Enclosure 1

PLANNED CHANGE NOTICE:

SALT DISPOSAL INVESTIGATIONS WITH A FIELD SCALE HEATER TEST

AT THE WASTE ISOLATION PILOT PLANT

Submitted to the U.S. Environmental Protection Agency (EPA)

Under the EPA's 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant

August 5, 2011

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Acronyms

CBFO	Carlsbad Field Office
CCDF	complementary cumulative distribution function
CFR	*Code of Federal Regulations*
CRA	Compliance Recertification Application
DOE	U.S. Department of Energy
DRZ	Disturbed Rock Zone
EPA	U.S. Environmental Protection Agency
NMED	New Mexico Environmental Department
PA	Performance Assessment
PABC-2009	Performance Assessment Baseline Calculation performed in 2009
PCN	Planned Change Notice
SDI	Salt Disposal Investigations
WIPP	Waste Isolation Pilot Plant

Executive Summary

The U.S. Department of Energy (DOE) Carlsbad Field Office (CBFO) is notifying the U.S. Environmental Protection Agency of its plan to perform a field scale heater test at the Waste Isolation Pilot Plant (WIPP). This field test is part of a broader program of Salt Disposal Investigations (SDI) that is described in *A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP* (DOE 2011). As demonstrated in this planned change notice (PCN), there is no appreciable impact to either the operation of Station A or to the long-term performance of the WIPP as a result of the proposed SDI activities. As a result of the conservative assumptions used in the analyses and the lack of discernible impact, the test parameters analyzed in this PCN could be expanded with minimal effect on repository performance. The focus in this PCN is on the potential impacts from the *in situ* testing on the operation and long-term performance of the WIPP; the plans for laboratory-based salt testing are beyond the scope of this PCN because this type of testing does not directly affect the operation and closure of the WIPP facility.

A primary goal of the SDI field test is to measure the properties and behavior of *in situ* salt in response to temperature in excess of 160°C. The preliminary planning for the SDI test uses five 8.5 kilowatt (kW) heaters in mined alcoves of a central pillar. The preliminary design envisions a two-year heating phase followed by an 18- to 24-month cool-down phase after the heaters are turned off. After the cool-down phase, personnel will reenter the test alcoves to perform additional testing on the halite adjacent to the heaters. This PCN uses a test with a two-year heating/two-year cool-down phase as the base case and considers a test with a four-year heating/two-year cool-down phase as a bounding case.

The operational impacts to WIPP resulting from the construction and operation of the SDI test will be negligible because the SDI facility[1] will be in a remote, newly mined area of the WIPP repository that will be far from underground waste emplacement operations at WIPP. All mining for the SDI test occurs in the northern section of the underground facility, historically termed the "Experimental Area." The access drifts and alcoves for the SDI heaters will be approximately 700 meters from Panel 1, which is the waste panel closest to the test area. In addition, there are no significant impacts from mining for SDI because there will be no mining of waste emplacement panels while the SDI facility is being mined, with the exception of minor maintenance activities in the main facility.

The potential impacts from the construction of the SDI facility on the density of salt aerosol and on the return air at the shrouded probes at Station A have been evaluated. Based on the estimated travel times in the SDI airways and the dilution of salt aerosol from SDI mining with the return air from the main facility, the mining of the SDI facility will not impose a significantly greater aerosol loading on the return air at Station A than current mining operations at WIPP. The maximum temperature change at Station A is predicted to be very small, less than 0.3°C, because the heat from the SDI test would be diluted in the total return air flow. It follows that the operation of the SDI test will not have significant impacts on the shrouded probes at Station

[1] As used in this PCN, the term "SDI facility" refers to the total underground excavations for this field test, including the entries that provide access to and ventilation air for the test area. The term "SDI test area" refers to the test alcoves and test access mains directly surrounding the test pillar, as shown in Figure 2.

A. This impact assessment does not change the existing procedures to inspect the shrouded probes on a periodic basis to ensure that salt buildup does not impact the ability of these probes to take a representative sample of particulates in the ventilation air stream.

Long-term impacts to the WIPP facility resulting from the construction and operation of the SDI test will be negligible because the SDI test area will be in a remote, newly mined area that is at least 700 meters away from the waste emplacement areas in the WIPP repository. The following long-term impacts have been considered:

- The SDI test will generate a thermal pulse that moves outward from the test area into the surrounding halite. The magnitude of this thermal pulse at Panel 1, the repository panel that is closest to the SDI test area, is less than 0.1°C and therefore small enough to be screened out of performance assessment (PA) calculations on the basis of low consequence.

- The SDI heaters may induce peak salt temperatures well above 160°C near the back of the alcoves, and higher temperature results in a significant increase in the creep rate of intact salt. Deformation of the host rock surrounding the alcoves will redistribute mechanical stresses as the alcoves close. However, this stress redistribution near the alcoves is primarily a local effect because salt creeps most rapidly in high temperature regions with the greatest deviatoric stresses, and will not have a significant impact on the waste emplacement panels, which are at least 700 meters away.

- Mining of the SDI facility does not result in a significant increase in subsidence relative to the subsidence from the WIPP waste emplacement areas because the extraction ratio[2] for the SDI facility is on the order of 0.15. In addition, there are no significant impacts from mining for SDI because there will be no mining of waste emplacement panels while the SDI facility is being mined, with the exception of minor maintenance activities in the main facility.

- The impact of the SDI facility on long-term performance has been evaluated in the SDI PA (Camphouse et al. 2011). The mean total normalized releases for the SDI PA are essentially identical to the mean total normalized releases for the Performance Assessment Baseline Calculation performed in 2009 (PABC-2009), which is the current PA baseline. There is therefore no impact on long-term performance of the disposal system as a result of the construction and operation of the SDI field test and the disposal system remains in compliance with the containment requirements of 40 Code of Federal Regulations (CFR) Part 191 (EPA 1993), as implemented by the criteria in 40 CFR Part 194 (EPA 1996).

[2] The volumetric extraction ratio is the ratio of the volume of mined salt to the total volume of the facility, which includes the volume of the pillars). For a room and pillar mine like the WIPP, the volumetric extraction ratio and the areal extraction ratio (i.e., the ratio of the excavated area to the total footprint of the facility, including pillars) are equal and referred to as the extraction ratio.

1.0 Description and Rationale for the Field Test at WIPP

1.1 Introduction

The Waste Isolation Pilot Plant (WIPP) is the first underground repository for disposal of transuranic waste generated by defense-related activities. This dry and geologically inactive site is situated 42 km (26 miles) east of Carlsbad, New Mexico, at a depth of 655 meters (2,150 feet) below land surface. The WIPP facility is situated on a 42 km^2 (16 square mile) tract that is permanently withdrawn from operation and occupancy under federal land laws and administered by the U.S. Department of Energy (DOE). The underground facility is comprised of a series of panels and entry drifts mined in the halite of the Salado Formation, and accessed through four shafts. The repository received its first waste shipment on March 26, 1999 and has received 9,598 waste shipments as of May 25, 2011.

The Secretary of Energy has made areas of the mine available for scientific research, beginning with the OMNISita and Majorana projects in April and December of 2001, respectively. Since 2001, other experiments have been installed in the north section of the underground facility, provided the experiments could be performed without compromising the WIPP's primary mission of waste disposal. Figure 1 illustrates the locations of the current underground experiments.

