 0.05 in 100 years when the cited source Hansen and Thompson (2002) concludes that the salt will consolidate to a porosity of only 0.10 within 100 years.*

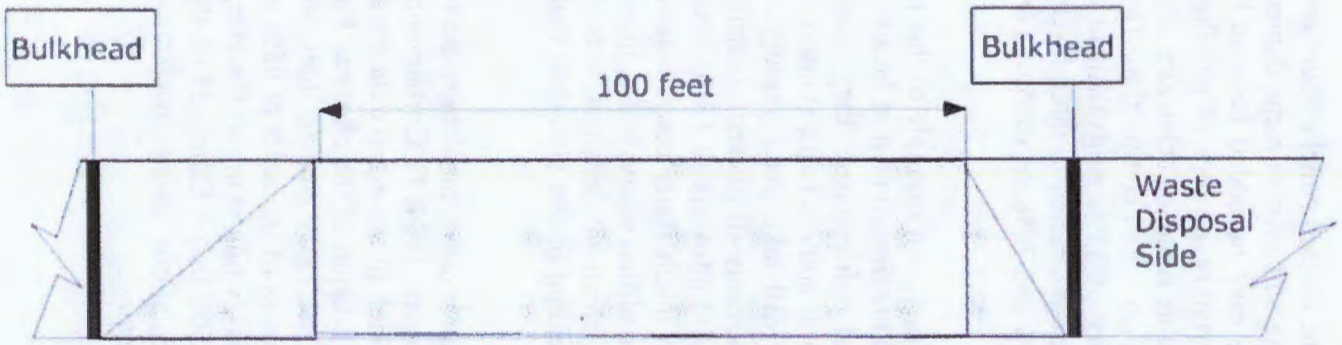
DOE Response to Technical Questions 1.1a and 1.1b:

The revised panel closure design will consist of 100 feet of run-of-mine (ROM) salt that is planned to be compacted to varying degrees (referred to herein as "crushed salt") emplaced so as to fill the entries, with additional barriers at each end of the crushed salt (Figure 1a). These barriers will consist of ventilation bulkheads similar to those currently used in the panels as room closures (Figure 2). The ventilation bulkheads are designed to restrict air flows and prevent personnel access into waste-filled areas during the operational phase. In Panels 1, 2, and 5, where explosion walls have already been emplaced in the panel entries, the explosion wall will be the inbye barrier and the ventilation bulkhead will be the outbye barrier (Figure 1b).

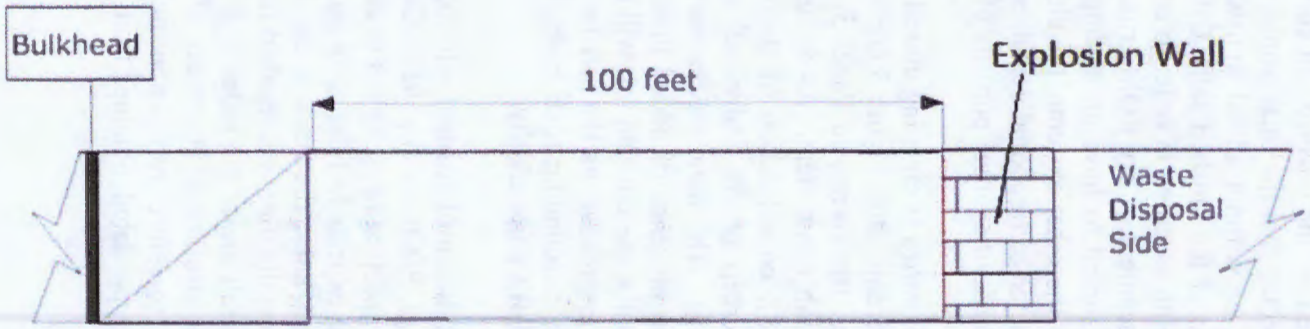
Final details of the emplacement of the crushed salt component of the revised panel closure are being developed, but it is expected that the final emplacement scheme will involve some degree of in-place compaction, with or without added moisture (moisture may be added because it accelerates the reconsolidation of the crushed salt). Given this uncertainty, a range of possible emplacement strategies are being assumed in order to cover the possible range of behaviors. At one end of the range is emplacement of dry ROM crushed salt with no initial compaction. The uncompacted ROM salt is assumed to have an as-emplaced porosity of 33%, equivalent to a fractional density of 67%. At the other extreme, the closure may be constructed in three layers that will be wetted and compacted to fractional densities of 85%, 80% and 70%, representing an average fractional density of 80%, or average porosity of 20%.

The salt rock surrounding the entries is creeping closed at a known rate. An example of this is shown in Figure 3. The measurements in Figure 3 are in the East-300 (exhaust) drift at location South-2833, which is between the entries to Panel 3. As the panel entries close, they cause consolidation of the crushed salt component. As discussed by several authors (e.g., Hansen et al., 1998; Spiers et al., 1988), consolidation of the crushed salt will take place through a combination of dislocation creep of the individual grains and various diffusional transfer mechanisms (pressure solution). The latter mechanisms, especially Fluid-Assisted Diffusional Transfer, will dominate in the presence of added brine and lead to much faster consolidation (Hansen et al., 1998). Eventually, the crushed salt will approach a condition equivalent to intact salt. During the consolidation process, as the salt reaches higher fractional densities, a back stress will be imposed on the surrounding rock mass, leading to healing of the disturbed rock zone (DRZ) and reduction in DRZ permeability.

Sources of data on the consolidation of crushed salt abound, although most of the data relate to the loading characteristics (e.g., Pfeifle et al., 1987; Kappei and Gessler, 1984; IT Corporation, 1987) or short-term creep compaction (e.g., Spiers et al., 1988). Much of the creep data are at stress levels higher than those expected in the early stages of consolidation of the closure. For example, as will be discussed later, the back stress imposed by the entry closure does not increase substantially until consolidation has reached fractional densities of the order of 98% or greater. Early stresses in the salt are of the order of 4 MPa (580 psi), while many of the creep tests have been performed at stresses of the order of 17 MPa (2500 psi). Estimates of the consolidation process must therefore rely upon numerical calculations using mechanical properties, both elastic and creep-related, obtained from laboratory testing.



(a) Panel closure with 100 feet of run-of-mine salt between two ventilation bulkheads



(b) Panel closure with 100 feet of run-of-mine salt between a ventilation bulkhead and an explosion wall

Figure 1. Schematic diagrams of the revised panel closure design (developed from descriptions obtained in "Design Report for a Panel Closure System at the Waste Isolation Pilot Plant," November 2011)

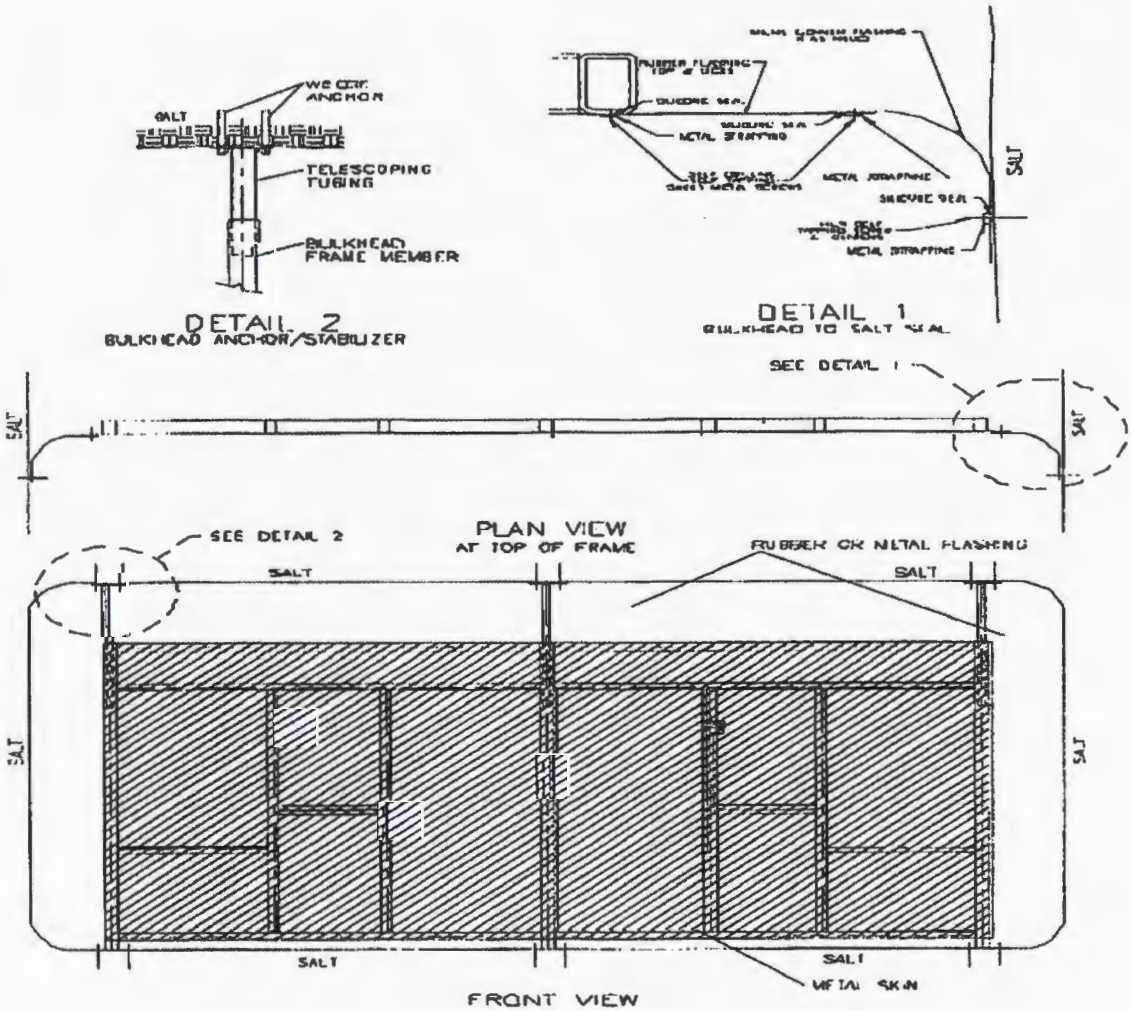


Figure 2. Typical design of a ventilation bulkhead that blocks the panel entry (U.S. DOE, 2009)

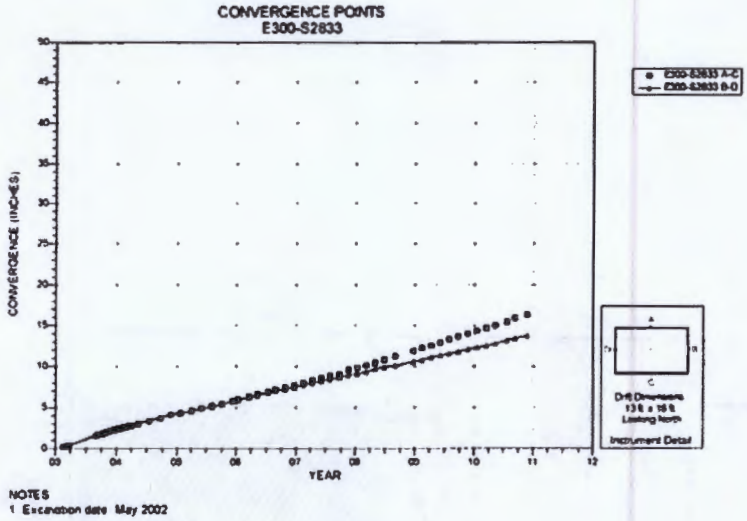


Figure 3. Convergence in the East-300 drift at South-2833 (U.S. DOE, 2011a)

A number of creep models for crushed salt have been developed by various authors (Hansen et al., 1998); however, the creep models most applicable to Waste Isolation Pilot Plant (WIPP) salt are those developed by Sjaardma and Krieg (1987), with further developments by Callahan (1999) and Hansen et al. (1998). These models have been used to estimate the time-dependent consolidation process.

