RESPONSE TO EPA COMMENT DATED JUNE 7, 2012:
Review of Alternate Data Sets for Defining Permeability of Crushed Salt

EPA Comment Dated June 7, 2012:
Please provide an explanation why DOE believes that the current approach of using only the Brodsky 1994 porosity (density) – permeability correlation is appropriate, even though there appears to be additional applicable and relevant data (e.g., Spiers et al 1988) on the salt permeability and density relationship.

EPA-Provided Background
DOE has elected to use the Brodsky 1994 (SAND93-7058) permeability versus density data set to establish permeability ranges for the T2 and T3 times for the ROM salt panel closure.

In addition to the Brodsky 1994 data, our review identified that there are laboratory and in situ permeability test results that may be applicable to the panel closure permeability issue. For example, Hansen et al., 1993 (Figure 4, SAND-93-1348C) and Case et al. 1987 provide additional relevant data. In addition Spiers et al. 1988 reports laboratory results on the constitutive properties of ROM salt which include permeability, porosity/density correlations (pages 82-93) with several correlations dependant on the moisture content and porosity type of the consolidated salt. IT (IT Corporation, 1987) conducted laboratory tests on crushed salt producing permeability with respect to density. The data are given in Table 1 and plotted in Figure 1 below. Figure 2 provides a slightly different perspective.

DOE RESPONSE

1.0 Introduction

The U.S. Department of Energy (DOE) has prepared recommendations for defining the hydrologic parameters for run-of-mine (ROM) salt in a panel entry (Camphouse et al., 2012). The ROM salt will be generated by ongoing mining operations at WIPP. The grain size of the ROM salt is generally less than 1.5 inches, but includes some large pieces of salt between 2 and 6 inches on a side. The ROM salt has a moisture content of 0.5% to 2% by weight, based on recent measurements in the underground (personal communication from Ty Zimmerly of Washington TRU Solutions, 2012). After emplacement in a panel entry, creep closure of the entry is expected to consolidate the ROM salt to a state approaching that of the intact salt in the Salado formation. Given the dynamic nature of this process, DOE has defined the porosity-permeability relationship for ROM salt during three time periods: 0 to 100 years, 100 to 200 years, and 200 to 10,000 years. These time periods are denoted as T1, T2, and T3, respectively.

The DOE’s proposed porosity-permeability relationship during the T2 and T3 time periods is based on brine permeability measurements performed by Brodsky (1994). Other investigators have also performed permeability measurements on partly consolidated salt cores from various sites, including Brodsky et al. (1996), Hansen and Ahrens (1996), and Case et al. (1987) using WIPP salt, Spiers et al. (1988) using an engineered salt backfill, Zhang et al. (1987) using salt from the Asse mine in Germany, and Case et al. (1987) using salt from the Avery Island mine in
Kansas. (IT Corporation, 1987) provides additional details on the experiments by Case et al. (1987).

This response provides a critical review of these alternate data sources and explains the DOE’s rationale for selecting specific data sets and excluding other data sets in defining the porosity-permeability relationship during T2 and T3. This response also summarizes the DOE’s basis for assigning the permeability range of ROM salt during the T1 time period.

2.0 Observations on Long-Term Consolidation of ROM Salt

The studies of Spiers et al. (1988) and Hurtado et al. (1997) demonstrate that permeability measurements of dry salt core in the laboratory are biased toward permeability values that are much greater than would be observed in situ for ROM salt in a panel entry during the T2 and T3 time periods. This is an important observation because it implies that laboratory testing with moistened or wet salt core is more relevant to the T2 and T3 time periods than testing with dry core. The technical basis for these statements is summarized here, with additional details provided in Appendix A of this response.

The consolidation of ROM salt in a panel entry occurs in a quasi-static, low strain rate environment over a time scale of 100 years to as much as 300 years. Spiers et al. (1988) carried out a series of experiments to investigate the influence of the quasi-static consolidation process on the microstructure, permeability, and cohesion properties of salt backfill under long-term repository conditions (Spiers et al., 1988, Section 6.3). Based on the results of these “annealing” experiments, they concluded that: (1) the laboratory measurements for the permeability of moistened core versus total porosity gives an upper bound estimate for long-term permeability (Spiers et al., 1988, Section 6.3.4, Item (1)), and (2) the long-term microstructure and physical properties of the salt backfill can be expected to approach those of intact halite (Spiers et al., 1988, Section 6.3.4, Item (2))

The conclusions from the work of Spiers et al. (1988) are confirmed by a number of independent observations:

- In situ observations from the BAMBUS II project at the Sigmundshall mine in Germany (Bechthold et al., 2004, Figure 2.57) and at the Rocanville mine (Van Sambeek et al., 1995) indicate consolidation of crushed salt to essentially an intact condition within tens of years. These results confirm that crushed salt can be expected to consolidate to a state approaching that of intact halite, as Spiers et al. (1988) concluded.