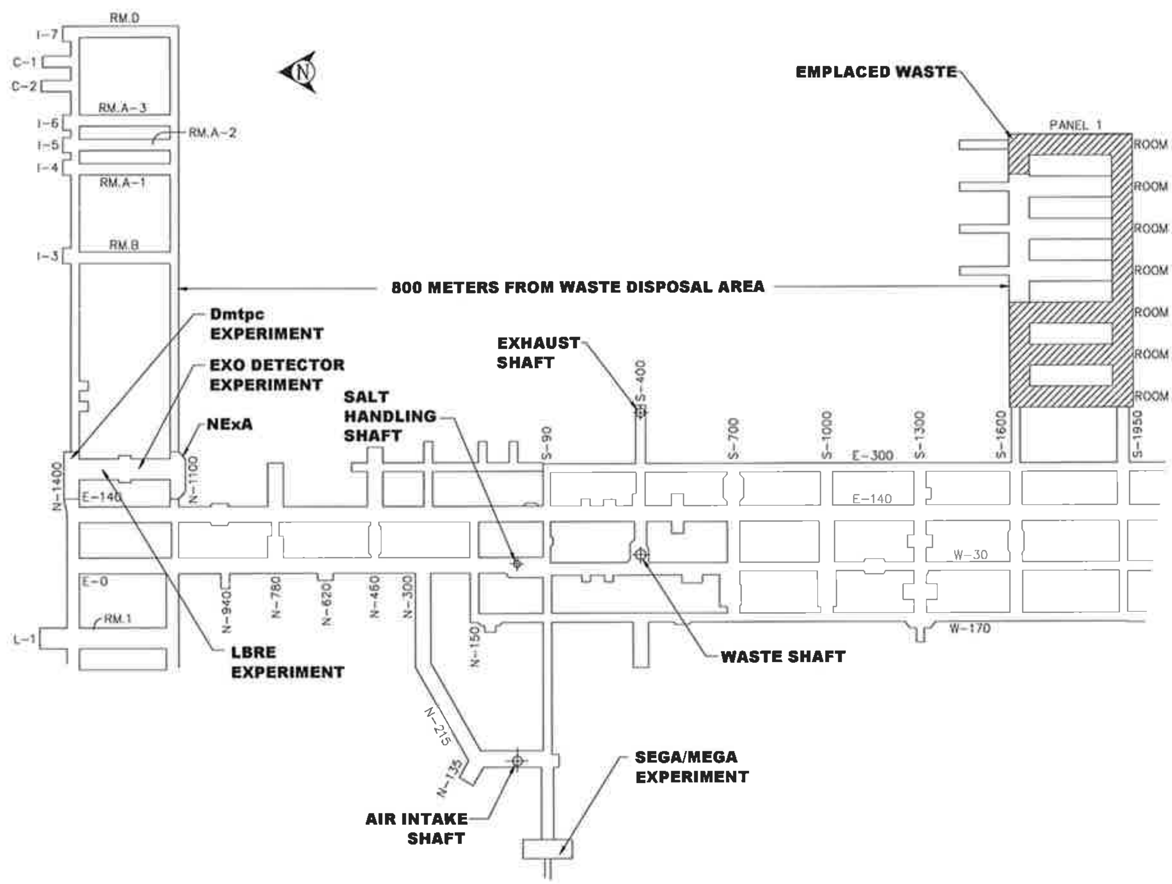

Figure 1. Locations of Current Underground Experiments at the WIPP Facility

The proposed facility for Salt Disposal Investigations (SDI) will be located in a remote, newly mined area of the existing experimental region of the WIPP repository and therefore separate from the operational/waste emplacement side of the WIPP repository. The SDI field test will be conducted by multiple participants; however, the procedures of the WIPP facility operating contractor with respect to health, safety, and all underground operations will control operational aspects of the SDI test.

1.2 Description of the SDI Facility

The preliminary design of the SDI field test is described in *A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP* (DOE 2011). A primary goal of the SDI field test is to measure the properties and behavior of *in situ* salt in response to temperature in excess of 160°C. The preliminary planning for the SDI test uses five 8.5 kW heaters in mined alcoves of a central pillar that is surrounded by two test access drifts (see Figure 2).

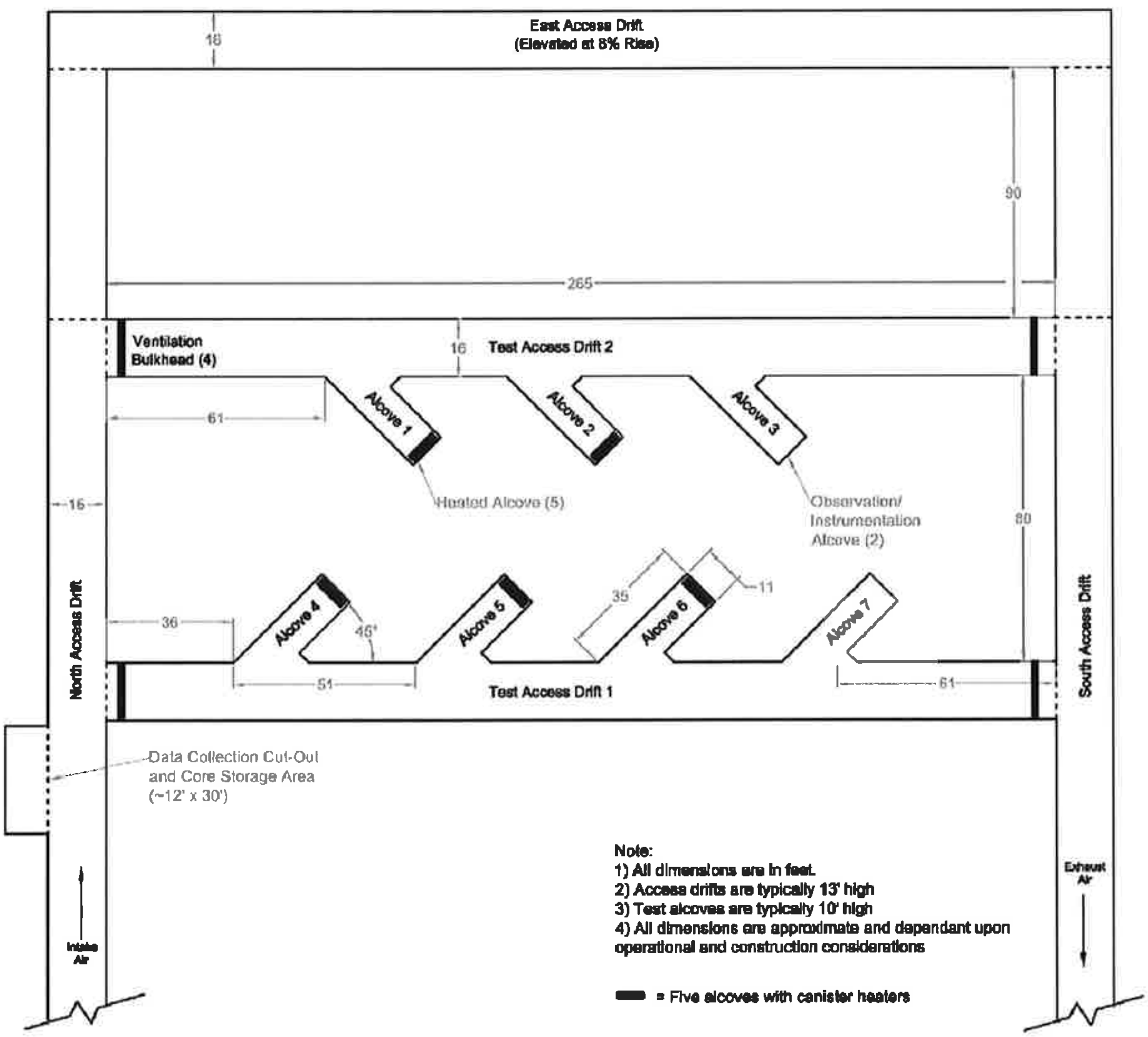

Figure 2. Plan View of the SDI Test Area

The preliminary design for the SDI test envisions a two-year heating phase followed by an 18 to 24 month cool-down phase after the heaters are turned off (DOE 2011, Section 3.5.2). After the cool-down phase, personnel will reenter the test access drifts and test alcoves to perform additional testing on the halite adjacent to the heaters.

SDI-related activities include extensive laboratory studies and thermo-mechanical analyses that will assist in defining the final configuration and duration of the field scale test. This planned change notice (PCN) uses a test with a two-year heating/two-year cool-down phase as the base case, and considers a test with a four-year heating/two-year cool-down phase as an alternative, bounding case.

2.0 Impacts during Mining and Operation of SDI

The operational impacts to the WIPP facility resulting from the construction and operation of the SDI facility are expected to be minimal because the SDI facility will be in a remote, newly mined area of the existing experimental region of the WIPP repository and therefore far from underground waste emplacement operations. In addition, there will be no mining of waste emplacement panels during the mining for the SDI facility.