Estimates of the consolidation process have been made in a series of calculations (Herrick, 2012) carried out using JAS3D (Blanford et al., 2001) with the Sjaardema and Krieg (1987) model for crushed salt, modified with a deviatoric creep compaction response (Stone, 1997). Simulations started with the crushed salt in the drift. The results are summarized in Figures 4 through 7 for initial emplacement porosities of 15%, 20%, 25%, and 33% (fractional densities of 85%, 80%, 75%, and 67%, respectively). These calculations show consolidation to a porosity of 5% in 40 years from an initial porosity of 15% (Figure 4) and in 140 years from an initial porosity of 33% (Figure 7). Based on these results and the current uncertainty over the emplacement of crushed salt, DOE is proposing to assume that 100 years is an appropriate value for the first time period during consolidation (i.e., T1 = 100 years), and that the porosity at 100 years, called the T1 porosity, has an expected value of 5%. Support for this approach comes from a number of sources, as described in the next few paragraphs.

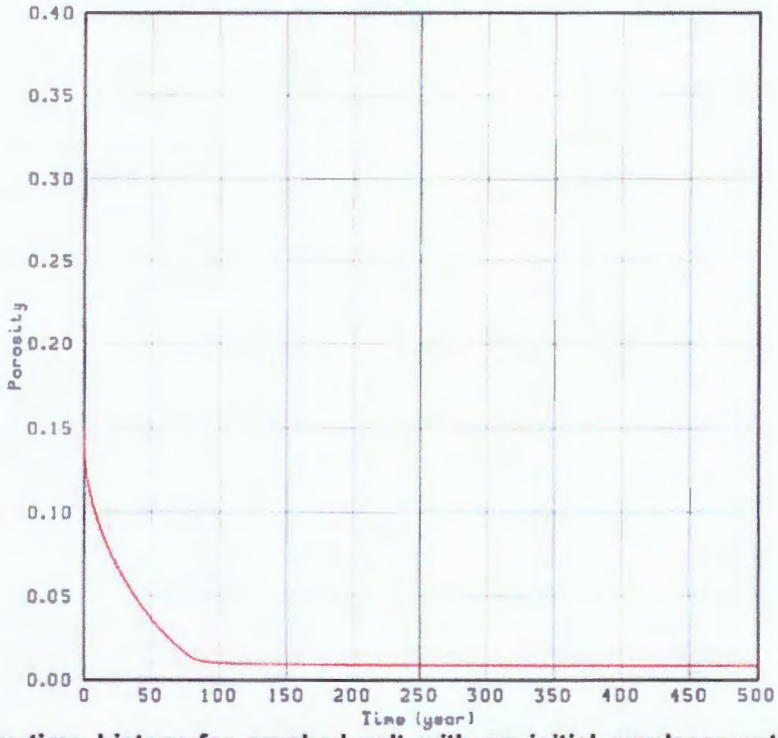


Figure 4. Porosity time history for crushed salt with an initial emplacement porosity of 15% (fractional density of 85%)

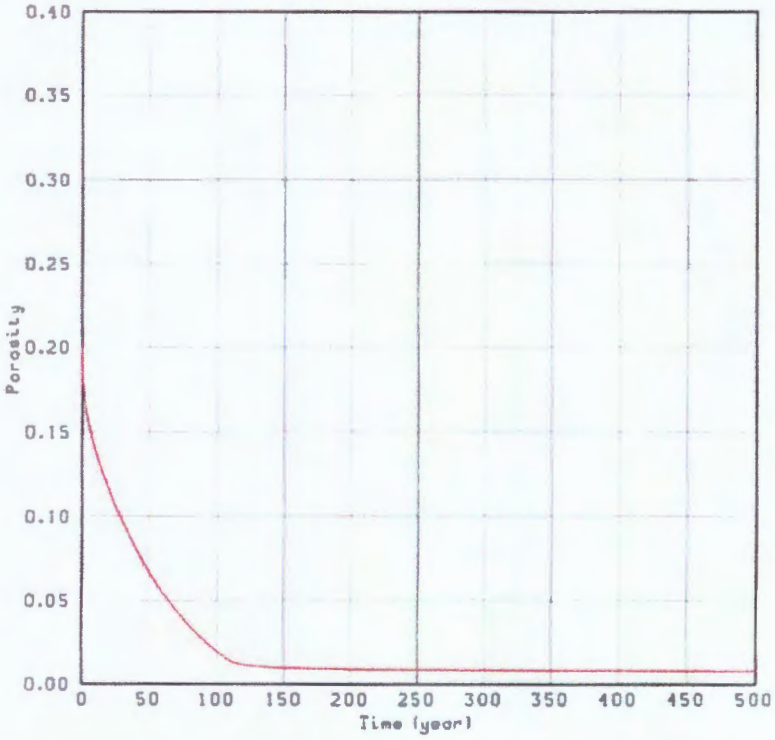


Figure 5. Porosity time history for crushed salt with an initial emplacement porosity of 20% (fractional density of 80%)

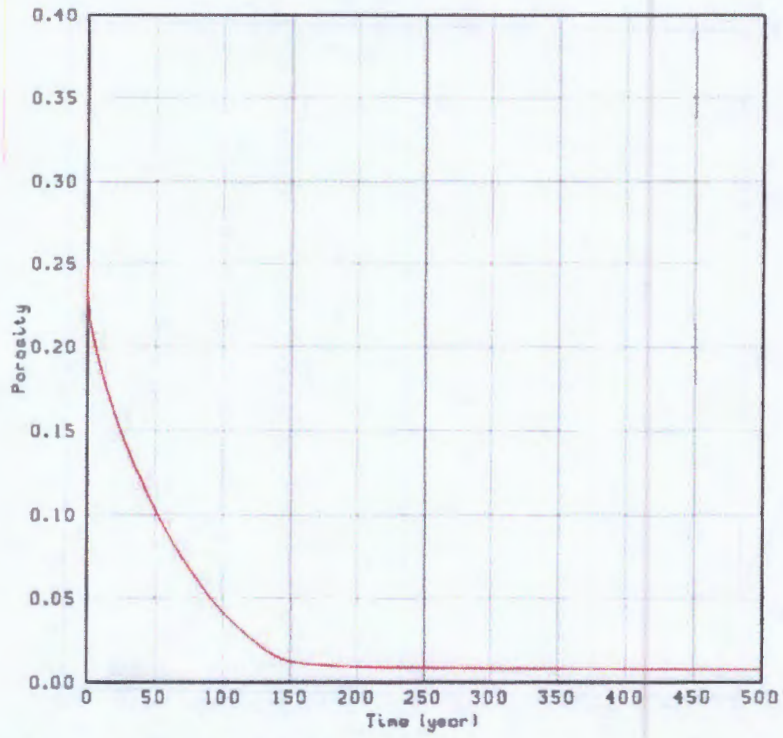


Figure 6. Porosity time history for crushed salt with an initial emplacement porosity of 25% (fractional density of 75%)

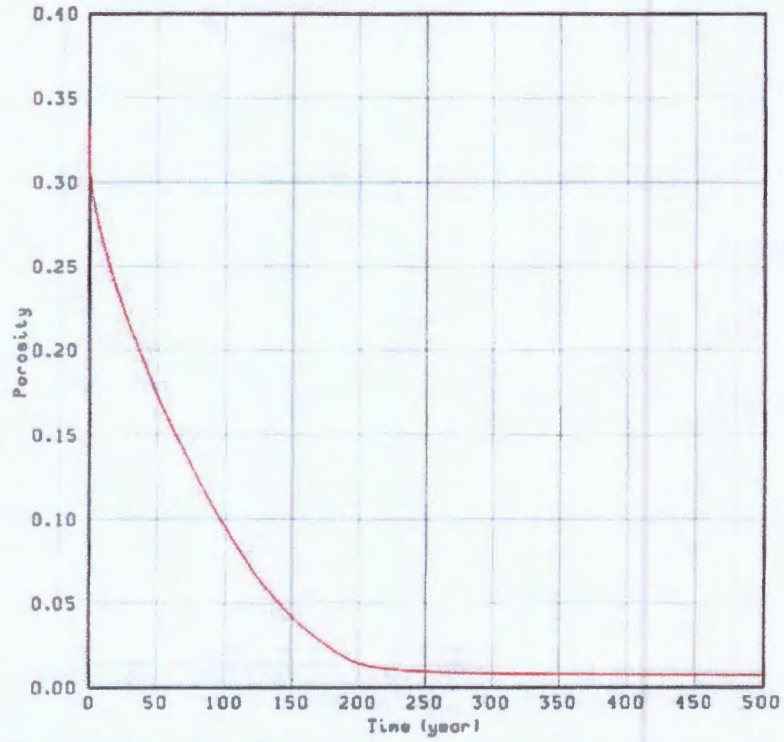


Figure 7. Porosity time history for crushed salt with an initial emplacement porosity of 33% (initial fractional density of 67%)

Hurtado et al. (1997) carried out a number of consolidation estimates for the proposed crushed salt component of the shaft seal. The crushed salt component of the proposed shaft seal will consist of mined WIPP crushed salt, dynamically precompacted with added moisture to a porosity of 10%. Calculations of the consolidation of this component due to creep closure of the shaft indicate that the crushed salt will be at an essentially intact condition (a fractional density approaching 1) within 100 years at a depth of 515 m and within 60 years at a depth of 600 m (Hurtado et al., 1997, Figure 2-3). Longer times are required at shallower depths due to the strong stress-dependence of shaft creep closure and consolidation. It should be noted that the closure rates of the approximately rectangular entries in which panel closures will be placed will be greater than for the circular shaft, and the panel closure entries are at a greater depth, about 655 m. Consolidation within the entries is therefore expected to proceed more quickly.

Additional calculations by Callahan (1999) show consolidation results for different crushed salt models at depths of 430 m, 515 m, and 600 m, indicating similar results (see Figure 8). Callahan and DeVries (1991) conducted calculations on the closure of disposal rooms backfilled with crushed salt that show closure to essentially intact densities in about 25 years (see Figure 9). These calculations used the Sjaardma and Krieg model, and while the closure of the disposal rooms would be expected to be faster than the entries because of the greater span of the rooms, the results confirm that the assumption of 100 years for T1 is reasonable for the panel entries.

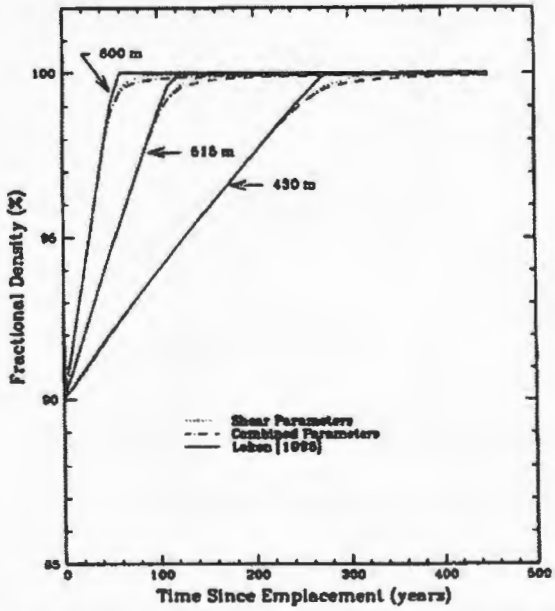


Figure 8. Fractional density versus time for a crushed salt shaft seal (Callahan, 1999, Figure 6-3)

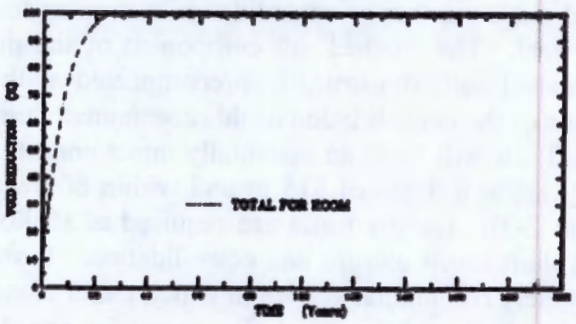


Figure 9. Void reduction versus time for a disposal room filled with crushed salt (Callahan and Devries, 1991, Figure 4-2)

Further support for T1 equal to 100 years comes from non-WIPP sources. For example, Shor et al. (1981) give results for compaction of wet salt at stresses of 20 bars (2 MPa, 290 psi), showing compaction from a void fraction of slightly more than 0.4 (porosity of 29%) to less than 0.2 (porosity 17%) in 10^4 minutes (about 7 days) (Shor et al., 1981, Figure 3). Spiers et al. (1988) show results for wet salt showing volume strains between 15% and 22% (porosities between 10% and 20%) in about 22 weeks of testing at 2 MPa (290 psi) (see Figures 10 and 11). Holcomb and Shields (1987) estimate times to 95% fractional density of 1.2×10^8 seconds (3.8 years) for salt under pressure of 0.69 MPa (100 psi) (Holcomb and Shields, 1987, Table 2).