- The data from Brodsky (1994) ignore the reduction in permeability that is observed during individual tests (Brodsky, 1994, Tables 5-10 and 5-11). This reduction, which occurred over a typical time scale of 60 days, indicates the potential for slow consolidation to cause pore occlusion that further reduces the long-term permeability of consolidating salt, similar to the effect of the quasi-static annealing mechanism discussed by Spiers et al. (1988).
Laboratory measurements of permeability with moistened salt core are generally greater than the permeability of intact salt. Measurements by Brodsky (1994) and by Case et al. (1987, Test 3) are generally greater than $10^{-21} \, m^2$, while the permeability of intact salt is represented as less than $10^{-21} \, m^2$ in WIPP performance assessment. This confirms that laboratory measurements provide an upper bound on the permeability of intact halite, as Spiers et al. (1988) concluded.

The permeability of cores of WIPP crushed salt has been observed to be sensitive to the microstructure of the cores. At equivalent fractional densities, the pressure solution/redeposition observed for moistened core produces more deformation and lower permeability than crystal plasticity, which is observed for dry salt core (Hurtado et al. 1997, Figure 2-1; Case et al., 1987, data for Test 3 in Figure 1). Spiers et al. (1988, Section 3.4 (ii) and (iii)) also observe similar differences in the microstructure of wet-versus dry-compacted material.

DOE’s conclusion from the studies of Spiers et al. (1988) and Hurtado et al. (1997) is that laboratory measurements of the permeability of dry salt core are biased toward permeability values that are much greater than would be observed in situ for ROM salt in a panel entry during the T2 and T3 time periods. Testing with moistened or wet salt core is more relevant to the T2 and T3 time periods because the long-term annealing caused by quasi-static consolidation of ROM salt in a panel entry results in significant pore occlusion, similar to that found in the microstructure of a wet or moistened core. Note that the long-term mechanism driving annealing, identified as fluid assisted diffusional transfer by Spiers et al. (1988), should occur in ROM salt from the WIPP as well as in salt from other sources.

3.0 Criteria for Selection of Data Sets

In evaluating the various sources of permeability data for crushed salt, the DOE has used the following criteria to define the data sets that are most relevant to ROM salt in a panel entry:

- **Porosity or Fractional Density.** Crushed salt cores are precompacted to a specific porosity or fractional density prior to testing. Cores with porosity or fractional density that falls within the predicted ranges for ROM salt during the T1, T2, or T3 time periods are most relevant for defining permeability. Table 1 defines the predicted porosity ranges of ROM salt as a function of time (Camphouse et al., 2012, Section 5.1.1 and Table 2). Table 1 also defines the corresponding values of fractional density, defined as the ratio of core density to the density of intact salt. In terms of porosity, fractional density equals 1 minus the (total) porosity of the core.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Porosity*</th>
<th>Fractional Density**</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1, from 0 to 100 years</td>
<td>6.6% to 18.7%</td>
<td>0.813 to 0.934</td>
</tr>
<tr>
<td>T2, from 100 to 200 years</td>
<td>2.5% to 7.5%</td>
<td>0.925 to 0.975</td>
</tr>
<tr>
<td>T3, from 200 to 10,000 years</td>
<td>0.1% to 5.19%</td>
<td>0.948 to 0.999</td>
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</table>

* The range of porosity during T1 is based on the midpoint of the time interval, 50 years.
** Fractional density is defined as 1 minus the (total) porosity.
• **Dry versus Wet Salt.** The measured permeability of dry cores of crushed salt is often significantly greater than the measured permeability for moistened core. DOE believes that the primary cause of this difference is the variation in the microstructure of dry core versus wet core. A secondary cause of this difference is the Klinkenberg effect for "gas slippage" (Bear, 1988, Section 5.3.3). In practice, the Klinkenberg effect is relatively modest and the orders of magnitude difference between wet and dry permeability measurements for salt cores is caused primarily by differences in microstructure.