Figure 3 is a plan view of the overall mining plan for the SDI facility. All mining for the SDI test occurs in the northern section of the underground facility. The test access drifts and alcoves for the SDI heaters, shown in detail in Figure 2, are located in the northeast quadrant of the WIPP repository. In particular, the test alcoves and test pillar are located outside the shaft pillar area, which is shown by the red curves in Figure 3. This is important because it minimizes the potential impacts from mining and from the test heaters on the host rock surrounding the shafts, ensuring that the shafts remain in a stable geomechanical environment.

This section considers the potential impacts on Station A, at the top of the Exhaust Shaft, from mining the SDI facility and from the heating phase of the SDI test. This section considers the potential impacts on the conduct of underground operations at WIPP from mining and operation of the SDI facility. The potential impacts on long-term performance are discussed in Section 3.

2.1 Response at Station A

2.1.1 Mining Plan for SDI

The total mined tonnage for the SDI entries is approximately 150,000 tons (see Figure 3), which corresponds to a mined volume of 61,200 m^3 (2,160,000 ft^3) (personal communication from Ty Zimmerly). The SDI entries will typically be 3.96 m (13 ft) high and 4.88 m (16 ft) wide. Representative dimensions for the test alcoves are shown in Figure 2. The planned sequence of mining for the SDI facility will be as follows:

- Mine two north-south drifts, denoted as E-500 and E-650 in Figure 3, to provide a connection for ventilation air to flow directly from the SDI facility to the exhaust shaft. The new mining extends east from E-140 at the N-780 cross-drift and at N-940, then turns south and runs to the extension of the S-400 cross-drift at the exhaust shaft. Until E-500 and E-650 connect to the exhaust shaft, the return air from mining will be routed to flow in the E-140 drift from N-780 to S-90, cross over into the E-300 drift, mix with exhaust air from the maintenance shop, and flow down E-300 to S-400 and the exhaust shaft. After E-500 and E-650 connect to the exhaust shaft, the return air from the SDI flows directly to the exhaust shaft, separately from the return air from other parts of the WIPP underground facility. The pathway for the return air is an important consideration in evaluating the settling of salt aerosol particles out of the return air.
- Mine four east-west drifts, with two to the south and two to the north of the SDI test area. The return air from this mining will go directly to the exhaust shaft through the newly mined E-500 and E-650 drifts, as noted above.

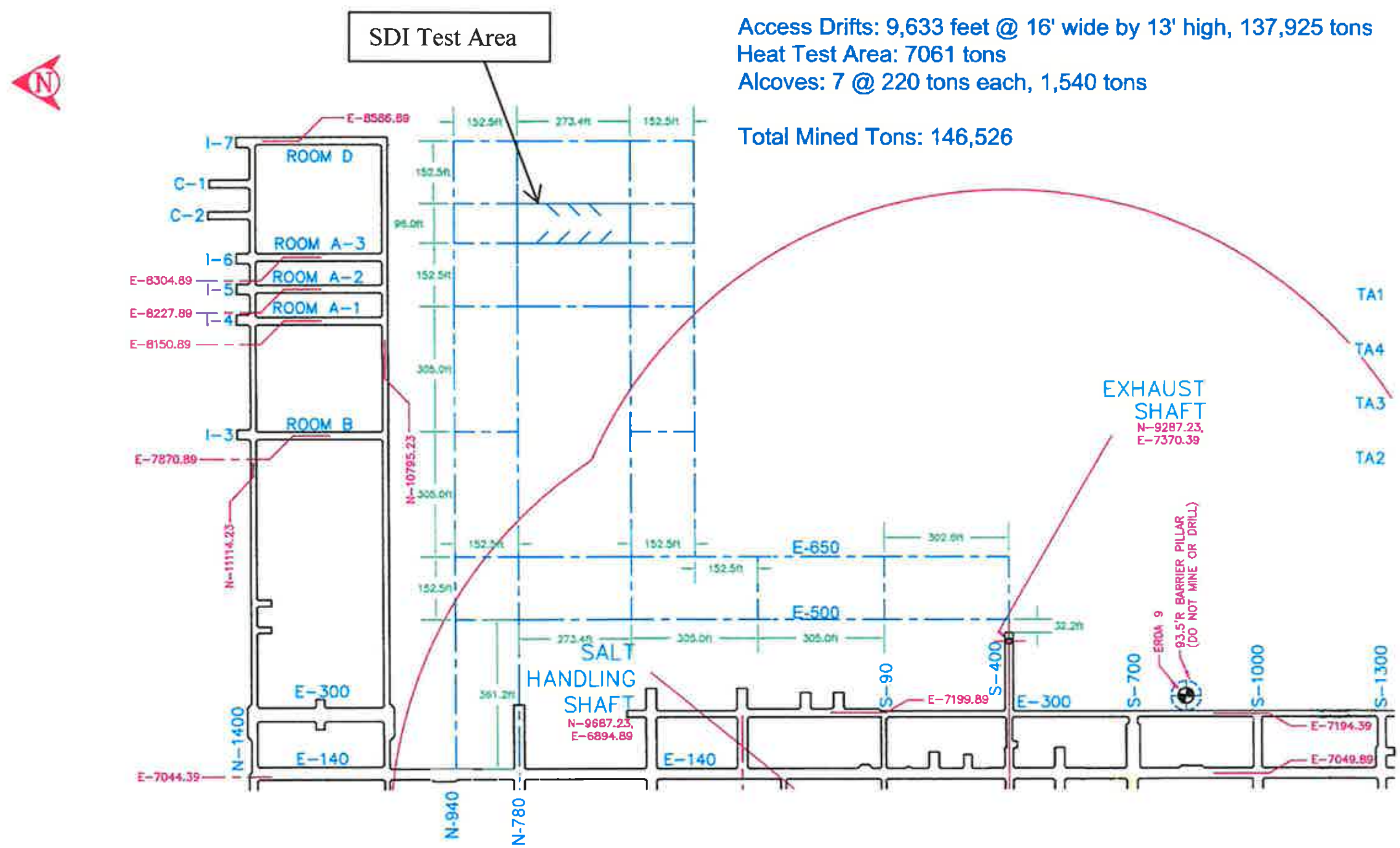

Figure 3. Mining Plan for the SDI Test Area to the Northeast of the Existing Repository

Mining will be performed in two stages: an initial cut that is typically 4.27 m (14 ft) wide by 3.05 m (10 ft) high and the final cut to trim the ribs then the floor to 4.88 m (16 ft) wide by 3.96 m (13 ft) high. The sequencing of initial and final cuts will be different for the major drifts:

- E-500 and E-650 will be mined to the initial cut just short of connecting to S-400. Then a small portion of drift just north of S-400 will be cut to final so that ventilation controls can be installed. Then E-500 and E-650 will be connected to S-400 and these drifts will be completed to the final cut, with the return ventilation air flowing directly to S-400.

- When mining of the four east-west access drifts to the SDI test area begins, the north-south drifts to S-400 will be at their final dimension and the return ventilation air will flow directly through these north-south drifts to S-400. The final cut for the east-west access drifts will directly follow the initial cut.

The ventilation air flow during mining will be about 26.0 m^3/s (55,000 cubic feet per minute (cfm)) through the SDI facility. Before E-500 and E650 connect to the exhaust shaft, the air velocity[3] in the E-140 drift will be about 0.65 m/s (127 ft/min) north of N-250 (where E-140 is about 7.32 m (24 ft) wide and 5.49 m (18 ft) high) and about 0.83 m/s (164 ft/min) south of N-250 (where E-140 is about 7.32 m (24 ft) wide and 4.27 m (14 ft) high). All drift dimensions are nominal. After connecting to the exhaust shaft, the air velocity will be about 2.0 m/s (394 ft/min) in the initial cut drift and about 1.3 m/s (256 ft/min) in the final cut drift, assuming that all the return air flow goes through a single drift (i.e., E-500 or E-650).