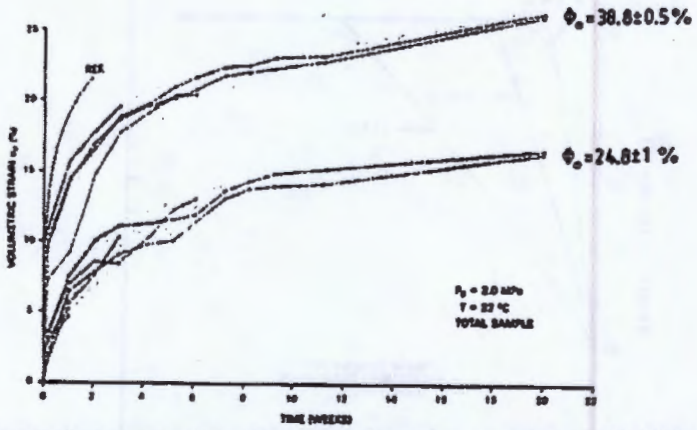


Figure 10. Volumetric strain versus time for wet salt under pressure of 2 MPa (Spiers et al., 1988, Figure 6.5)

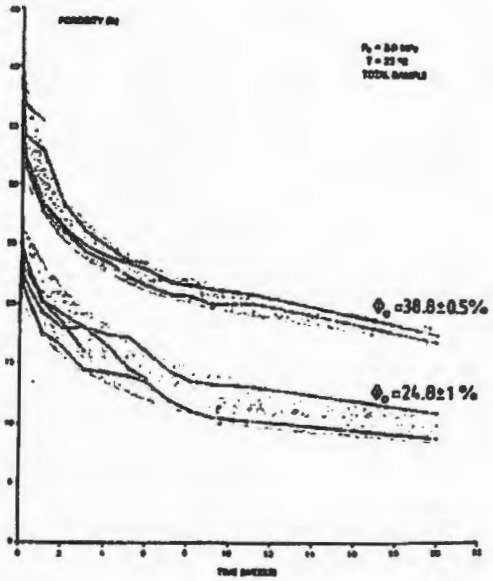


Figure 11. Total porosity versus time for wet salt under pressure of 2 MPa (Spiers et al., 1988, Figure 6.6)

As noted in Hansen and Thompson (2002), an estimate of the time to compaction can be made using the closure data for the entries. Unimpeded closure of entry drifts has been modeled and shows closure of the order of 10% in 10 years (Hansen et al., 1993). Actual measurements of roof-to-floor and rib-to-rib closure in the entries corroborate these closure rates (see Figure 3). These data also indicate that closure rates are reasonably stable and uniform. If it is assumed that the rates measured over the last 10 years continue, then the volume closure expected of the two entries is as shown in Figure 12, with volume closure of more than 30% by about 35 years. A volume closure of 30% increases the fractional density from 67% to 96% and decreases the porosity from 33% to 4%. It was noted in Hansen and Thompson (2002) that somewhat slower consolidation might be expected due to back pressure developed as the consolidation proceeds. However, recent JAS3D results show that a significant back stress does not develop before a fractional density of the order of 99%, suggesting that this effect may be rather small.

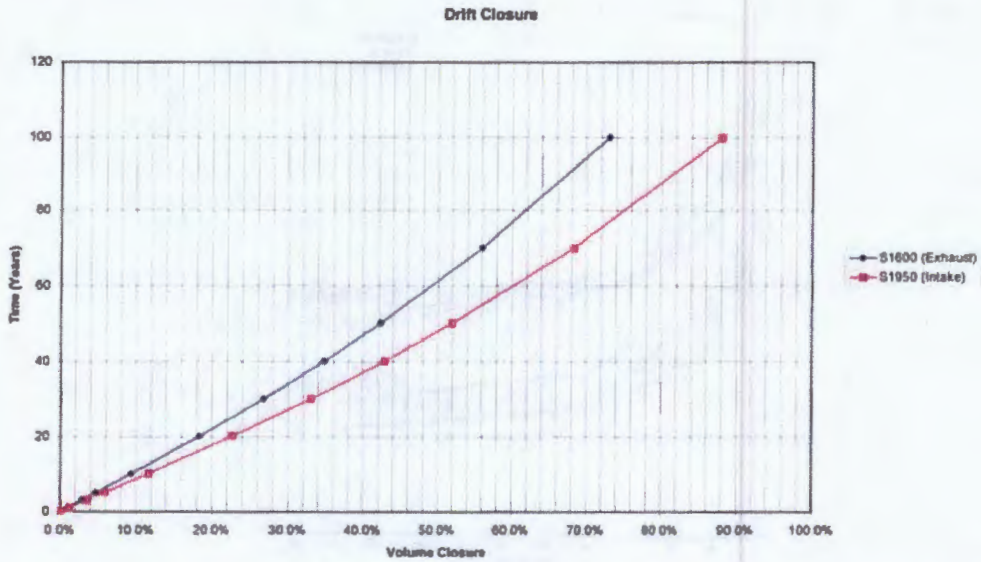


Figure 12. Calculated drift closure assuming constant closure rates and no backstress (from Hansen and Thompson, 2002)

As noted above, JAS3D results demonstrate that porosity will reach a value of 5% in less than 100 years when some compaction takes place during emplacement, and will reach this value in about 140 years when the salt is emplaced without compaction. The JAS3D results also demonstrate that compaction continues beyond these times, achieving porosity of the same order as for intact salt in 200 years after emplacement. It is therefore reasonable to assume that porosity will reach a value between 2.5% and 7.5% in the first 100 years (the range purposefully covers those cases which consolidate faster and those which consolidate slower), and that by 200 years the closure will have a porosity similar to the intact salt. The additional consolidation of crushed salt between 100 and 200 years will be accounted for by using three time periods: 0 to 100 years for the initial reconsolidation, 100 to 200 years for the intermediate state around 5% porosity, and 200 to 10,000 years to represent the long-term behavior of the fully reconsolidated crushed salt. Table 1 summarizes the proposed approach for porosity that is defined by three time periods.

Table 1. Definition of porosity using three time periods

Time Period	Assumed Porosity	Notes
0 to T1 (0 to 100 years)	33%	Assumes crushed salt is initially emplaced with minimal compaction.
T1 to T2 (100 to 200 years)	2.5% to 7.5%	Assumes that the expected T1 porosity is 5% at 100 years, consistent with the JAS3D results and supporting information from many sources. The range is designed to encompass the variability in initial emplacement (moistened versus dry; compacted versus uncompacted) for crushed salt.
T2 to 10,000 years (200 to 10,000 years	0.1% to 5.19%	Assumes that the porosity of crushed salt after 200 years is equal to the porosity for intact halite. Range is based on the S_HALITE:POROSITY parameter in performance assessment.

Technical Question 1.1c: *Please justify the use of two time periods to represent consolidation of the ROM salt panel closure material, when additional time periods could provide a more refined representation of salt consolidation over time.*

DOE Response to Technical Question 1.1c:
As discussed in the response to Questions 1.1a and 1.1b, the DOE intends to use three time periods, 0 to 100 years, 100 years to 200 years, and 200 years to 10,000 years, to provide a more refined representation of time-dependent consolidation of crushed salt in a panel closure. The rationale for the three time periods is discussed in the previous response.

Completeness Question 1.1d: *Please identify the effect of the rock bolts installed at WIPP for ground control on the consolidation rate for the ROM salt panel closure material.*

DOE Response to Technical Question 1.1d:
Rock bolts are used to control the skin around an opening by binding laminated strata or suspending weak or fractured material from more competent overlying rocks. Rock bolts are installed in all panel access/egress locations; the closure rates in Figure 3 are from entries with rock bolt support. Initially, 4-foot or 5-foot roof bolts are installed in new rooms and entries. If ground conditions deteriorate, 12-foot rock bolts are installed to further stabilize the rock around the opening.

Creep closure of an opening in salt is driven by the response of the rock mass surrounding the opening, and the rock bolts have no discernible impact on long-term creep closure of rooms and entries. As noted in the most recent Ground Control Annual Plan for the WIPP (U.S. DOE 2011b, section 6.2):

> "Geotechnical data indicate that roof bolt systems have little or no measurable effect on creep closure. The mechanism of creep and the ability of the salt to flow are driven by differential stresses initiated by excavation. The lithostatic stress at the disposal horizons is approximately 2,000 pounds per square inch. When dealing with stresses of this magnitude, it is nearly impossible from an engineering standpoint, and impractical from an economics standpoint, to design and install a mine-wide ground control system that would arrest these forces. Such a system would also reduce the waste isolation performance of the facility (the ability of salt to creep and encapsulate the waste), which is its primary function."

References for Responses to Questions 1.1

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1.2 Panel Closure Porosity

Parameter Name	PABC 2009 Value	Used in PC3R PA ERMS 555489	Units
PCS_T2: POROSITY	0.05 for CONC_PCS	0.05	--

EPA Concerns

DOE's reasoning in selecting the final T2 porosity value of 0.05 is not explicit. Because the assigned porosity of the panel closure at T2 is the value from which the long-term permeability and compressibility of the panel closure are defined, EPA is asking for more information on the parameter's justification and the importance of the specific value used.

Technical Question 1.2a: *Please provide justification that the T2 porosity is an appropriate target value that correlates to the permeability and compressibility values used in the PC3R PA.*

DOE Response to Technical Question 1.2a:

As discussed in the response to Question 1.1, room closure resulting from creep deformation of intact halite is expected to reconsolidate the crushed salt in a panel entry. The closure process is predicted to increase the fractional density of the crushed salt from its as-emplaced condition to a fractional density near 1.0, so that the consolidated salt becomes indistinguishable from the intact halite over long periods of time, estimated in the response to Question 1.1 to be 200 years. Drift closure calculations predict that the crushed salt in a panel entry will reconsolidate within 100 years to an expected porosity of about 0.05 (i.e., a fractional density greater than 0.95) at repository depth. Laboratory experiments on consolidated cores of crushed salt confirm that the intrinsic permeability of crushed salt decreases as the fraction density of the cores increases (Hurtado et al., 1997, Figure 2-1). Other observations of the behavior of crushed salt in similar situations support these results; it should be noted that although these examples are for different salt materials, the overall behavior of the crushed material may be expected to be similar in general. Observations from the BAMBUS II project at the Sigmundshall mine in Germany indicate consolidation of a crushed salt slurry to essentially an intact condition within tens of years (Bechthold et al., 2004, Figure 2.57). Consolidation to an essentially intact condition is also confirmed by observations at the Rocanville mine, where a consolidated salt plug was emplaced after a water inflow, and has been effective in sealing off a hydrostatic groundwater pressure of about 1200 psi (8.3 MPa) (Van Sambeek et al., 1995).