• **Grain Size.** The grain size of ROM salt from the WIPP site is generally less than 1.5 inches (38 mm), and has a maximum size of 6 inches (150 mm) (personal communication from Ty Zimmerly, Washington TRU Solutions, 2012). However, most cores for laboratory testing use smaller grain sizes. For example, Brodsky used crushed WIPP salt with a maximum grain size of 9.5 mm (Brodsky, 1994, Section 2.2.2). The testing by Spiers et al. (1988) used a backfill with 75-80% mass fraction composed of sieved analytic grade NaCl powder with a grain size of 275±25 μm (0.275±0.025 mm) (Spiers et al., 1988, pp. 81 and 83).

For porosities above 20%, the permeability of wet or dry core is a function of both porosity and grain size (Case et al., 1987, Section 4). On the other hand, Spiers et al. found that permeability of wet backfill is largely independent of grain size (Spiers et al., 1988, Section 6.2.5). The impact of grain size on permeability measurements for moistened cores of crushed salt is ambiguous at this time.

• **Origin.** Cores based on mined salt from the WIPP site are more relevant than salt cores from other sites, such as the Asse mine in Germany. It is unclear whether or not origin and the presence of impurities is a major factor in permeability measurements.

### 4.0 Sources of Permeability Data

DOE has considered permeability data for crushed salt from six sources, listed below. The key features of each data set relative to the selection criteria are also summarized.

• Brodsky, 1994. Brine permeability testing with wet cores of WIPP salt (data presented in Figure 1). Porosity range of 0% to 10.5% for the cores is relevant to the T2 and T3 time periods, which have a porosity range from 0.1% to 7.5%. These brine permeability data are directly relevant to the T2 and T3 time periods.

• Brodsky et al., 1996 and Hansen and Ahrens, 1996. Brodsky et al. performed gas permeability testing with dry cores of WIPP salt, and Hansen and Ahrens performed *in situ* testing using a gas permeant (data presented in Figure 1). The porosity range of 6.6% to 17.8% for the cores and *in situ* tests is directly relevant to the T1 time period, which has a porosity range of 6.6% to 18.7%. These data were also considered for the T2 and T3 time periods, although most data points are outside the porosity range for T2 and T3.
Case et al., 1987. Gas permeability testing with dry and moistened cores of WIPP salt and with salt from the Avery Island Mine (data presented in Figure 2). The results from Consolidation Test 3 are directly relevant to the T2 and T3 time periods. Test 3 consisted of WIPP salt with a moisture content of 2.3% and a maximum particle size of 20 mm. Test 3 achieved a final porosity of about 5% and a final permeability of about $10^6$ millidarcy ($10^{-21} \text{ m}^2$). The data from Tests 1, 2, and 4 are not relevant to time periods T2 and T3 because these tests used dry cores, but are considered for the T1 time period. The detailed test data are documented in (IT Corporation, 1987).

Zhang et al., 2007. Crushed salt with maximum grain size of 32-mm was used to create cores with porosity between 7% and 30% (data presented in Figure 3). These results are relevant to the T1 time period, which has a porosity range of 6.6% to 18.7%. Crushed salt with a maximum grain size of 8-mm was used to create dry cores with porosity between 1.5% and 10%. This porosity range is relevant to the T2 and T3 time periods, although the use of salt from the Asse mine and the use of dry core for testing make these data less relevant than the (Brodsky, 1994) data set.
Figure 2. Permeability data from (Case et al., 1987) and (IT Corporation, 1987)

Figure 3. Permeability data from (Zhang et al., 2007)
Spiers et al., 1988. Spiers et al. conducted a series of experiments on engineered backfill under dry and wet conditions. The engineered backfill had the following composition:

- **Dry backfill:** ~80% fine salt (275 μm ± 25 μm), ~17% coarse salt filler (1 to 5 cm), 2-3% plus Fe₂O₃ (Spiers et al., 1988, Section 6.1)
- **Wet backfill:** 75.5% ± 0.5% fine salt (275 μm ± 25 μm), ≈ 14.3% ± 0.5% coarse salt filler (1 cm), 2.5% ± 0.5% anhydrite plus Fe₂O₃, 4.75% ± 0.1 weight percent brine (Spiers et al., 1988, Section 6.2.2).

Samples were compacted dry to a starting porosity of 38.8% ± 0.5% or 24.8% ± 1% and the prescribed amount of brine was subsequently added. The final value of total porosity for the “Bazooka” experiment with wet backfill is above 6% (Spiers et al., 1988, Figure 6.7) and not directly applicable to the T2 and T3 time periods. The “Bazooka” experiment with dry backfill has four points below 10% porosity (Spiers et al., 1988, Figure 6.2), although the use of dry core for testing makes these data less relevant than the (Brodsky, 1994) data set. In addition, the relevance of permeability data for a very fine grained (275 μm ± 25 μm) salt powder relative to the ROM salt from WIPP is unknown at this time.