2.1.2 Settling of Aerosol Particles during Mining

DOE will continue to monitor and inspect the shrouded probes at Station A, at the top of the exhaust shaft, on a periodic basis to ensure that salt buildup from mining activities does not impact the ability of these probes to take a representative sample. The analysis in this section evaluates the likely size distribution of suspended aerosol particles at the base of the exhaust shaft from mining the SDI facility, but does not imply that DOE expects there will be a need to make changes to the procedure for monitoring and inspecting the shrouded probes at Station A.

Mining the SDI facility will produce nuisance dust, halite particles, and soot particulates (from the operation of machinery) with a wide range of particle sizes. Mining of the SDI facility will use the same equipment and methods as those that are used in mining the waste panels, so the aerosol produced by mining will generally be the same in terms of composition and size distribution as those from waste panel mining. However, the size distribution of the aerosol at the base of the exhaust shaft may be different because of different travel times for the return air. The impact of travel times through SDI entries on the size distribution of aerosol particles is analyzed here.

Smaller aerosol particles will remain suspended in the ventilation air, while larger aerosol particles will settle out while the ventilation air passes through the return airways of the SDI facility. This settling process is important for the shielded probes at Station A, at the top of the exhaust shaft. Operational experience shows that a high density of salt aerosol particles in the

[3] Air velocity is calculated as the volumetric flow rate divided by the cross-sectional area of the opening. For example, velocity in the E-140 drift is $(26.0\ m^3/s)/(7.32\ m * 5.49\ m) = 0.65\ m/s$

ventilation return air enhances salt buildup on the shrouded probes, which could affect the representativeness of sampling by the probes.

Until E-500 and E-650 connect to S-400, the return air from mining will be routed through the E-140 drift from N-780 to S-90, cross over into the E-300 drift, mix with the exhaust air from the maintenance shop, flow down E-300 to S-400, and then flow to the base of the exhaust shaft. The travel time in E-140 is approximately (530 ft)/(127 ft/min) + (340 ft)/(164 ft/min) = 6.2 minutes or 370 s. This calculation incorporates the different flow velocities between N-780 and N-250 and between N-250 and S-90, as calculated at the end of Section 2.1.1. This is a minimum travel time because additional time will be required for flow down E-300.

Once the final cut on the north-south drifts is completed, the two sets of east-west drifts, one on each side of the SDI test area, will be mined. The minimum flow distance in E-500 or E-650 is slightly greater than 900 ft (see Figure 2), allowing a minimum settling time of (900 ft)/(264 ft/min) = 3.4 minutes or 200 s. This flow velocity is based on the final cut drift, as defined at the end of Section 2.1.1. This is also a minimal travel time because mining may occur far from the entry to the E-500 or E-650 drifts.

Terminal settling velocities for a wide range of particle sizes have been tabulated (Avallone et al., 2007, Figure 18.1.1). For example, a 20 μm diameter aerosol particle has a terminal settling velocity of about 2.5 cm/s. At this terminal velocity, a 20 μm diameter aerosol particle will fall from the top to the bottom of a 3.96 m (13-ft) high drift in (396 cm)/(2.5 cm/s) = 158 s, or less than 3 minutes. It follows that most 20 μm diameter aerosol particles from mining of the SDI facility will settle out before they reach the exhaust shaft, based on the minimum travel times of 3.4 minutes or 6.2 minutes calculated above. On the other hand, a 10 μm diameter aerosol particle has a terminal settling velocity of about 0.5 cm/s (Avallone et al., 2007, Figure 18.1.1) and a settling time in a 3.96 m high drift of about 800 s or 13 minutes. So the settling of 10 μm diameter aerosol particles is expected to be minimal before the return air reaches the exhaust shaft. This behavior is similar to the salt aerosol generated by mining the waste emplacement panels, wherein the maximum particle size is estimated to be on the order of 10 to 15 μm in diameter.

An additional consideration is that the flow in the SDI facility during mining is a small fraction of the total flow up the exhaust shaft. During normal operation of the WIPP facility, one or two main fans (called "700" fans), draw air through the facility and up the exhaust shaft. In the normal ventilation mode, with two main fans running, the nominal flow rate in the exhaust shaft is 201 (standard) m^3/s (426,000 standard cfm). In the alternate ventilation mode, with one main fan running, the nominal flow rate is 123 standard m^3/s (260,000 standard cfm). The planned flow through the SDI section during mining is 26.0 m^3/s (55,000 cfm), or 13% and 21% of the total flow in normal and alternate ventilation modes, respectively. The salt aerosol from SDI mining will therefore be significantly diluted with the relatively clean ventilation air from the main facility. The return air from the main facility will be relatively clean because there will be no mining (except for occasional maintenance activities) in the main facility when mining for SDI occurs, and hence little salt aerosol in the return air from the main facility.

Based on the estimated travel times in the SDI facility and the dilution of salt aerosol from SDI mining with the return air from the main facility, the mining of the SDI facility should not impose a significantly greater aerosol loading on the return air at Station A than current mining operations at WIPP. The shrouded probes will continue to be inspected on a periodic basis, as noted at the beginning of this section, to ensure that salt buildup does not impact the ability of these probes to take a representative sample.

2.1.3 Temperature Change at Station A from SDI Heaters

During the heating phase of SDI, current plans call for 8.5 kW heaters in each of five test alcoves (DOE 2011, Section 3.5.2 and Figure 3-11). These heaters have a maximum total power of 42.5 kW. If ventilation air is flowing through the test access drifts and heater alcoves, heat transfer from the hot host rock will increase the temperature of the return air stream from the SDI facility. The following analysis demonstrates that the temperature increase at Station A, at the top of the exhaust shaft, is minor because the return air from the SDI facility mixes with the return air from the main facility.

The temperature change at Station A can be estimated from the total heat released by the five SDI heaters, assuming that all of their thermal energy is transferred directly to the ventilation air flow. This is an extremely conservative, "worst case" calculation because most of the energy released by the heaters goes into the surrounding salt, rather than being immediately released into the ventilation air. For example, there may be very limited or no ventilation air flowing through the SDI test area during the heating phase, and hence no thermal energy is transferred to the ventilation air during the heating phase. During the cool-down phase, the heat emitted from the rock to the ventilation air is generally smaller than the total capacity of the SDI heaters because the energy from the SDI heaters is stored in the surrounding body of rock and is not immediately released into the ventilation air stream.

This calculation does not consider the cooling that occurs as the return air ascends in the upcast exhaust shaft. The cooling in a vertical, upcast shaft occurs for all ventilation flows and can be analyzed in detail (McPherson 1993, Section 8). However, the focus of the present analysis is on the heat energy from the SDI test providing an additional change in the temperature of the total return air at Station A, excluding the cooling associated with an upcast shaft.

A simple energy balance for a constant pressure process estimates the maximum temperature change from the SDI heaters on the total air flow in the exhaust shaft:

$$\dot{Q} = \dot{V}\rho_{air}c_{p,air}\Delta T, \qquad (1)$$

or

$$\Delta T = \frac{\dot{Q}}{\dot{V}\rho_{air}c_{p,air}}, \qquad (2)$$

where $\dot{Q}$ is the total power generation of the heaters [kW = kJ/s], $\dot{V}$ is the total volumetric flow rate through the exhaust shaft [m^3/s], ρ_{air} is the density of the ventilation air [kg/m^3], $c_{p,air}$ is the specific heat capacity of air [kJ/kg/°C], and ΔT is the change in temperature of the ventilation air [°C] . The values of these parameters are as follows:

$\dot{V}$ $\approx$ 201 m^3/s (standard) in normal ventilation mode, with two 700 fans running;
ρ_{air} = 1.2 kg/ m^3 (for dry air at atmospheric pressure and 25°C); and
$c_{p,air}$ = 1.021 kJ/kg/°C ((Avallone et al., 2007, Table 4.2.22 at 300K).