The state of the intact halite therefore provides an analog for the long-term state of the crushed salt in a panel entry. Intact halite may not always be an exact analog for the long-term state of the consolidated salt because the interconnected porosity of the *in situ* halite may be different than the interconnected porosity of the consolidated crushed salt; however, it is expected to be a good analogy in terms of porosity. The measured effective porosity used in performance assessment (PA) for intact halite varies from 0.001 to 0.0519 (parameter S_HALITE:POROSITY) (U.S. DOE, 2009, Appendix PA, Parameter 17; Ismail, 2007). This range is consistent with the predictions outlined in the answer to question 1.1a, which show a porosity for consolidated salt of less than 0.05 after 100 years in the case of moistened salt, and after 140 years for dry salt.

Based on this discussion, a target or expected value of 0.05 for the porosity at 100 years is quite reasonable, in part because it lies at the upper limit of the effective porosity for intact halite. Significant uncertainties exist in the consolidation process because of the uncertainties in the initial fractional density of the crushed salt and in wet versus dry emplacement. These uncertainties are represented by defining a range of values for the porosity at 100 years from 0.025 to 0.075. The proposed lower limit for the porosity range, 0.025, accounts for the fact that, under certain conditions of emplaced compaction and moisture, a porosity of 0.05 is achieved in less than 100 years. The upper limit of 0.075 acknowledges that more than 100 years may be required to achieve very low *in situ* porosities and permeabilities. The consolidation process will continue after 100 years, particularly for salt that is emplaced dry with minimal compaction. This is accounted for by assigning a second time period (100 to 200 years) during which consolidation of the crushed salt will continue and achieve essentially intact salt conditions regardless of the emplacement strategy.

As noted above, although the state of the intact halite provides an analog for the long-term state of the crushed salt in a panel entry, this analogy may not always be exact in the case of the permeability because the interconnected porosity of the *in situ* halite may be different than the interconnected porosity of the consolidated crushed salt. In this condition, the permeability of intact halite would be different than the permeability of the reconsolidated ROM salt at equal porosity. A similar effect has been observed in laboratory testing of consolidated crushed salt cores. At equivalent fractional densities, dry consolidated salt cores are more permeable than wet consolidated salt cores because of the difference in the mechanism causing consolidation. Under dry conditions, the effective consolidation mechanism is crystal plasticity, while under wet conditions the effective consolidation mechanism is pressure solution/redeposition (Hurtado et al., 1997, page 2-7). Pressure solution/redeposition under wet conditions generally produces higher consolidation rates and more deformation than crystal plasticity under dry conditions, leading to lower measured permeabilities for wet consolidated salt than for dry consolidated salt (Hurtado et al., 1997, Figure 2-1). For these reasons, the permeability assigned to the closure at a particular porosity will be determined in PA using actual data on consolidated salt, as discussed in the answer to Q1.3.

The pore-volume compressibility of consolidated salt has been determined as a function of porosity and bulk modulus (Hurtado et al., 1997, section 2.1.4). The bulk modulus of crushed salt has been measured experimentally by Holcomb and Hannum (1982). In this study, hydrostatic compaction tests were conducted with unload/reload cycles performed at prescribed levels of density. The data were later used by Sjaardema and Krieg (1987) to define an empirical model relating bulk to fractional density. For a porosity of 0.05, which is the mean porosity value at 100 years, the pore-volume compressibility is calculated as 1.6×10^{-9} 1/Pa (Hurtado et al., 1997, page 2-21). This value is the recommended value for the crushed salt during all time periods because the pore-volume compressibility is not expected to be a sensitive parameter in PA.

Technical Question 1.2b: *How sensitive a parameter is the final porosity of the panel closure? That is, how much would changing the value of PCS_T2: POROSITY (e.g. to 0.01 or 0.075) change calculated results, such as waste area saturation and pressure, that are known to impact performance?*

DOE Response to Technical Question 1.2b:

In the PC3R PA, material PCS_T2 is used to represent the crushed salt panel closure after it has undergone consolidation (Camphouse and Clayton, 2011). The porosity of material PCS_T2 is a constant value, 0.05, in the PC3R PA. In order to test the sensitivity of PA results to the final porosity of material PCS_T2, two additional BRAGFLO replicates were executed: one with a PCS_T2:POROSITY of 0.01 and the second with a PCS_T2:POROSITY of 0.075. These two values provide reasonable lower and upper limits for the porosity of material PCS_T2, as discussed in the response to Question 1.2a. The two additional BRAGFLO replicates used the same BRAGFLO grid as for the PC3R PA, providing a consistent comparison. Input files and simulation results corresponding to these BRAGFLO calculations can be found in CMS library LIBPC3R_BF in class COMMENT_CALCS.

The impact of changing the final porosity to 0.01 or 0.075 on the mean waste panel pressure for an E1 intrusion that hits a brine pocket at 350 years is presented in Figure 13. The mean waste panel pressure for PCS_T2:POROSITY values of 0.01, 0.05, and 0.075 are virtually identical for an E1 intrusion occurring at 350 years. Figure 14 shows that the same conclusion is true for an E2 intrusion into the waste panel at 350 years. Consequently, mean waste panel pressure is highly insensitive to changes in the long-term porosity of the panel closure.

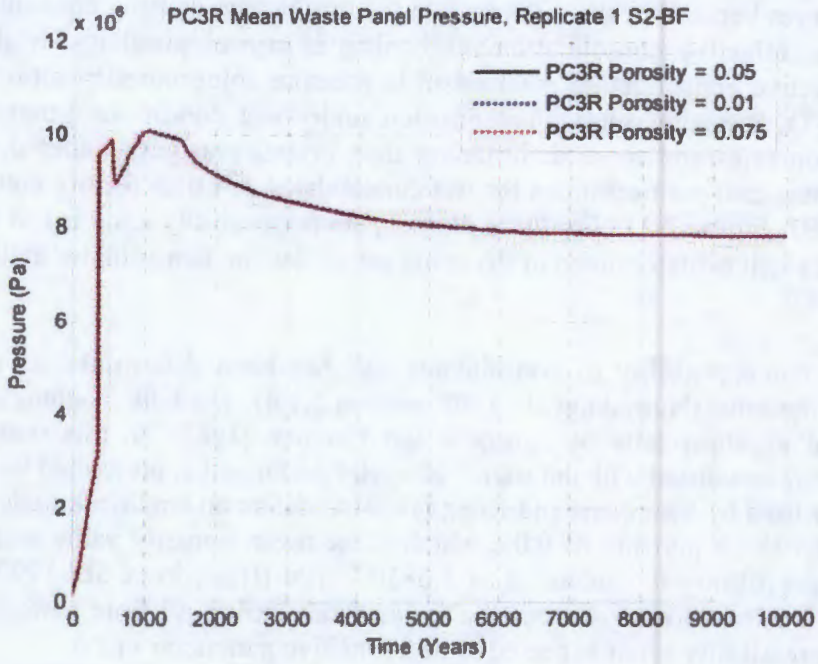

Figure 13. Mean waste panel pressure for long-term panel closure porosity values of 0.01, 0.05, and 0.075. E1 Intrusion at 350 years, Replicate 1.

A similar conclusion is true for mean brine saturation in the waste panel. Figures 15 and 16 show that the mean waste panel brine saturation for PCS_T2:POROSITY values of 0.01, 0.05, and 0.075 are indistinguishable for the case of an E1 intrusion into a waste panel at 350 years (Figure

15) or for an E2 intrusion into a waste panel at 350 years (Figure 16). Mean brine saturation in the waste panel is highly insensitive to changes in the long-term porosity of the panel closure.

From these results, it can be inferred that direct releases due to drilling intrusions into the repository are also insensitive to changes in long-term porosity of the panel closure. Cuttings and cavings releases are not a function of repository conditions, and are therefore completely independent of long-term closure porosity. Spallings release volumes are a function of waste panel pressure at the time of intrusion. Waste panel pressure is insensitive to changes in long-term closure porosity and consequently, spallings releases are also insensitive to long-term closure porosity. Direct brine release (DBR) volumes are dependent on waste panel pressure and brine saturation at the time of intrusion. DBRs will also be insensitive to changes in long-term closure porosity because waste panel pressure and waste panel brine saturation are insensitive to changes in long-term closure porosity.

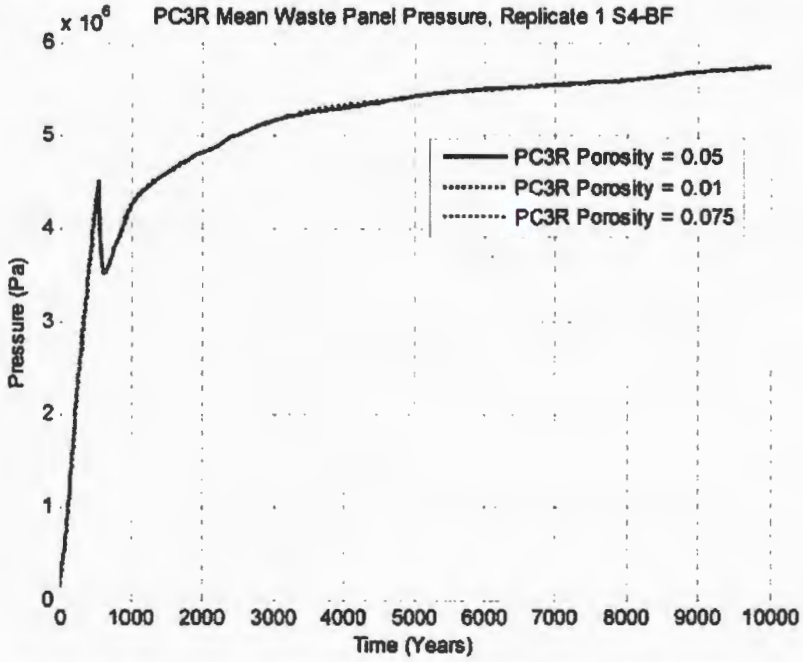

Figure 14. Mean waste panel pressure for long-term panel closure porosity values of 0.01, 0.05, and 0.075. E2 intrusion at 350 years, Replicate 1.

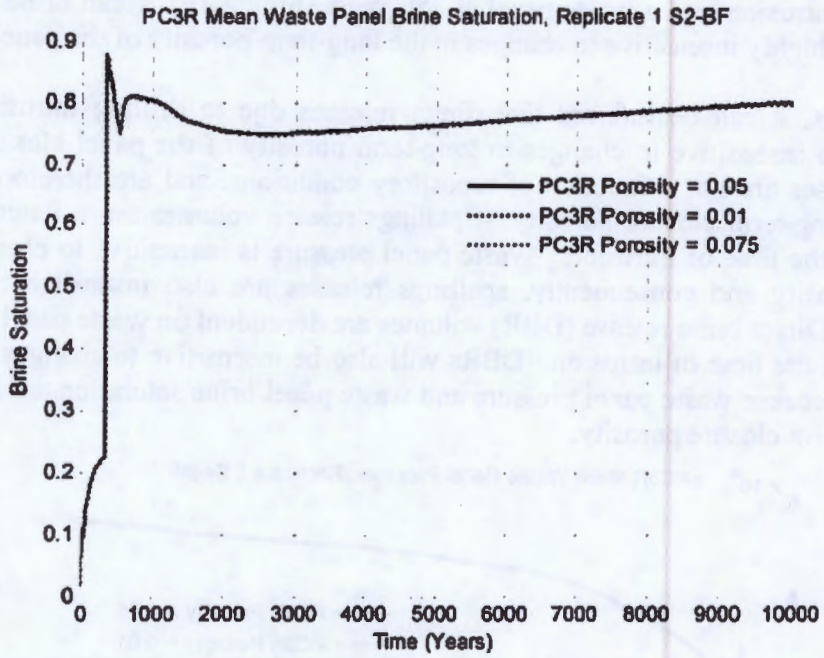

Figure 15: Mean waste panel brine saturation for long-term panel closure porosity of 0.01, 0.05, and 0.075. E1 intrusion at 350 years, Replicate 1.