### 5.0 Porosity-Permeability Relationship During Time Period T1

The permeability range during T1 is based on data for dry and wet cores from Brodsky (1994), Brodsky et al. (1996), Hansen and Ahrens (1996), Case et al. (1987) and Zhang (2007). The rationale for this approach is that the ROM salt may have undergone minimal compaction or substantial compaction during this initial time period, so test results for dry and wet core have been considered in defining the permeability range during T1.

A porosity-permeability relationship is not defined during the T1 time period. Instead, the limits of the porosity range are used to define the minimum and maximum permeability during T1. More specifically, the minimum porosity of 6.6% during T1 (see Table 1) is the basis for defining the minimum permeability during T1 and the maximum porosity of 18.7% is the basis for defining the maximum permeability during T1. This approach propagates the variability in permeability during the T1 time period into the performance assessment.

Table 2 summarizes the permeability data for cores of crushed salt that are relevant to the maximum porosity of 18.7%. The data are from three sources: Brodsky et al. (1996), Case et al. (1987), and Zhang et al. (2007). The data from Brodsky et al. (1996) provide an upper bound for the data from Brodsky (1994) and from Hansen and Ahrens (1996), so these latter sources are implicitly included in Table 2.

The permeability data in Table 2 are remarkably consistent and provide a basis for defining the maximum permeability during T1 as 10⁻¹² m². The data from Spiers et al. (1988) for dry or wet core are also consistent with this choice. The permeability of the dry and wet cores is between 10⁻¹³ and 10⁻¹² m² at 18.7% porosity (Spiers et al., 1988, Figures 6.2 and 6.7). However, the relevance of testing an engineered backfill with very fine grained (275 μm ± 25 μm) salt powder to WIPP’s ROM salt is unclear at this time, so these data are not included in Table 2.
Table 2. Permeability data for cores of crushed salt at 18.7% porosity

<table>
<thead>
<tr>
<th>Source</th>
<th>Porosity</th>
<th>Permeability (m²)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Brodsky et al., 1996),</td>
<td>16.5%</td>
<td>1.1×10⁻¹² m²</td>
<td>For dry WIPP salt at fractional density of 0.835 (porosity of 16.5%). This core has the greatest permeability of the data in (Brodsky et al., 1996) and (Brodsky 1994).</td>
</tr>
<tr>
<td>summarized in Table 2-1 of (Hurtado et al., 1997)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case et al., 1987, Figure 1</td>
<td>18.7%</td>
<td>1×10⁻¹⁰ m² to 2×10⁻¹² m²</td>
<td>For dry WIPP salt with 0.9 mm and 10 mm maximum grain sizes (Tests 1 and 2) and for moistened WIPP salt with 20 mm maximum grain size (Test 3).</td>
</tr>
<tr>
<td>Zhang et al., 2007, Figure 4</td>
<td>18.7%</td>
<td>2×10⁻¹⁴ m² to 1×10⁻¹² m²</td>
<td>For dry Asse salt cores with maximum grain size of 32 mm.</td>
</tr>
</tbody>
</table>

At the minimum porosity of 6.6%, there is a wide range of permeability because of the microstructure of dry versus wet core. Table 3 summarizes the measured values that are relevant to a porosity of 6.6%. The permeability data in Table 3 for dry cores are relatively consistent, falling within a permeability range of 10⁻¹⁵ m² to 10⁻¹³ m². The permeability data in Table 3 for wet cores are significantly lower, with a minimum value of 2.26×10⁻²¹ m² from Test 3 of Case et al. (1987). (Numerical values for Test 3 are documented in (IT Corporation, 1987, Appendix D.1.).

Table 3. Permeability data for cores of crushed salt at 6.6% porosity

<table>
<thead>
<tr>
<th>Source</th>
<th>Porosity</th>
<th>Permeability (m²)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Brodsky et al., 1996) &amp; (Brodsky, 1994), summarized in Table 2-1 of (Hurtado et al., 1997)</td>
<td>6.61%</td>
<td>4.95×10⁻¹⁵ m²</td>
<td>For dry WIPP salt at a fractional density of 0.9339 (porosity of 6.61%). (Brodsky et al., 1996)</td>
</tr>
<tr>
<td>Case et al., 1987, Figure 1</td>
<td>6.7%</td>
<td>2.14×10⁻¹⁰ m²</td>
<td>For wet WIPP salt at a fractional density of 0.9333 (porosity of 6.67%). (Brodsky 1994)</td>
</tr>
<tr>
<td>IT Corporation*, 1987, Appendix D.1, Consolidation Test 3 - Test Data</td>
<td>6.5%</td>
<td>2.26×10⁻²¹ m²</td>
<td>Minimum permeability between 5% and 7% porosity for moistened WIPP salt with 20 mm maximum grain size (Test 3).</td>
</tr>
<tr>
<td>Zhang et al., 2007, Figure 4</td>
<td>6.6%</td>
<td>7×10⁻¹⁵ m² to 9×10⁻¹⁴ m²</td>
<td>For dry Asse salt cores, maximum grain size of 8 mm. For dry Asse salt cores, maximum grain size of 32 mm.</td>
</tr>
</tbody>
</table>