Then the maximum temperature change in the normal ventilation mode with five heaters running is calculated as:

$$\Delta T_{norm} = (42.5\ \text{kW})/(201\ \text{m}^3/\text{s})/(1.2\ \text{kg/m}^3)/(1.021\ \text{kJ/kg/°C}), \\ = 0.17°\text{C},$$

and the maximum temperature change in the alternate ventilation mode, with a flow rate of 123 standard m^3/sec, is calculated as:

$$\Delta T_{alt} = (42.5\ \text{kW})/(123\ \text{m}^3/\text{s})/(1.2\ \text{kg/m}^3)/(1.021\ \text{kJ/kg/°C}), \\ = 0.28°\text{C},$$

Even if all the heat from the SDI heaters is transferred directly to the ventilation air flow, the maximum temperature change at Station A is very small, less than 0.3°C, because the heat from the SDI test is being diluted in the total return air flow. The thermal energy from the SDI tests will therefore not adversely affect the samples taken at Station A. This conclusion is independent of the duration of the heating phase or of the split of ventilation air flow within the SDI facility because the calculation is a simple, bounding energy balance that is independent of these considerations.

2.2 Closure Phase

After completion of the SDI testing, the experimental facilities will be closed according to a predetermined protocol. This will include:

- Removal of equipment from the underground, including the equipment for thermal and mechanical measurements of high temperature salt and any supporting equipment and materials.
- Closure of the experimental cavities when no further use is planned. Closure be in accordance with standard mining practice.

During permanent closure of the repository, the total facility will be closed according to an approved closure plan. This closure plan will determine the appropriate closure requirements for the underground experimental areas.

3.0 Impacts of SDI Testing on Long-Term Performance

Long-term impacts to the WIPP facility resulting from the construction and operation of the SDI field experiment are expected to be minimal because the SDI test area will be in a remote, newly mined area of the existing experimental region of the WIPP, separated from the WIPP emplacement areas by at least 700 meters of intact halite with minimal excavation. This section considers the potential impacts on long-term performance from the presence of the heaters for the SDI test, from the potential for test alcoves to partially or completely close during the heating phase, and from the additional excavated volume required to construct the SDI experimental area.

3.1 Thermal Analysis

The SDI test will generate a thermal pulse that moves outward from the test area into the surrounding halite. The magnitude of this thermal pulse at Panel 1, the repository panel that is closest to the SDI test area, has been analyzed using a model for heat conduction that represents the SDI test as two line sources in a cylindrical disk that is bounded on bottom by Marker Bed 139 and on top by Marker Bed 138. These Marker Beds are assumed to be adiabatic boundaries, with no heat flow upward or downward through the Marker Beds. This is an extremely conservative assumption for temperature rise because the adiabatic boundaries confine the thermal pulse to the disk between the Marker Beds.

Kuhlman (2011) provides the analytic methodology for the solution of this thermal conduction problem in cylindrical symmetry and the numerical results for the temperature rise at 40 m, 100 m, 200 m, 400 m, and 700 m as a function of time (Kuhlman 2011, Figure 1). The peak temperature rise at Panel 1 is calculated to be less than 0.02°C at about 1,500 years (Kuhlman 2011, Figure 1). These calculations are for the base case with a two-year heating phase. Calculations were not performed for the bounding case, but the peak temperature rise is estimated to be less than 0.04°C because the bounding case has twice as much energy input to the halite as the base case.

The conclusion from this model is that the long-term temperature rise from the SDI test will be significantly less than 0.1°C in Panel 1 and in the rest of the repository. This temperature rise is much less than the temperature increases of 2°C to 3°C that have been screened out of performance assessment (PA) calculations for Feature, Event, and Process (FEP) W13, *Heat from Radioactive Decay*:

> "*In summary, previous analyses have shown that the average temperature increase in the WIPP repository caused by radioactive decay of the emplaced CH- and RH-TRU waste will be less than 2 °C (3.6 °F). Temperature increases of about 3 °C (5.4 °F) may occur in the vicinity of RH-TRU containers with the highest allowable thermal load of about 60 W (based on the maximum allowable surface dose equivalent for RH-TRU containers). Potential heat generation from nuclear criticality is discussed in Section SCR-6.2.1.4 and exothermic reactions and the effects of repository temperature changes on mechanics are discussed in the set of FEPs grouped as W29, W30, W31, W72, and W73 (Section SCR-6.3.4.1). These FEPs have been eliminated from PA calculations on*

the basis of low consequence to the performance of the disposal system." (DOE 2009, Appendix SCR-2009, Section SCR-6.2.1.2).

The long-term temperature rise from the SDI test, less than 0.1°C at the repository, is therefore small enough to be screened out of PA calculations on the basis of low consequence, and will not have a significant impact on any temperature-dependent processes in the repository.

3.2 Mechanical Effects

The SDI heaters may induce peak salt temperatures well above 160°C (DOE 2011, Figure 3-2). Salt deformation is dominated by viscoelastic creep (plastic behavior) at elevated temperatures, and higher temperature results in a significant increase in the creep rate of intact salt (DOE 2011, Figure 3-1). Given the sensitivity of creep rate to temperature, it is possible that the alcoves with heaters may partly or completely close during the heating phase of the SDI test. Deformation of the host rock surrounding the alcoves will redistribute mechanical stresses as the alcoves close. This deformation continues until the salt creep reduces the magnitude of the deviatoric stress components to zero and a lithostatic state of stress is reestablished in the host rock.

Stress redistribution near the alcoves is primarily a local effect because salt creeps most rapidly in high temperature regions with the greatest deviatoric stress. High temperature and high deviatoric stress occur in the host rock near the alcoves, enhancing the local deformation of the rock salt. Far from the alcoves, the enhanced deviatoric stresses and elevated temperature effects in the alcoves are greatly reduced or eliminated. In this context, "far" is often interpreted as outside the "zone of influence" of an excavation (Brady and Brown 2006, Section 7.2). For example, stresses tend to asymptote by 2 to 3 times the radius of a circular opening in rock (Jaeger, Cook and Zimmerman 2007, Figures 8.1, 9.2(b), and 9.3(a)) or by 5 times the radius of a circular opening in an elastic/fractured rock mass (Brady and Brown 2006, Figure 7.20). Since the alcoves are 3.4 m (11 ft) wide and 3.0 m (10 ft) high (DOE 2011, Figure 3-12), partial or complete closure of the alcoves for the SDI test will have no impact on the mechanical response of the repository panels, which are at least 700 m (2300 feet) away from the SDI test. A similar argument also indicates that closure of the entry mains leading from the repository to the SDI test area will also have negligible impact on the mechanical response of the repository panels because these entries will be in a remote, newly mined area of the existing experimental region of the WIPP and separated from the waste emplacement panels by hundreds of meters.

Mining of the SDI facility will not result in a significant increase in surface subsidence relative to the surface subsidence from the WIPP waste emplacement areas. The extraction ratio for the SDI facility is quite low, on the order of 0.15, in order to ensure that the integrity of the shaft pillar is not compromised by the SDI-related mining activities. This approach also ensures that the mining of the SDI facility will not result in a significant increase in surface subsidence relative to the subsidence from the panels, rooms, and access mains for the underground waste emplacement areas.

3.3 Long-Term Performance Prediction

SDI testing will require new mining in the northeastern quadrant of the existing repository (see Figure 3). The mined volume for the SDI facility is about 62,000 m^3 (2,200,000 ft^3). By way of comparison, the volumes of the Operations Area and Experimental Area in the BRAGFLO grid for the Performance Assessment Baseline Calculation-2009 (PABC-2009) (Clayton et al. 2010) are 37,300 m^3 and 87,700 m^3, respectively. The mined volume for the SDI facility therefore increases the volume of the combined Experimental and Operations Areas by almost 50%.

In general terms, increasing the volume of these areas reduces the pressure within the waste emplacement panels because the larger volume of these areas provides a low pressure reservoir for any gas generated in the waste emplacement areas. Reduced pressure in the repository will tend to increase brine inflows from the disturbed rock zone (DRZ) and from the anhydrite marker beds into the repository. The presence of the lower pressure reservoir in the Experimental and Operations Areas will also increase brine flows from the waste emplacement panels to the Operations and Experimental Areas because gas generation in the waste emplacement panels maintains these areas at higher pressure than the Operations and Experimental Areas. Assessing the impacts of the competing effects of reduced repository pressure and increased brine flows on long-term performance requires a performance assessment.