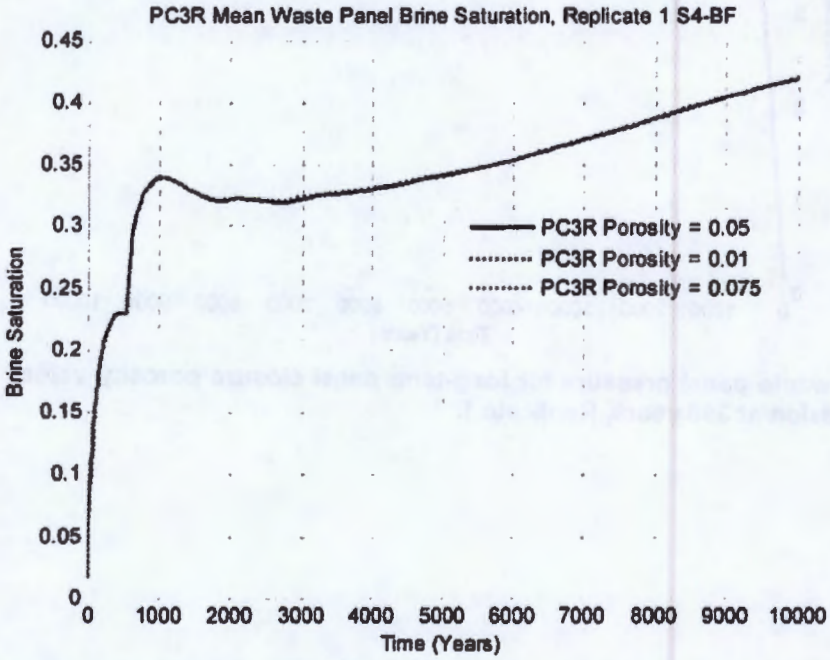

Figure 16. Mean waste panel brine saturation for long-term panel closure porosity of 0.01, 0.05, and 0.075. E2 intrusion at 350 years, Replicate 1.

References for Questions 1.2

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1.3 Long-Term Panel Closure Permeability

Parameter Name	PABC 2009 Value	Used in PC3R PA ERMS 555489	Units
PCS_T2:PRMX_LOG PCS_T2:PRMY_LOG PCS_T2:PRMZ_LOG	-17, -20.8, -18.8 for CONC_PCS	-17.6, -22.8, -20.2 Triangular Distribution	$\log(m^2)$

EPA Concerns

EPA is looking for clarification on the justification of the long-term panel closure permeability.

A compilation of laboratory-measured permeability values for WIPP crushed salt at various fractional densities was prepared by Hurtado et al. (1997, Table 2-1 SAND97-1287). The most relevant results were taken from Brodsky (1994, SAND93-7058), who measured the permeability of compacted ROM salt at fractional densities near 0.95 (equivalent to a porosity of 0.05) using brine as the fluid rather than gas.

Kelley et al. (1996, p. 1 ERMS 230995) provide a summary of permeability values at various densities. The T2 permeability values recommended by Camphouse (2010b, p. 4) are most similar to those reported by Kelley et al. (1996, Table 6) for 200-years, which represented full reconsolidation. The values recommended by Camphouse are not identical to any of those presented in the 1996 Kelley report.

The PC3R T2 permeability values are similar to the values for fully reconsolidated crushed salt reported by Kelley et al. (1996) and Hurtado et al. (1997), but not representative of porosities equivalent to 0.05. The T2 permeabilities used to represent ROM salt at a porosity of 0.05 are generally 1.5 to 2 orders of magnitude lower than those reported by Butcher et al. (1991, reported in Hansen and Callahan, 1993), Brodsky (1994), Hurtado et al. (1997, SAND97-1287), and Hansen and Thompson (2002) for compacted salt equivalent to a porosity of 0.05.

Technical Question 1.3a: *Please provide a source for the permeability values assigned to the ROM salt panel seal during time period T2 that provides traceability to original sources.*

Technical Question 1.3b: *Please justify the assignment of permeabilities to the ROM salt panel seal during time period T2 that represent fully consolidated salt rather than ROM salt consolidated to a porosity of 0.05.*

<u>DOE Response to Technical Questions 1.3a and 1.3b:</u>

This response identifies the sources for the permeability values and an improved method for the assignment of permeabilities during the time periods from 100 to 200 years and from 200 years to 10,000 years. The proposal to use multiple time periods differs from the approach for the PC3R PA, which used a single time period from 100 years to 10,000 years.

The permeability values for consolidated crushed salt are based on experimental measurements of consolidated WIPP salt cores (Hurtado et al., 1997). The experimental program is summarized

in Hurtado et al., 1997 and further documented in additional Sandia documents (Brodsky, 1994; Brodsky et al., 1996; Ahrens and Hansen, 1995). These experimental data provided the basis for defining the permeability of the crushed salt component of the shaft seal system (U.S. DOE, 1996, Appendix SEALS, Figure A-7), and are an appropriate starting point for defining permeability ranges for the consolidated crushed salt in a panel closure. The experimental data have fractional densities[1] from 0.822 to 1.005[2] (porosities 0.178 to -0.005) (Hurtado et al., 1997, Table 2-1), a range that encompasses the recommended porosity range of 0.025 to 0.075 during 100 to 200 years and 0.001 to 0.0519 during 200 to 10,000 years (see response to Question 1.2a).

In assigning permeability values from porosities for PA, the data in Hurtado et al., 1997, Table 2-1, are represented as a function of porosity through a two-step relationship: (1) a least squares fit to the permeability data as a function of fractional density, and (2) a distribution that represents the residuals of the data about the least squares fit. This approach captures the mean variability of permeability with porosity and represents the uncertainty in the data set.

The values presented in Table 2-1 of Hurtado et al., 1997, include various sets of data. This analysis uses the brine permeability data from Brodsky, 1994, because the fractional densities of the samples for the brine data, 0.8953 to 1.0051, are equivalent to porosity from ~ 0 to 0.1047, which spans the porosity ranges of interest. The cores for gas permeability measurements (Brodsky et al., 1996; Ahrens and Hansen, 1995) have fractional densities from 0.8220 to 0.9339 (porosities 0.178 to 0.0661), which are generally beyond the range of interest here. Figure 17 presents the least squares fit to the logarithm (base 10) of the brine permeability data in the Table 2-1 of Hurtado et al., 1997.

Figure 18 is a plot, called a quantile-quantile plot, which shows the relationship between the quantiles of the residuals of the logarithm (base 10) of the permeability data relative to the least squares fit and the predicted residuals at the corresponding quantiles on a normal distribution. The residuals of the data completely define the parameters for the normal distribution: the mean is 0.0 and the standard deviation is 0.86. No subjective judgment is needed or used to define the parameters for the normal distribution. If the agreement with a normal distribution were exact, all points in Figure 18 would lie on the line with a slope of 1. Most points are quite close to the line in Figure 18, indicating that a normal distribution provides a very good representation of the residuals.

Figure 19 presents the range of permeability with uncertainty characterized by the normal distribution with $\mu = 0$ and $\sigma = 0.86$. The lines for ±2 standard deviations in Figure 19 are used to provide the effective upper and lower bounds for permeability. All the experimental data lie within ±2 standard deviations with the exception of the data point with a $\log_{10}$ permeability of -21.5.

[1] The relationship between porosity, ϕ, and fractional density, *fd*, is $\phi = 1 - fd$.

[2] Note that a recorded fractional density greater than 1 probably implies an uncertainty in the assumed intact salt density.

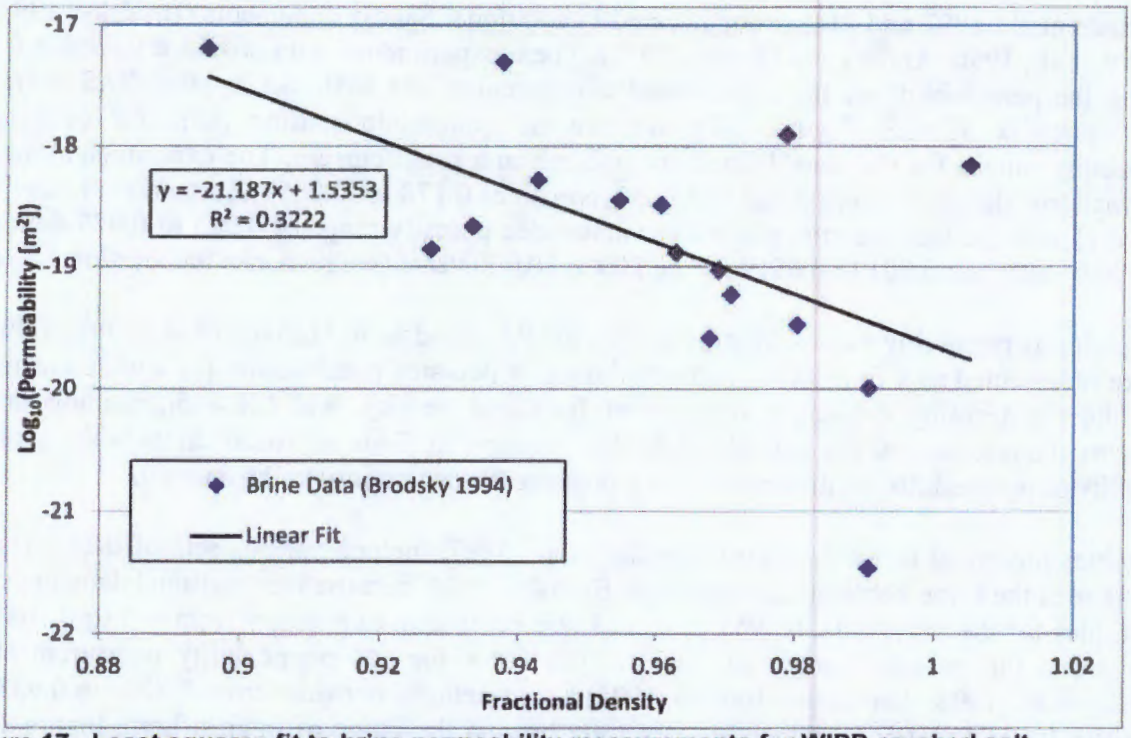

Figure 17. Least squares fit to brine permeability measurements for WIPP crushed salt

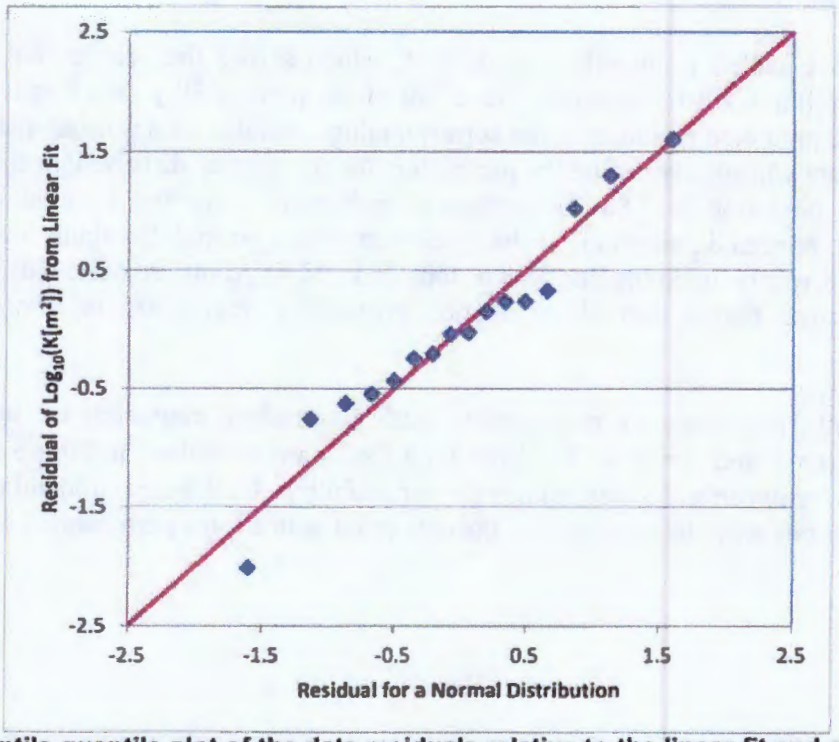

Figure 18. Quantile-quantile plot of the data residuals relative to the linear fit and of the predicted residuals for a normal distribution, $\mu = 0$ and $\sigma = 0.86$