*(IT Corporation, 1987) provides numerical data for the results presented in (Case et al., 1987).

The data from Spiers et al. (1988) for dry or wet core lie between 10⁻¹³ and 10⁻¹⁵ m² at a porosity of about 6% (Spiers et al., 1988, Figures 6.2 and 6.7). These data have not been included in Table 3 because of testing an engineered backfill with very fine grained (275 μm ± 25 μm) salt powder to WIPP's ROM salt is unclear at this time.

The minimum value from Test 3 of (Case et al., 1987), 2.26×10⁻²¹ m², has been corrected for the Klinkenberg effect, based on the formulation in the BRAGFLO code (Nemer, 2007, Section 4.12, Equation (139)). The corrected value is 1.07×10⁻²¹ m², based on an average flowing pressure of 500 psi (3.45×10⁶ Pa) (IT Corporation, 1987, Section 3.1.5). The minimum permeability during the T1 time period is based on this value and approximated as 10⁻²¹ m².
In summary, the recommended porosity range during T1 is $10^{-21}$ m$^2$ to $10^{-12}$ m$^2$. The upper bound is the same value that is recommended in (Camphouse et al., 2012, Section 4.1.2), while the lower bound is reduced by approximately two orders of magnitude from the value in (Camphouse et al., 2012, Section 4.1.2). DOE also recommends that the permeability of the ROM salt during T1 should be sampled from a log-uniform distribution to provide robust representation of the full range of permeability in performance assessment. The sampled value for the permeability of ROM salt is independent of the sampled value for the porosity of ROM salt during the T1 time period.

6.0 Assessment of Data for the Porosity-Permeability Relationship During Time Periods T2 and T3

During the second and third time periods, the permeability of consolidated ROM salt is based on the experimental measurements of Brodsky (1994) because the salt cores are based on ROM salt from the WIPP, because the salt cores are wetted with a brine permeant, resulting in a microstructure that is more similar to quasi-static compaction during T2 and T3 than dry core, and because the initial porosity of the core has a range of 0% to 10.5%, which spans the porosity range of interest during the T2 and T3 time periods, which is 0.1% to 7.5%. The porosity-permeability relationship based on (Brodsky, 1994) is defined in (Camphouse et al., 2012, Section 4.1.2, particularly Figures 5 and 7), and not repeated here.

The alternate data sets identified in Section 4 are less suitable for WIPP performance assessment than the data in (Brodsky, 1994):

- (Brodsky et al., 1996) and (Hansen and Ahrens, 1996) have gas permeability data for WIPP salt in the porosity range of 6.6% to 17.8%. However, only 2 out of 14 data points are within the T2 and T3 porosity range, which is 0.1% to 7.5%. Figure 1 (on page 5) presents the permeability measurements for these two sources and for (Brodsky, 1994).

DOE's position is that (1) the dry cores do not represent the long-term pore structure of the ROM salt during the T2 and T3 time periods, (2) the porosity range for the dry cores is not applicable to the porosity range of ROM salt during the T2 and T3 time periods, and (3) these gas permeability data represent a distinct data set that should not be combined with the brine permeability data of (Brodsky, 1994). This final point is illustrated in Figure 4, which includes: (1) a fit to the brine permeability data (Brodsky, 1994), shown in purple, (2) a fit to the gas permeability data (Brodsky et al., 1996; Hansen and Ahrens, 1996), shown in green, and (3) a fit to the combined data, shown as a black dashed line.

The fits to the individual data sets, for brine data only or for gas data only, provide good representations of the mean permeability of these data sets as a function of fractional density. A least squares fit to all the data provides a poor representation of the mean permeability of the individual data sets, in spite of its $R^2$ value of 0.77, as shown in Figure 4. This poor representation is attributed to the difference in the microstructure of the dry cores for gas permeability testing versus the microstructure of the wet cores for brine permeability testing. DOE believes the gas permeability data represent a separate...
and distinct data set that should not be combined with the brine permeability data from (Brodsky, 1994).