The impact of the SDI facility on long-term performance has therefore been evaluated in the SDI PA (Camphouse et al. 2011). The SDI PA is based on the PABC-2009, which is the current PA baseline. The volume of the Experimental Area has been increased to represent the presence of the SDI test facility in the northeast quadrant of the repository. The SDI PA uses the Option D panel closures, which are included in the PABC-2009.

Figure 4 demonstrates that the presence of the SDI facility results in mean total normalized releases that are essentially the same as the mean total normalized releases for the PABC-2009 at all probability levels. The numerical values in Table 1 (Camphouse et al. 2011, Table 6) also demonstrate that the statistics for the distribution of complementary cumulative distribution functions (CCDFs) for total normalized release about the mean are similar for the SDI PA and for the PABC-2009. Any differences in Table 1 are primarily caused by lower releases from spallings due to reduced gas pressure in the waste emplacement areas. A more complete discussion of the inputs to and results from the SDI PA can be found in Camphouse et al. (2011).

Table 1. SDI PA and PABC-2009 Statistics on the Overall Mean for Total Normalized Releases in EPA Units at Probabilities of 0.1 and 0.001

Probability	Analysis	Mean Total Release	90^{th} Percentile	Lower 95% CL	Upper 95% CL	Release Limit
0.1	SDI PA	0.093	0.15	0.090	0.095	1
	PABC-2009	0.094	0.16	0.091	0.096	1
0.001	SDI PA	1.1	1.0	0.38	1.8	10
	PABC-2009	1.1	1.0	0.37	1.8	10

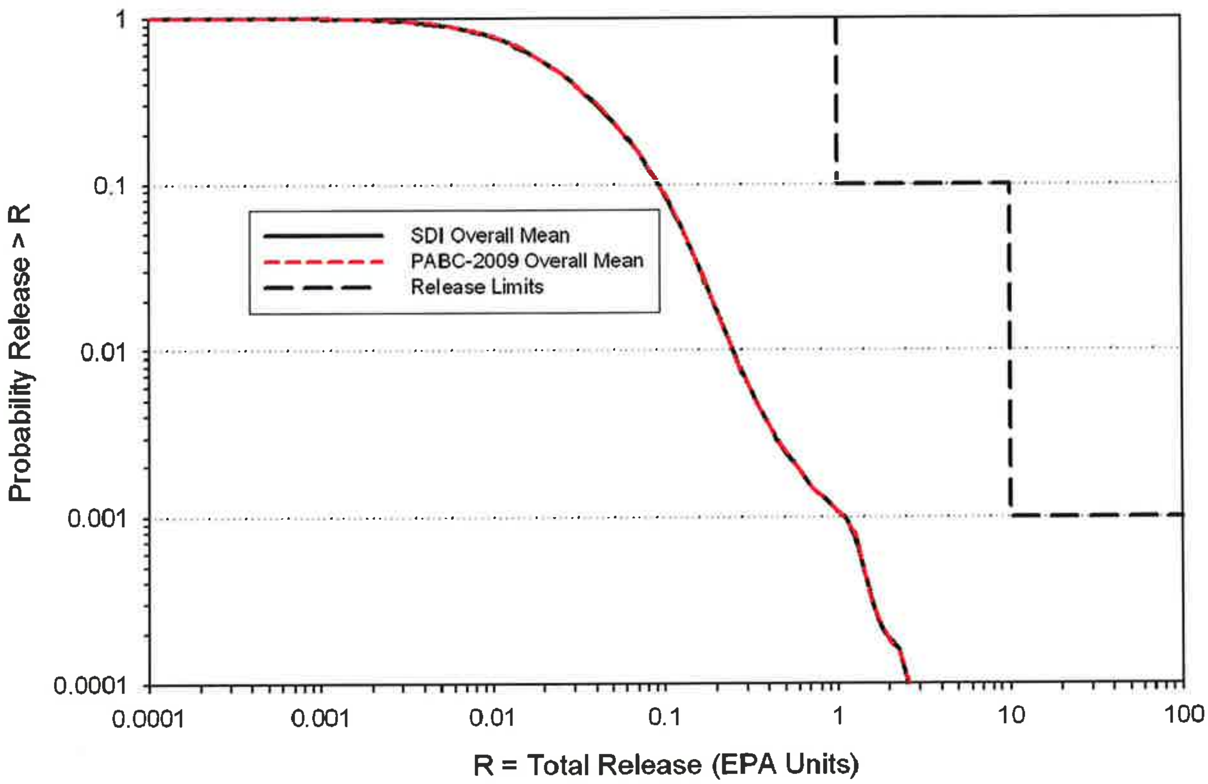

Figure 4. Overall Mean CCDFs for Total Normalized Releases from SDI PA and PABC-2009

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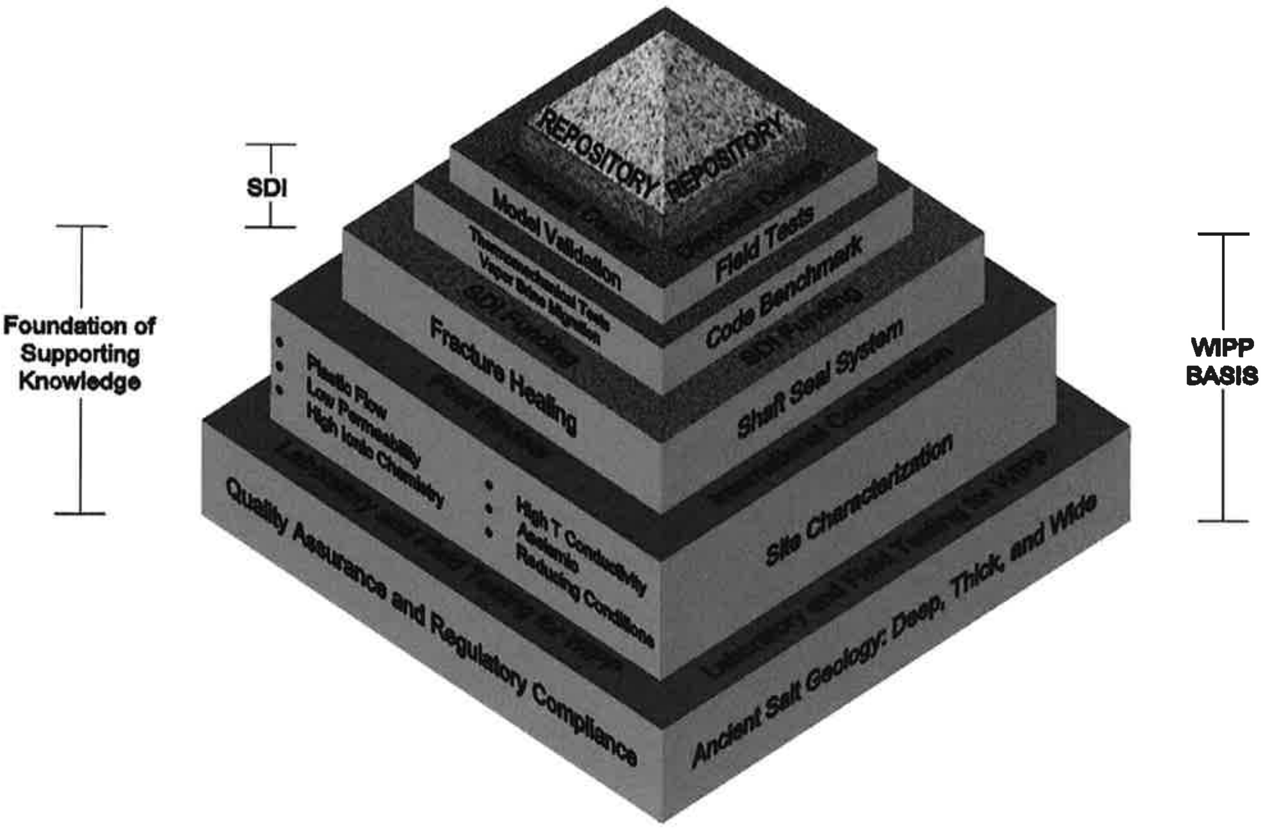
Enclosure 2