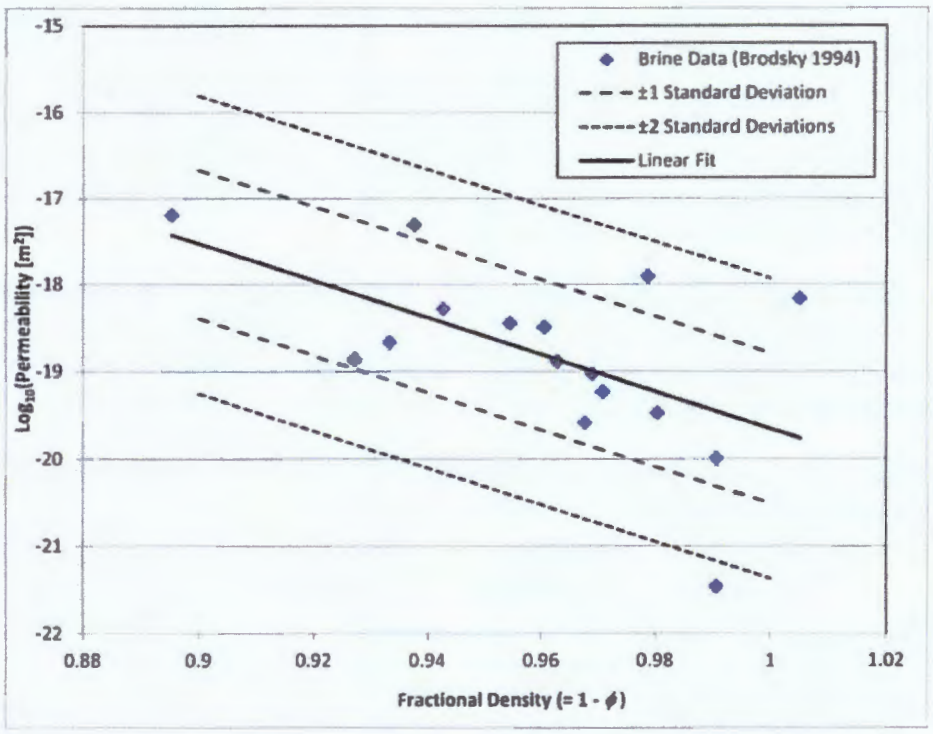

Figure 19. Variation of permeability with fractional density, based on the least squares fit with uncertainty defined by a normal distribution with $\mu = 0$ and $\sigma = 0.86$

Table 2 presents the expected permeabilities from 0 to 100 years, from 100 to 200 years, and from 200 to 10,000 years based on the analysis presented above. For the latter two time periods, the permeabilities are determined from the range of porosities established in the answer to question 1.1 (0.025 to 0.075 for 100 to 200 years, 0.001 to 0.0519 for 200 to 10,000 years), with the mean permeability for each porosity defined by the least squares fit (see Figure 17) and the minimum and maximum permeability values defined at ±2 standard deviations on the normal distribution (see Figure 19).

The permeability values in Table 2 are reasonable from several viewpoints:

- From 0 to 100 years, the crushed salt is assigned a permeability value of 10^{-11} m^2, representative of a very loose granular material.

- From 100 to 200 years, the permeability range in Table 2 encompasses a wide range of possible outcomes, from a very low permeability of 1.44×10^{-21} m^2 to a maximum permeability of 4.55×10^{-17} m^2, which is more than 4 orders of magnitude greater than the minimum value. This range will produce a range of hydrologic responses for the panel closure, from "tight" to much "looser" in terms of brine and gas flows across the closure, because of the uncertainties in emplacement of the crushed salt.

- From 200 to 10,000 years, the permeability range in Table 2 represents the response of almost fully compacted salt, with a minimum value of 4.46×10^{-22} m^2 and a maximum value

of 1.47×10^{-17} m^2. This range of values is purposefully greater than the range for intact halite in PA, which is 10^{-24} m^2 to 10^{-21} m^2. As noted previously, the consolidation mechanisms for moistened versus dry crushed salt are different and can lead to different levels of interconnected porosity and permeability for a given effective porosity (see response to Question 1.2a). Stated differently, the very low permeability of intact salt may not be attained for thousands of years, and the recommended permeability will produce a range of hydrologic responses for the panel closure.

- After 100 years, the range of permeabilities in Table 2 is similar to the permeability range for material DRZ_PCS in the PABC-2009, which is 2×10^{-21} m^2 to 1×10^{-17} m^2 at all times (Clayton et al., 2010). The permeability after 100 years is therefore consistent with the expected response for a healed DRZ above a panel closure, as represented in PABC-2009.

Table 2. Expected, Minimum, and Maximum Permeability Values Corresponding to the Least Squares Fit with Uncertainty Defined by a Normal Distribution

Porosity	Fractional Density	Expected Permeability (m^2)	Minimum[a] Permeability (m^2)	Maximum[a] Permeability (m^2)
0 to T1 (0 to 100 Years):				
0.33	0.67	1×10^{-11}	N/A	N/A
T1 to T2 (100 Years to 200 Years):				
0.025	0.975	7.55×10^{-20}	1.44×10^{-21}	3.96×10^{-18}
0.075	0.925	8.66×10^{-19}	1.65×10^{-20}	4.55×10^{-17}
T2 to 10,000 Years (200 Years to 10,000 Years):				
0.001	0.999	2.34×10^{-20}	4.46×10^{-22}	1.23×10^{-18}
0.0519	0.9481	2.80×10^{-19}	5.34×10^{-21}	1.47×10^{-17}

[a]Minimum corresponds to -2 standard deviations below the least squares fit; maximum corresponds to +2 standard deviations above the least squares fit.

Within performance assessment, the permeability-porosity relationship in Figures 17 through 19 can be represented with the following algorithm:

1. For each realization, sample the T1 porosity from a uniform distribution with a minimum of 0.025 and a maximum of 0.075, and sample the T2 porosity from a uniform distribution with a minimum of 0.001 and a maximum of 0.0519.

2. Calculate the expected values of the $\log_{10}$ (permeability) using the equation for the least squares fit in Figure 17.

3. Sample a normal distribution (mean of zero, standard deviation of 0.86) that is truncated at ±2 standard deviations for the residual of the final value of the $\log_{10}$ (permeability) relative to the least squares fit. This sampling is performed once per realization.

This algorithm can be expressed mathematically as:

$$\log(k_e) = -21.187(1-\phi_{T2}) + 1.5353,$$

$$k_{T2} = 10^{\log(k_e)+\alpha} = k_e 10^{\alpha},$$

where k_e is the expected value of permeability from the least squares fit (Figure 17),
ϕ_{T2} is the sampled value of porosity,
k_{T2} is the final value of permeability, and
α is the sampled value of a normal distribution with a mean of 0 and standard deviation of 0.86.

Completeness Question 1.3c: *Please provide design and performance information that justifies the stated assumption that the "substantial barrier" will have no impact on panel seal performance during time period T2.*

DOE Response to Technical Question 1.3c:
The design configuration for the panel closure consists of 100 feet of crushed ROM salt between two barriers. The barriers consist of two standard ventilation bulkheads placed at the ends of the salt or alternately, one standard ventilation bulkhead and a concrete block wall (see Figure 1). The ventilation bulkhead, shown in Figure 2, is a thin steel structure that is designed to restrict ventilation air flow and control personnel access during the operational period. The concrete block wall is 12 feet thick and was installed in Panels 1, 2, and 5 as an explosion barrier during the operational period. Some degradation of the block walls from creep closure of the panel entries is observable in the underground facility.

The steel bulkheads are designed to perform only during the operational period. These barriers are not expected to remain intact 100 years after repository closure because of creep closure of the panel entries. The block wall is also designed for the operational period. This wall is inspected on a regular basis, and in addition, the expected condition of the wall is assessed through numerical modeling (e.g., Rocksol, 2006). Inspection of the condition of the walls in Panels 1 and 2 several years after installation show surface spalling of the concrete on the outbye free face as a result of loading caused by inward creep of the salt. Numerical stress analysis implies that the free faces and the rib contacts will be in a condition of plastic yield with an unyielded core. No long-term stress analyses have been carried out; however, it is expected that the spalling and yield will be progressive, and that the walls will not be significant structures after the initial 100-year time period. These barriers will therefore have no significant impact on the long-term performance of the panel closures.

Completeness Question 1.3d: *Please justify the unstated assumption that repository gas pressure buildup during time period T2 will not inhibit or reverse consolidation of the ROM salt panel seal, potentially resulting in higher porosities and therefore higher permeabilities than the recommended values.*

DOE Response to Technical Question 1.3d:
Gas pressure could build up during consolidation of crushed salt, either because of trapped air in the pores or because of pressure buildup due to gas generation from corrosion or microbial degradation of waste in a disposal room. The gas pressure in a room may continue to increase after consolidation of the crushed salt, particularly because of long-term corrosion of iron-based materials in the waste and waste containers.

During early time periods (0 to 100 and 100 to 200 years) gas pressure will remain low. First, compressibility of gas trapped in the pore space of the closure does not produce a large change in pressure. The magnitude of this change can be estimated by assuming a slow, isentropic compression of the gas, under which condition:

pV^{γ} = constant,

or

$$p = p_i\left(\frac{V_i}{V}\right)^{\gamma},$$

where p_i and V_i are the initial pressure and initial volume, resp., V is the final volume, p is the final pressure, and γ is the isentropic exponent of the gas. For a tenfold decrease in pore volume, the pressure increases by a factor of 25 for an isentropic exponent of 1.4, which is typical of air. An initial pressure of 0.10 MPa (14.7 psi) would increase to 2.54 MPa (368 psi). During the initial time period (0 to 100 years), permeabilities of the crushed salt will remain reasonably high so that any pressure buildup of this nature will leak out through the half-length of 50 ft in the times available (tens of years). During the second time period (100 to 200 years), volume reduction due to consolidation will be much less, leading to lower pressure buildup. IT Corporation (1987) carried out calculations of consolidation of crushed salt for a generic salt repository in the Permian Basin at an assumed depth of 2384 ft, and included the possible effects of pressure of trapped air. While the conditions for these calculations were not exactly equivalent to those at the WIPP, it is of note that they showed only a minor effect, of the order of 5% delay in consolidation times, from air pressure buildup.

Similarly, the pressure buildup due to gas generation from waste degradation remains low during time periods T1 and T2. The mean pressure in waste panel (see red curve in Figure 20) is less than 2 MPa (290 psi) at 200 years and less than 3 MPa (435 psi) at 300 years. These pressures are quite small compared to the lithostatic stress at the disposal horizon. It follows that pressure changes from compressibility of gas in the pore space or due to gas generation from waste degradation will not significantly retard consolidation of the crushed salt during time periods T1 and T2.