![Graph showing comparison of least squares fits to brine permeability data, gas permeability data, and combined data sets.](image)

Figure 4. Comparison of least squares fits to the brine permeability data (only), to the gas permeability data (only), and to the combined data sets.

- (Case et al., 1987, Table 1) has gas permeability data for two dry cores of WIPP salt with maximum particle sizes of 0.9 mm and 10 mm (Tests 1 and 2), for one core of moistened WIPP salt with maximum particle size of 20 mm (Test 3), and for one dry core of Avery Island Mine salt with maximum particle size of 10 mm (Test 4). Figure 2 (on page 5) presents the permeability measurements for Tests 1 through 4.

The final porosity of the dry cores is greater than 13.5% (IT Corporation, 1987, Appendix D.1). The DOE position is that the dry cores do not represent the long-term pore structure of the ROM salt during the T2 and T3 time periods and that the porosity range for the dry cores is not applicable to the porosity range of ROM salt during the T2 and T3 time periods. DOE recommends that the data from Tests 1, 2, and 4 of (Case et al., 1987) not be included in the porosity-permeability relationship for ROM salt during the T2 and T3 time periods.

Figure 5 presents the combined data from Test 3 of (Case et al., 1987) and from (Brodsky, 1994). Figure 5 includes the data from Test 3 with porosity less than or equal to 10.5%, which is the maximum porosity for brine permeability testing in (Brodsky, 1994). Numerical values for Test 3 are available in (IT Corporation, 1987, Appendix D.1,
tabular listing for Consolidation Test 3 – Test Data). These values were corrected for the Klinkenberg effect, using the formulation in the BRAGFLO code (Nemer, 2007, Section 4.12, Equation (139)). Figure 5 also includes least squares fits to the (Brodsky, 1994) data (alone), shown as the purple line, and to the combined data sets from (Brodsky, 1994) and (Case et al., 1987, Test 3), shown as the red line.

\[
y = -21.187x + 1.5353
\]

\[
y = -19.304x - 0.8914
R^2 = 0.1848
\]

Figure 5. Permeability data from (Case et al., 1987). Data from (Brodsky, 1994) are shown as purple diamonds and data from Test 3 of (Case et al., 1987) are shown as red squares. Purple line is linear fit to (Brodsky, 1994), and red line is linear fit to the combined data sets.

The least squares fits in Figure 5 are rather similar, although the scatter in the combined data set reduces the \( R^2 \) value from 0.3222 to 0.1848, implying that there is a weak correlation of porosity and permeability for the combined data set. This is caused, in part, by the fact that the data from Test 3 are skewed to very low values - there are a cluster of 8 points with permeability less than \( 10^{-20} \text{ m}^2 \) from Test 3. The clustering of these points is an artifact of the test procedure, wherein the single core for Test 3 was progressively compressed to lower porosity in a stepwise fashion, and permeability was measured at each of the individual steps. The number of points with permeability less than \( 10^{-20} \text{ m}^2 \) is then a reflection of the test procedure, not an indication of the relative frequency of randomly compacted core samples.

Given the bias toward low permeability in the data from Test 3 and the fact that the data from Test 3 do not represent a random sampling of tests with multiple cores (as is true for the data from (Brodsky, 1994)), DOE recommends that the Test 3 data should not be combined with the data from (Brodsky, 1994) in defining the porosity-permeability relationship for the ROM salt during the T2 and T3 time periods.
• (Zhang et al., 2007) provide a range of permeability data for Asse salt, including laboratory testing of dry crushed salt cores with maximum grain sizes of 32 mm and 8 mm (see Figure 3 on page 6). The test data for the coarse-grained cores span a porosity range from about 7% to almost 40%, and the fine-grained cores span a porosity range from 1.5% to 10%. DOE’s position is that (1) the dry cores do not represent the long-term pore structure of the ROM salt during the T2 and T3 time periods, (2) the porosity range for the dry coarse-grained cores is not applicable to the porosity range of ROM salt during the T2 and T3 time periods, and (3) the cores are based on salt from the Asse mine rather than WIPP salt, although the impact of this difference is unknown. DOE recommends that the data from (Zhang et al., 2007) not be included in the porosity-permeability relationship for ROM salt during the T2 and T3 time periods.