U.S. DEPARTMENT OF ENERGY
CARLSBAD FIELD OFFICE

A MANAGEMENT PROPOSAL FOR

SALT DISPOSAL INVESTIGATIONS

WITH A FIELD SCALE HEATER TEST AT WIPP



June 2011

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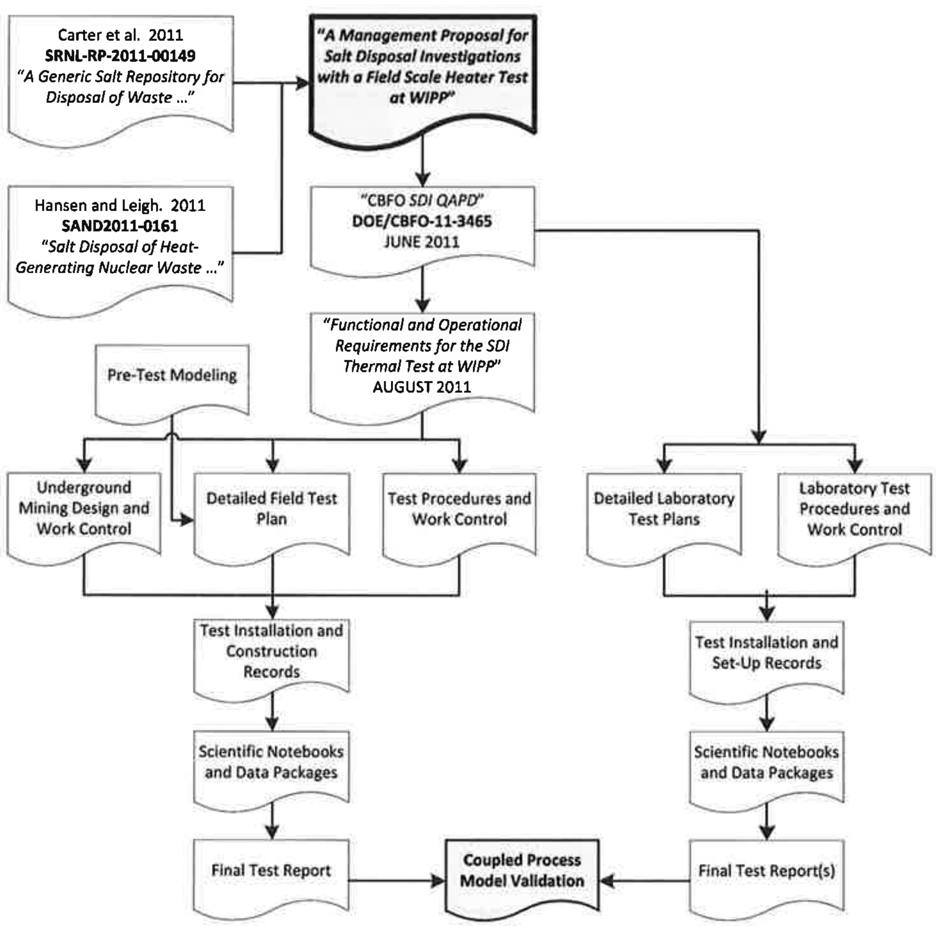
EXECUTIVE SUMMARY
SALT DISPOSAL INVESTIGATIONS

PROJECT INTRODUCTION

This management proposal provides a science-based scope of work (with time and cost estimates) for a defined scope of research (laboratory work and modeling efforts) intended to establish the foundation for a proof-of-principle field test for disposal of heat-generating nuclear waste. This management proposal is considered a preliminary and internal scoping proposal meant to reach a decision-in-principle within the United States Department of Energy (DOE) headquarters. Test-specific requirements such as parameter identification, data quality objectives, instrumentation, calibration requirements, precise borehole and gauge placement, sample control, test procedures, data collection processes, and other test or modeling specific information will be provided in an ensuing field test plan to be developed in fiscal year 2012. Detailed cost estimates and schedules will be developed as a function of DOE fiscal year planning. The figure below provides a general overview of how this management proposal fits in relationship to other Salt Disposal Investigations (SDI) documents and records planned as a result of this project.

Relationship of the Management Proposal to Other SDI Documents and Records



Disposal of nuclear waste in salt remains a viable, yet underutilized concept in the United States. The well-recognized success of the WIPP mission for the disposal and isolation of defense transuranic (TRU) waste provides strong positive testimony in support of salt disposal for a variety of nuclear wastes. Bedded salt formations in the United States hold great promise toward solving major disposal issues for thermally and radioactively hot waste currently managed by the United States DOE Office of Environmental Management (DOE-EM).

Previous salt repository studies and operations have been adequate to demonstrate safe disposal of TRU waste in salt. However, for thermally hot waste, there are gaps in the experimental data that are addressed in this management proposal. The developmental history of the current management proposal began in 2008 when DOE assessed the need for a second repository to augment the proposed Yucca Mountain Project. As a part of that process, the DOE Office of Nuclear Energy (DOE-NE) funded a scoping study for the feasibility and efficacy of a comprehensive repository in salt, with the DOE-EM Carlsbad Field Office (CBFO) and its science and operations contracting organizations providing support.

The final report of the scoping study (Carter et al. 2011) provided a proof-of-principle layout and operational strategy for a repository that would meet the combined disposal needs for reprocessed high-level waste, low-level waste, and greater-than-Class-C wastes for the next one hundred years. The report pointed toward a near-term science-based program to gain public confidence and provide a regulatory compliance framework that would close gaps in our current knowledge for salt repositories. To strengthen the SDI proposal, DOE-EM requested a formal and comprehensive compilation of all previous work in salt, current status, and additional science necessary to fill gaps and extend our current understanding, most specifically for heat-generating waste disposal. The resulting report (Hansen and Leigh 2011), coupled with the referenced scoping study, provides the primary basis for work proposed in this SDI proposal.

Directed laboratory and field research can help reduce uncertainties regarding thermally driven processes involved with decay storage and disposal in salt and increase technical understanding for those potential missions. The research program proposed would directly test a disposal arrangement that balances heat loading with waste and repository temperature limits. It would fill information gaps in current knowledge of the thermomechanical, hydrological, and chemical behavior of salt and wastes disposed in salt and form the technical foundation for design, operation, coupled process modeling, and performance assessment of future salt repositories for heat-generating nuclear waste.

This management proposal, originally developed in February 2010, was revised in March 2011 at the request of DOE Headquarters to reflect efficiencies and cost savings realized if the test program was conducted in the area of the WIPP and not in an existing salt or potash mine. The WIPP is an operational disposal facility permitted by the New Mexico Environment Department for disposal of hazardous (mixed) waste and certified by U.S. Environmental Protection Agency for radioactive waste disposal. As such, proposed activities in this proposal will be performed in accordance with applicable regulatory requirements (Section 2.3). This will ensure that all proposed activities will not impact disposal operations or long-term repository performance. The use of the WIPP underground for the field test portion of SDI realizes significant cost savings by avoiding the development and installation of mining infrastructure at some other existing salt or potash mine of similar depth. Of course, there remain substantial costs associated with performance of SDI, as delineated in this management proposal to perform the tests in WIPP. The area to the north of the access shafts (far north of waste disposal operations) is already configured with electrical power and fiber optic cable to service basic science experiments.

Additionally, an existing trained workforce, mining infrastructure, nuclear safety bases, and a quality assurance program will make the field test component of the SDI at WIPP cost appreciably less while supporting a more defensible experiment compared to bringing these essential elements of a field test to another commercial mine.

In June 2011, the CBFO developed a QAPD specific to these SDI activities (DOE. 2011). The SDI QAPD was modeled after the highly effective and time-proven CBFO QAPD and describes an NQA-1-2008 compliant Quality Assurance Program for the science-based studies concentrating on high thermal loading effects in bedded salt. Existing WIPP procedures are adapted as appropriate to accommodate the SDI program, thereby taking advantage of the existing mature and audit-tested programmatic and technical processes established for a successful repository program.