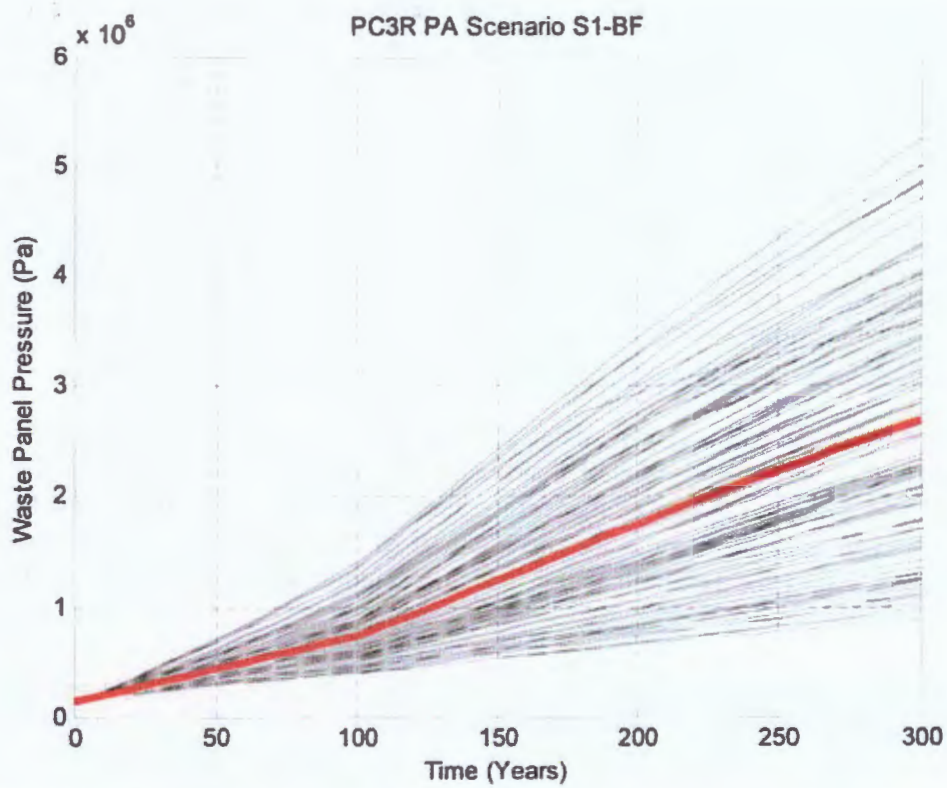

Figure 20. Waste panel pressure from the PC3R PA for Replicate 1, undisturbed scenario

After time T2, the gas pressure in the pores will not have a significant influence on the porosity or permeability of the crushed salt panel closures. Most of the consolidation has already taken place during T1 and T2, so the closure will have reached a condition largely indistinguishable from the intact halite, and the back stress from the surrounding rocks on the crushed salt will be increasing rapidly with time. If high gas pressure occurs in the disposal panels, the likely path for any fracture will be through the anhydrite marker beds, as currently assumed in performance assessment, rather than through the mass of the panel closure.

Completeness Question 1.3e: *Please justify the unstated assumption that backpressure reduction through lateral halite movement at the unconstrained ends of the 100-ft panel closure backfill can be ignored during the consolidation process.*

<u>DOE Response to Technical Question 1.3e:</u>
Three-dimensional (3D) calculations were performed to evaluate the magnitude of the lateral displacements throughout the 100-foot-long crushed salt component of the panel closure (Herrick, 2012). The 3D representation discretizes the central portion of the crushed salt component with grid blocks that are approximately 1 m on a side (see Figure 21). The crushed salt has an initial porosity of 33% and its dynamic response was simulated with the volumetric creep model in JAS3D (Blanford et al., 2001).

The boundary condition on the sides and bottom of the entry is one of zero normal displacement to represent the constraint from the walls. There is zero displacement in the x-direction (horizontal) at the mid-plane of the crushed salt because of symmetry. This symmetry plane passes through Node 1103, shown in the top portion of Figure 21. A vertical stress is applied on the upper surface of the model that increases from 0 to 15 MPa, the lithostatic stress at WIPP, over 500 years. No horizontal deformation is allowed on the sides in the z-direction since the goal of the calculations is to investigate horizontal behavior in the x-direction and to test for plane strain in that direction. Due to a lack of information on the coefficient of friction between the crushed salt and intact salt, an equivalent friction boundary condition was imposed that no displacements of the nodes on the top and bottom of the model were allowed in the horizontal directions. The JAS3D analyses for 1.3e do not include the underground stratigraphy.

Deformations, stresses, and strains were calculated at all nodes and elements of the mesh; however, emphasis is given to the material making up the inner rectangular block of material constituting the panel closure (shown as magenta-colored elements in the lower part of Figure 21). Due to symmetry, only the results for the left half of the salt are given. The nodes and elements considered within the left half of the inner rectangular block are shown in the lower drawing.

Figure 22 shows the deformed mesh at 0, 100, 200, 300, 400, and 500 years. Since it is a simplified model using an applied vertical stress on the upper surface only, the displacement of the top is not uniform. At the end of the simulation, it is obvious that the triangular end pieces are providing some lateral structural support as the deformation builds up. Note that there is no roof in this simulation to constrain the vertical deformation. There is visible horizontal bulging of the outer layers of the triangular ends as the deformation of the upper surface increases. Even though the triangular ends undergo apparent deformation, the interior elements that make up the panel closure do not show significant deviation from a plane strain condition. This is to be expected, and follows the well-established use of a plane strain assumption to represent the response of a cross-section in an entryway that is much longer than its characteristic lengths in the cross-section perpendicular to its longitudinal axis (see for example, Timoshenko and Goodier, 1951, Chapter 2, section 8).

The horizontal displacements in the x-direction (DISPLX) at the interior nodes are shown in Figure 23. The displacements (DISPLX) are in general small, the largest being about 15 cm (6 inches) at the ends. The temporary compaction as the material is stressed is a result of the uncoupling of deviatoric and volumetric inelastic behaviors in the model. The displacement decreases rapidly toward the center of the closure. By 5 m from the end, at Node 613, the displacement is approximately 15 mm; by 7 m from the end; at Node 627, the displacement is about 5 mm. The horizontal strains in the areas of these nodes are one to two hundredths of the vertical strain. These results suggest that the interior 70-75 feet can unequivocally be considered to be in a condition of plane strain. In addition, the small values of axial deformation away from the ends of the closure, and the rapid decrease of deformations away from those ends, indicate that the lateral movement of the ends will not have an effect on the rate of consolidation.

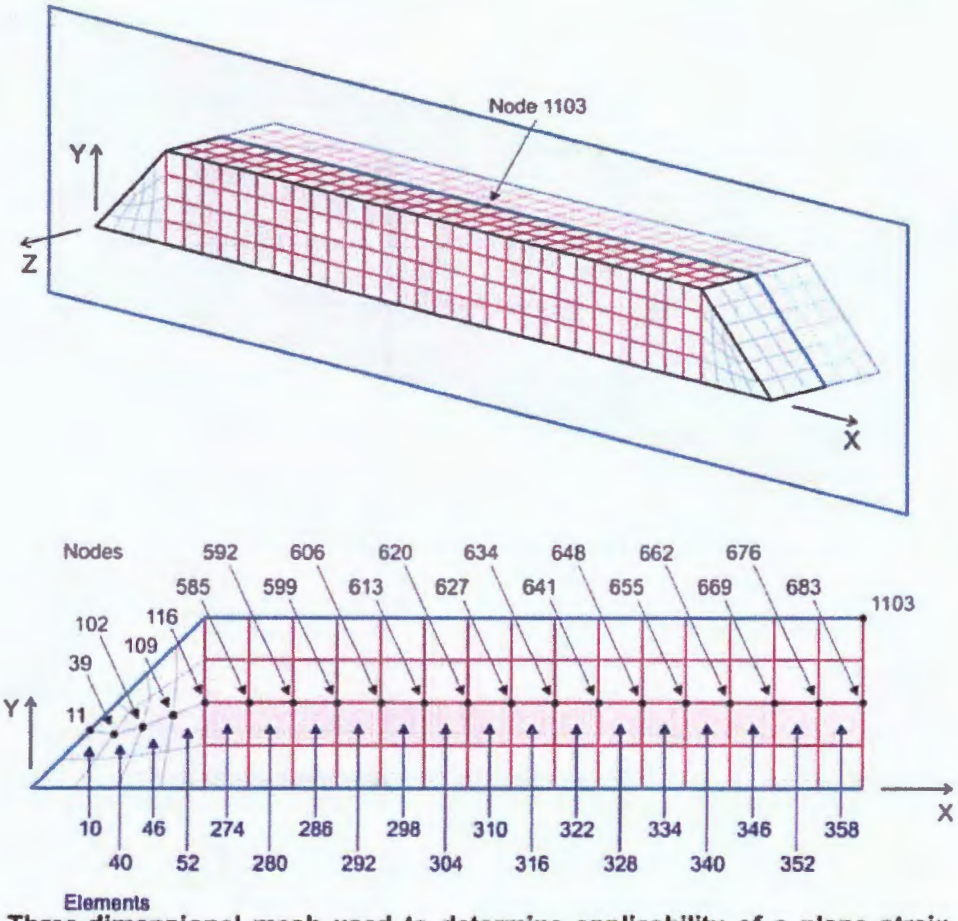

Figure 21. Three-dimensional mesh used to determine applicability of a plane strain condition. Lower figure shows the nodes and elements in the inner rectangular block (in cyan) that are used to define lateral displacements within the crushed salt.