• (Spiers et al., 1988, Figures 6.2 and 6.7) provide permeability testing on cores with an engineered backfill that is composed primarily of very fine grained (275 μm ± 25 μm) salt powder. The total porosity of the moistened cores is greater than 10% and is not relevant to the porosity range for the T2 and T3 time periods. The porosity of the dry cores is as low as 0.4%. DOE recommends that the data from (Spiers et al., 1988) not be included in the porosity-permeability relationship for ROM salt during the T2 and T3 time periods because the relevance of testing an engineered backfill versus the ROM salt at WIPP is unclear and because the pore structure of dry core is not relevant to the long-term pore structure of ROM salt during the T2 and T3 time periods.

DOE recommends that, for the T2 and T3 time periods, the PCS-2012 performance assessment should retain the original porosity-permeability model defined in (Camphouse et al., 2012) using the data from (Brodsky, 1994) alone, without the other data sources discussed in this section.

7.0 Conclusions


The review considered the short-term and long-term processes driving changes in the microstructure of the cores. DOE’s conclusion from the studies of Spiers et al. (1988) and Hurtado et al. (1997) is that laboratory measurements of the permeability of dry salt core are biased toward permeability values that are much greater than would be observed in situ for ROM salt in a panel entry during the T2 and T3 time periods. Testing with moistened or wet salt core is more relevant to the T2 and T3 time periods because the long-term annealing caused by quasi-static consolidation of ROM salt in a panel entry results in significant pore occlusion, similar to that found in the microstructure of a wet or moistened core. Note that the long-term mechanism driving annealing, identified as fluid assisted diffusional transfer by Spiers et al. (1988), should occur in ROM salt from the WIPP as well as in salt from other sources.
During the T1 time period, the permeability range is based on data for dry and wet cores from Brodsky (1994), Brodsky et al. (1996), Hansen and Ahrens (1996), Case et al. (1987) and Zhang (2007). The rationale for this approach is that the ROM salt may have undergone minimal compaction or substantial compaction during this initial time period, so test results for dry and wet core have been considered in defining the permeability range during T1.

A porosity-permeability relationship is not defined during the T1 time period. Instead, the limits of the porosity range are used to define the minimum and maximum permeability during T1. The recommended porosity range during T1 is $10^{-21}$ m$^2$ to $10^{-12}$ m$^2$. The lower bound of this range, $10^{-21}$ m$^2$, is two orders of magnitude less than the lower bound defined in (Camphouse et al., 2012). DOE also recommends that the permeability of the ROM salt during T1 should be sampled from a log-uniform distribution to provide robust representation of the full range of permeability in performance assessment.

During the T2 and T3 time periods, the PCS-2012 performance assessment should retain the original porosity-permeability model defined in (Camphouse et al., 2012) using the data from (Brodsky, 1994) alone. The rationale for this approach is that (1) the linear fit to the (Brodsky, 1994) data has a higher $R^2$ value, 0.32, than the corresponding value of $R^2$ for the combined (Brodsky, 1994/Case et al., 1987, Test3) data set, providing a stronger relationship between porosity and permeability; (2) the linear fit to the combined (Brodsky, 1994/Brodsky et al., 1996) data set provides a poor fit to the mean response of the wet core from (Brodsky, 1994), as illustrated in Figure 4. Again, the use of (Brodsky, 1994) data alone provide a stronger relationship between porosity and permeability; and (3) the alternate data sources are less suitable for WIPP performance assessment, as outlined in Section 6 of this document.
8.0 References


The consolidation of crushed salt core for laboratory experiments occurs over a much shorter time scale than the consolidation process for run-of-mine (ROM) salt in a panel entry. Individual salt cores may be prepared and consolidated over a day or two, although this is not always the case. The subsequent permeability measurements typically occur over a limited time frame, typically a week to a month. The consolidation of ROM salt, on the other hand, is anticipated to occur over 100 years to as much as 300 years.

Consolidation of ROM salt in a panel entry therefore occurs in a quasi-static, low strain rate environment. Spiers et al. (1988) carried out a series of annealing experiments to investigate the influence of static annealing processes on the micro-structure and permeability of consolidated salt. The rationale for the annealing experiments was:

"Examination of the theory of compaction creep by FADT\(^2\) shows that conditions of decreasing strain rate, decreasing effective pressure, and/or decreasing porosity are accompanied by a decrease in the grain-scale free energy gradients driving FADT. Under these conditions, surface energy driving forces will eventually become dominant, giving rise to "static annealing" processes such as static pore occlusion and fluid-assisted grain growth (Coble, 1961). These effects can be expected to have a substantial influence on the micro-structure, permeability and cohesion properties of salt backfill and cement under long term repository conditions...." (Spiers et al., 1988, Section 6.3)