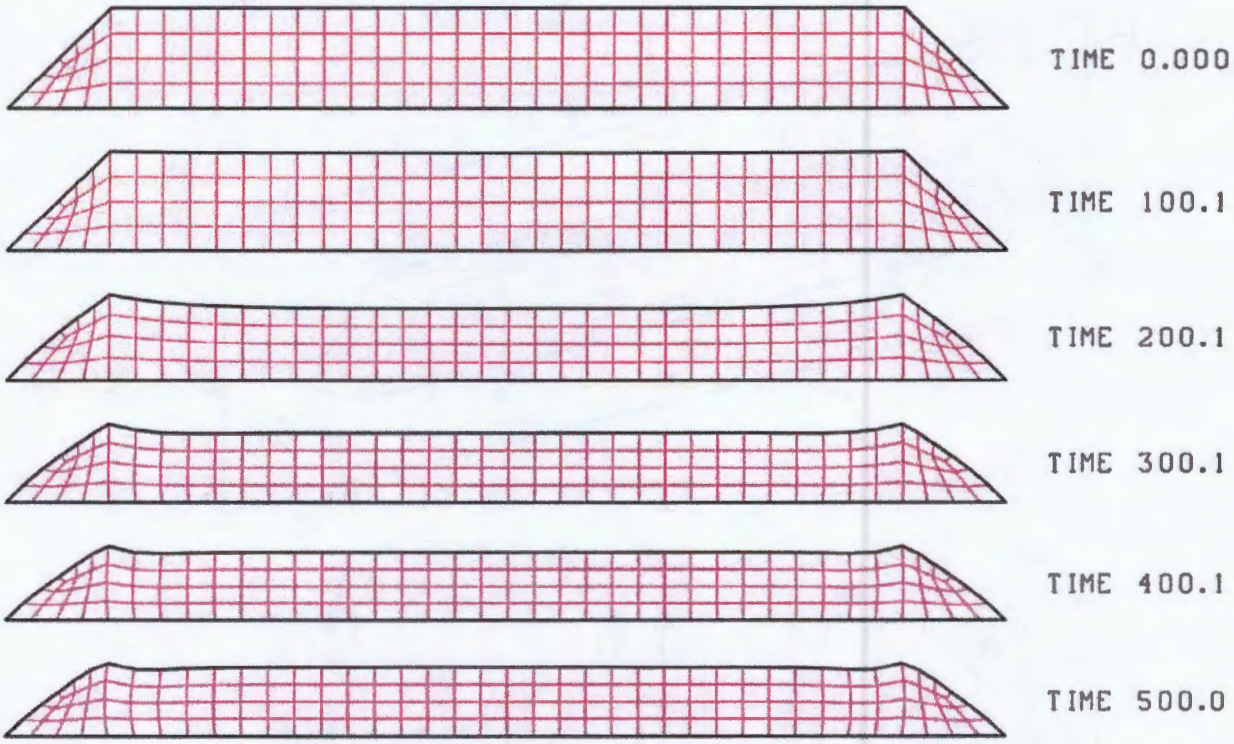

Figure 22. Deformed meshes at various times over the 500-year simulation period

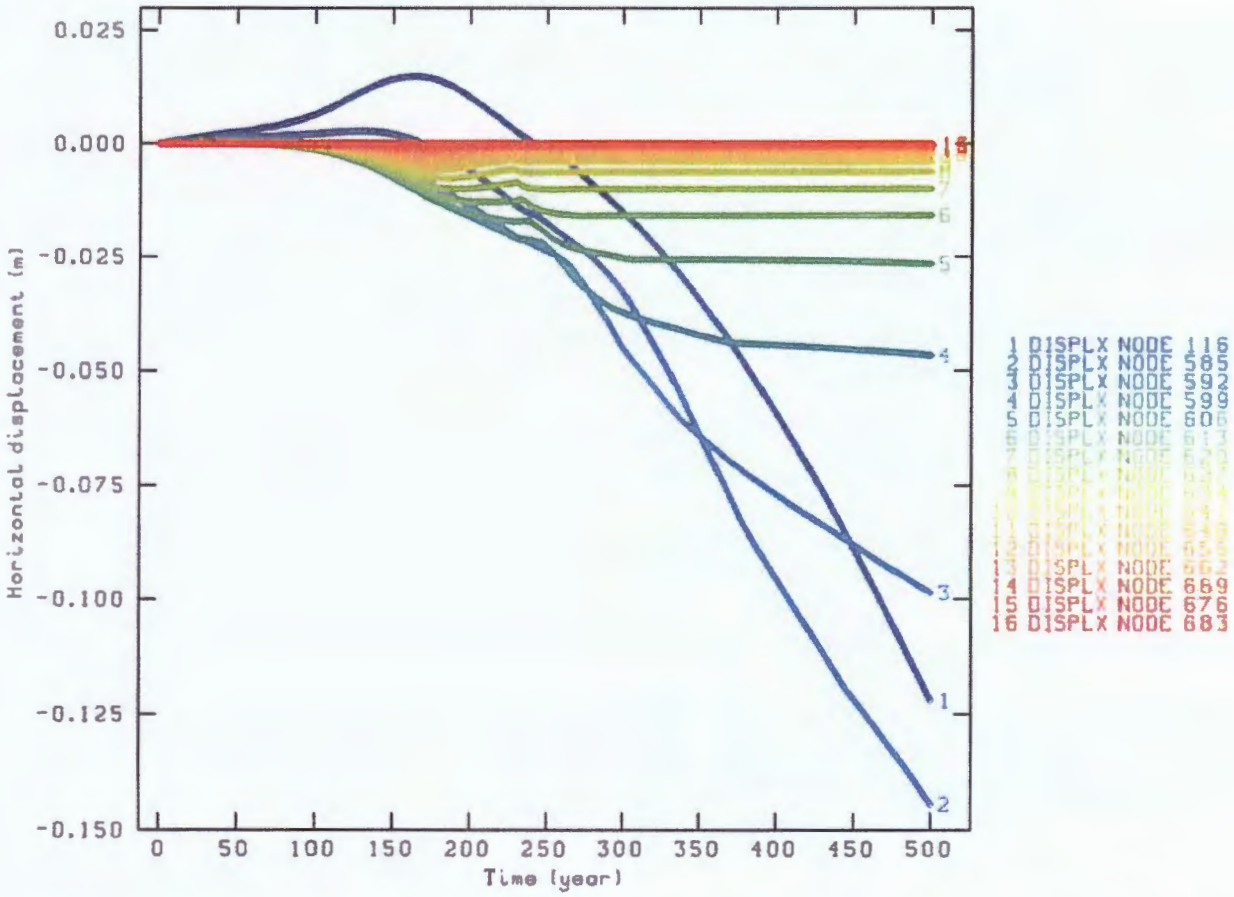

Figure 23. Plots of the horizontal displacements in the x-direction of the nodes shown in Figure 21~~Figure 21~~~~Figure 21~~

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1.4 Panel Closure DRZ Permeability

Parameter Name	PABC 2009 Value	Used in PC3R PA ERMS 555489	Units
Long-Term T2 Values for the PCS DRZ			
PCS_T2:PRMX_LOG PCS_T2:PRMY_LOG PCS_T2:PRMZ_LOG	-20.7, -18.8, -17.0 for material CONC_PCS	-22.8, -20.2, -17.6 Triangular Distribution	$\log(m^2)$

Technical Question 1.4a: *Please justify the assignment of permeability values to the PCS DRZ during time period T2 that appear to represent a fully reconsolidated material, when the ROM salt panel closure itself has not yet fully reconsolidated and stress equilibrium has not yet been achieved.*

DOE Response to Technical Question 1.4a:
This response identifies the values to be used for the DRZ permeability. As discussed in the answers to questions 1.1 and 1.3, it is our intent to use multiple time periods to represent the behavior of the PCS and the surrounding strata. This differs from the approach for the PC3R PA, which used a single time period from 100 years to 10,000 years.

Initially, it is expected that the DRZ around the closure will be no different from that around the disposal rooms, since there will be only very small back stress from the consolidating salt. Calculations of the back stress during consolidation (Figures 25 and 26) show that these stresses do not become appreciable until over 100 years after emplacement (Herrick, 2012). It is appropriate to maintain the same range of DRZ permeability around the closure as that around the disposal rooms for the first 200 years. The values assumed for the first two time periods will therefore range from $10^{-19.4}$ m^2 to $10^{-12.5}$ m^2.

After 200 years, back pressures will have built up to reasonable values of the order of 6 to 10 MPa (Figures 25 and 26). It has been shown by several authors that fractures in salt will heal rapidly under these levels of stress (e.g., IT Corporation, 1987, and Costin and Wawersik, 1980). For example, Costin and Wawersik state:

- Tensile fractures in salt will heal when subjected to nominal overburden pressures (10-35 MPa), to the extent that the resistance to crack propagation along the pre-existing fracture plane is approximately 70-80% of that through virgin material.
- The healing process takes place rapidly compared to the time scale over which mining or storage in salt occurs.
- The principal mechanism in healing appears to be creep of contact asperities along the fracture surface.

Given the values of back stress calculated for closures with some degree of emplaced compaction, and the rapid increase of stress even for the most extreme case of uncompacted dry salt, it is appropriate to assume a DRZ permeability after 200 years equivalent to that used for the

Option D case. The proposed values for DRZ permeability after 200 years are therefore 2×10^{-21} m^2 to 1×10^{-17} m^2 at all times (Clayton et al., 2010).

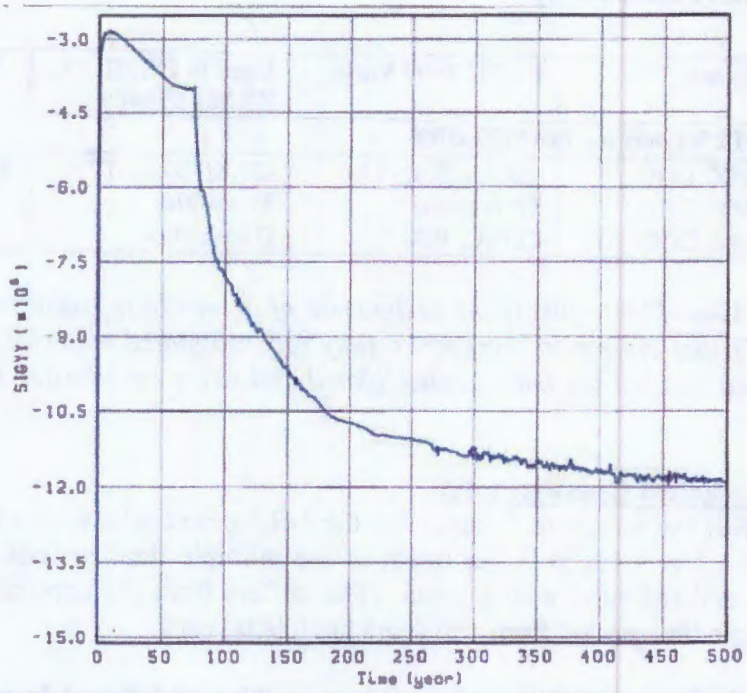

Figure 24. Vertical back stress on the roof of the panel entry for crushed salt with an initial emplacement porosity of 15% (fractional density of 85%)

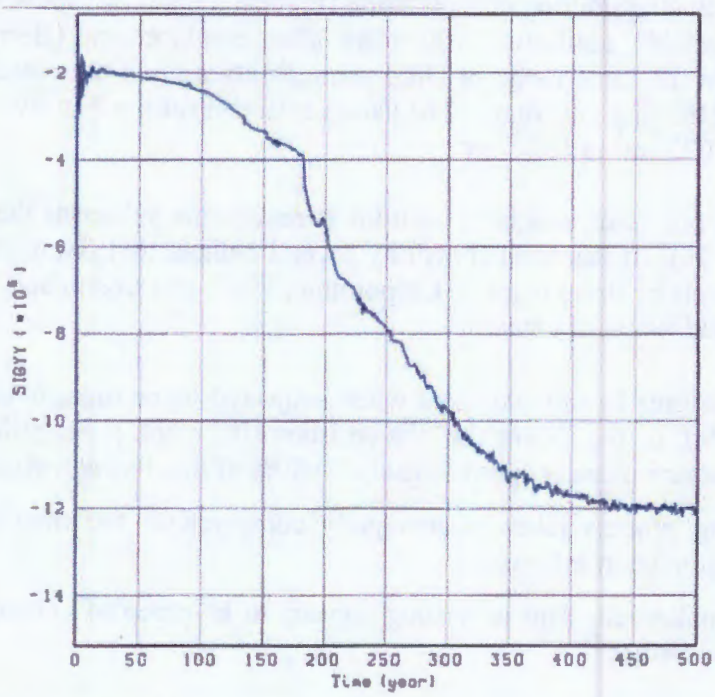

Figure 25. Vertical back stress on the roof of the panel entry for crushed salt with an initial emplacement porosity of 33% (fractional density of 67%)

EPA Technical Question 1.4b:
Please explain why the anhydrite marker beds surrounding the ROM salt panel seal are not treated in the same manner as those within the waste panel DRZ.

DOE Response to Technical Question 1.4b:
The anhydrite marker beds around the panel closure entries and the disposal room will have similar form prior to emplacing the crushed salt component of the panel closure. After emplacement and consolidation of the crushed salt, the vertical back stress on the roof of the panel increases to between 6 MPa and 10 MPA after 200 years (see Figures 25 and 26). This level of back stress will be sufficient to heal any fractures in the DRZ and to close fractures in the anhydrite, as discussed in the answer to Question 1.4a. The presence of high levels of back stress above the crushed salt component of the panel closure explains part of the reason why the anhydrite marker beds above the crushed salt component are not treated in the same manner as the marker beds above the waste panel.

A second reason relates to the representation of the marker beds in the BRAGFLO grid. The BRAGFLO simulations used in WIPP PA utilize an essentially two-dimensional representation of the repository to calculate brine and gas flow in a three-dimensional facility. The reasoning to include the anhydrite marker beds as elements separate from the "healed" DRZ above panel closures in BRAGFLO was based on BRAGFLO grid studies performed in 2003 (Stein and Zelinski, 2003).

Keeping the anhydrite marker bed material as a separate element above each panel closure in the BRAGFLO grid is done to capture a possible three-dimensional flow path in the two-dimensional BRAGFLO grid. More specifically, it is expected that fracturing may occur in the anhydrite marker beds for pressures above the fracture initiation pressure. When this fracturing occurs, it is expected that brine and gas under high pressure could go "around" panel closures by way of a flow path through the fractured anhydrite. In reference to the two-dimensional BRAGFLO repository representation, this flow path would be in the lateral direction, perpendicular to the 2-D plane considered in the model grid. The inclusion of separate anhydrite elements above panel closures in the BRAGFLO repository representation is intended to capture the effects of this out-of-plane flow path, around the panel closure through fractured anhydrite, in the two-dimensional BRAGFLO grid.

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