To investigate this effect, they carried out annealing experiments at elevated temperature (to accelerate the kinetics of mass transfer, and to allow these effects to be seen at laboratory time scales). Typical results quoted show a reduction in permeability of $1.21 \times 10^{-15}$ m\(^2\) to $9.96 \times 10^{-17}$ m\(^2\), or about 1 order of magnitude. This was accompanied by a reduction in connected porosity from 5.49% to 3.83%, but no change in total porosity. Spiers et al. conclude that:

"Under repository-relevant, pseudo-static conditions .. surface energy driving forces do lead to pore occlusion and grain growth in wet salt backfill and cement. These processes produce substantial permeability reduction, but their kinetics and influence on permeability cannot presently be quantified in a manner appropriate for long term numerical predictions. Nonetheless, the results obtained provide a firm basis for concluding that the $\kappa$ vs $\phi_t$ relation given in equation 6.3\(^3\) gives an upper bound estimate for the long term permeability of the proposed backfill recipe." (Spiers et al., 1988, Section 6.3.4, Item (1))

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\(^1\) (Case et al., 1987) performed a stepwise compaction of a single core over approximately 30 days.

\(^2\) Fluid Assisted Diffusional Transfer

\(^3\) Equation 6.3 is the relationship between permeability, $\kappa$, and total porosity, $\phi_t$. 

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They also conclude that:

"... the long term microstructure and physical properties of these materials can be expected to approach those of natural salt rock..." (Spiers et al., 1988, Section 6.3.4, Item (2))

The conclusions from the experimental and theoretical work of Spiers et al. (1988) on annealing processes are corroborated by a number of independent observations:

- *In situ* 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). These results indicate that crushed salt can be expected to consolidate to a state approaching that of intact halite, as Spiers et al. (1988) concluded.

- The data from Brodsky (1994) ignore the reduction in permeability that is observed during individual tests (Brodsky, 1994, Tables 5-10 and 5-11). This reduction, which typically occurred over a typical time scale of 60 days, indicates the potential for processes causing pore occlusion to further reduce the long-term permeability of consolidating salt, similar to the annealing mechanism discussed by Spiers et al. (1988).

- Laboratory measurements of permeability are generally greater than the permeability of intact salt with moistened salt cores. Brodsky (1994) measured the brine permeability of 16 salt cores with porosities between ~0% and 10.5%. Fifteen of these cores had permeability greater than $10^{-21}$ m$^2$, which is the upper limit for the permeability of intact halite in WIPP performance assessment. Similarly, the measured permeability for a crushed salt core with 2.3% moisture content was greater than $10^{-21}$ m$^2$ for porosity between 5 and 10% (Case et al., 1987, Test 3). These results demonstrate that the permeability in the laboratory for moistened or wet salt cores provides an upper bound on the permeability of intact halite, as Spiers et al. (1988) concluded.

The permeability of cores of WIPP crushed salt has been observed to be sensitive to the microstructure of the 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; Case et al., 1987, Section 4). Pressure solution/redeposition generally produces more deformation than crystal plasticity, leading to occlusion of pores and lower permeability for wet consolidated salt than for dry consolidated salt at equivalent fractional densities (Hurtado et al. 1997, Figure 2-1; Case et al., 1987, data for Test 3 in Figure 1).
Spiers et al. (1988, Section 3.4 (ii) and (iii)) also observe significant differences in the microstructure of wet- versus dry-compacted material. Dry compacted material had a highly porous aggregate structure consisting of a more or less randomly packed array of cubes with relatively few contact points and little evidence for plastic deformation or indentation/truncation structures at grain contact points (Spiers et al., 1988, Section 3.4 (ii)). Wet compacted material had a very different microstructure and was observed to have grain-to-grain indentation, contact truncation, grain shape changes, and overgrowth changes on pore walls that provide evidence of fluid assisted diffusional transfer (Spiers et al., 1988, Section 3.4 (iii)).

DOE's conclusion from the studies of Spiers et al. (1988) and Hurtado et al. (1997) is that laboratory measurements of the permeability of dry salt core are biased toward permeability values that are much greater than would be observed in situ for ROM salt in a panel entry during the T2 and T3 time periods. Testing with moistened or wet salt core is more relevant to the T2 and T3 time periods because the microstructure of the wet or moistened core has more deformation and more pore occlusion, similar to the effects of long-term annealing caused by quasi-static consolidation of ROM salt in a panel entry. Note that the long-term mechanism driving annealing, identified as fluid assisted diffusional transfer by Spiers et al. (1988), should occur in ROM salt from the WIPP as well as in salt from other sources.