Pursuant to the completion of the SDI QAPD, this current version of the management proposal (June, 2011) was revised to addresses technical and programmatic comments received from a review commissioned by the DOE-NE Fuel Cycle Technologies Program's Used Fuel Disposition Campaign. This process was controlled through the CBFO procedure for document review, Management Procedure CBFO-MP-4.2. Additionally, this version of the proposal reflects a funding strategy of a two million dollar annual budget for the next two consecutive fiscal years from DOE-EM, with DOE-NE contributing to the laboratory and modeling efforts (see reference 22), followed by increased budgets in subsequent fiscal years to start the heating phase in fiscal year 2015. The overall life cycle of the salt disposal investigations has consequently been extended to ten years as a result of the restrained start to the field proof-of-principle test.

PROJECT MANAGEMENT, QUALITY ASSURANCE, AND SAFETY

The overall management of the work proposed within this SDI project will be through CBFO. The CBFO defines quality requirements through a Quality Assurance Program Document (QAPD), similar to that used for the WIPP program. The SDI QAPD describes an American Society of Mechanical Engineers Nuclear Quality Assurance 2008 Edition (NQA-1) compliant QA program for the science-based studies concentrating on high thermal loading effects in bedded salt. Those portions of the SDI investigations funded by Used Fuel Disposition Campaign (UFDC) of the DOE-NE will be managed according to the judgment of the UFDC management team.

The Los Alamos National Laboratory's Carlsbad Operations (LANL-CO) office will function as the project management organization, responsible for day-to-day test management and coordination, similar to a successful model used at the Nevada Test Site and the Yucca Mountain Project, ensuring that all test-related information and data activities are consistent and focused. In its management capacity, LANL-CO will report to the CBFO Project Manager. Sandia National Laboratories (SNL), LANL, and other potential scientific entities, will provide Principal Investigators to inform and advise test management to ensure the test is as productive, integrated, and efficient as can be achieved.

Washington TRU Solutions (WTS), the WIPP Management and Operating Contractor, will provide engineering, construction, and test support personnel to provide for the test bed (e.g., drift mining, borehole coring, electrical, ventilation) and aid in test installation.

The primary collaborators on this management proposal, predominantly from LANL and SNL, have direct salt repository experience and have conducted decades of salt research and thermal testing, both in the laboratory and the field. Experience directly relative to the types of field and laboratory activities described in this management proposal include field work at the Nevada Test Site, large in situ thermal tests at Yucca Mountain, and experimentation at WIPP. The authors have vast experience in broader repository science efforts in the areas of process and performance assessment modeling, and licensing. Appendix C provides a list of key contributors to this proposal and a summary of related experience.

Each proposal participant has extensive experience and an exemplary record of safety related to field and laboratory work activities, including a culture and value structure that promotes safety in the workplace. Each participant will conduct work safely and responsibly; ensure a safe and healthful working environment for workers, contractors, visitors, and other on-site personnel; protecting the health, safety, and welfare of the general public. This is done through an institutional framework which embodies processes that align with the principles and functions of Integrated Safety Management.

PROPOSED RESEARCH PROGRAM

The proposed research program would substantially enhance our knowledge of the behavior of thermally and radioactively hot nuclear waste in salt and will provide fundamental data for the model validation and evaluation of concepts for disposal in salt. The program has been divided into six elements:

1. **Functional and Operating Requirements and Test Planning**
   The project benefits greatly from the fact that it can utilize existing infrastructure at WIPP and will be situated in well characterized rock salt. The test itself will require a description of functional and operational requirements (F&OR) for a field test. The work to develop the F&OR document has been funded in FY11. Detailed test plans will then be developed, reviewed, and delivered in FY12.

2. **Laboratory Thermal and Mechanical Studies to Support the Field Test**
   Elevated salt temperatures will cause accelerated salt-creep deformation, which leads to a more rapid encapsulation of the waste. Laboratory studies on the salt from the field-test site are designed to examine intact and crushed salt at the high temperatures expected for alcove disposal.

3. **Laboratory Chemical, Hydrologic, and Material Studies**
   Laboratory studies will establish the key factors that control brine migration, radionuclide solubility, and mobility at elevated temperatures. In addition, material interaction data will be obtained that can be used to evaluate waste forms.

4. **Coupled Process Modeling**
   Prediction of the behavior of the field test will initially be made using the best-available models of thermomechanical behavior, including creep, damage, healing, reconsolidation, and coupled processes. Improvements have been identified for certain elevated temperature constitutive models and brine availability including vapor phase transport. Some of the thermomechanical information will be gleaned from laboratory studies and validated as the field test progresses. The models will be updated using data collected in this study to continuously improve and validate predictive capability. Thus, a rigorously developed modeling capability will be available for use in future design and performance assessment activities for disposal in salt.

5. **Field Test Installation and Operation**
   The conceptual field test provides full-scale, real-world data for the models used to predict behavior of salt and brine at elevated temperatures. The proposed test is designed to push the limits of salt heat loading and waste temperature. One important field test design criterion is high thermal loading. If the test proceeds at a design thermal load of 40 watts per square meter (W/m^2), the test bed will experience temperatures in excess of 160°C in the salt mass (see section 3.4.1), above where most data have been acquired to date. Steady state creep rate of WIPP horizon salt accelerates one order of magnitude for each increase of approximately 12 degrees Centigrade (°C). The affected salt near the heater is expected to flow rapidly and perhaps decrepitate (i.e., burst owing to the pressure of fluid inclusions). Upon review of this very aggressive temperature limit, a decision to modify the test temperature in the formal review of the test configuration will be made. However these considerations will be informed early by the laboratory testing. Experimentation in the laboratory will also present significant technical challenges in terms of instrumentation survival and data acquisition. As the laboratory thermomechanical testing proceeds in advance of the field test, laboratory experience will greatly inform the field-test team. In addition, the field test will produce data directly applicable to a potential repository by testing a disposal arrangement.

6. **International Collaboration**
   Collaboration with the European Union countries (particularly Germany) will avail technical staff of the latest international developments in salt repository sciences.

GOALS FOR CONDUCTING THIS PROPOSED WORK

The primary reasons to conduct the work described in this proposal are: 1) demonstrate a proof-of-principle concept for disposal in salt, 2) bound salt thermomechanical response, 3) investigate thermal effects on intact salt in situ, 4) apply laboratory research to intact and crushed salt, 5) develop full-scale response for dry, crushed salt, 6) observe and document fracture healing in situ, 7) characterize and understand brine liberation and migration, 8) track moisture movement and vapor phase transport in situ, 9) measure the thermodynamic properties of brines and minerals at elevated temperatures, 10) study repository interactions with waste container and constituent materials, 11) measure the effect of temperature on radionuclide solubility in brine, and 12) develop a validated coupled process model for disposal in salt for high heat-load wastes.

Information derived from the proposed field test, laboratory tests, and modeling activities will be transferable to other potential salt repositories. Transferability of experimental and analogue information forms a fundamental scientific tenet, and has been recognized in repository programs, including salt, for decades.

COST AND SCHEDULE

The total project cost is approximately $43M over 10 years. Mining and engineering labor are included as existing WIPP resources and infrastructure; therefore, those total costs are shown, but not included in the SDI specific budget necessary to complete the work. Consumables and equipment, however, are included as direct costs. Costs (in thousands of dollars) by element and year are shown below:

Element	FY11	FY12	FY13	FY14-20	Totals
2.0 Management, QA, and Safety	$250	$1,000	$900	$4,600	**$6,750**
2.4 International Collaboration	$0	$200	$200	$1,550	**$1,950**
3.1 Operating Rqmts. and Test Planning	$200	$0	$0	$0	**$200**
3.2 Laboratory Thermal and Mech. Studies	$250	$400	$600	$2,200	**$3,450**
3.3 Laboratory Hydrologic, Chemical, and Material Studies	$0	$210	$700	$2,600	**$3,510**
3.4 Coupled Process Modeling	$0	$300	$700	$1,900	**$2,900**
3.5. Field Test Installation and Operations	$0	$800	$900	$22,400	**$24,100**
** Existing WIPP Mining Resources and Infrastructure		($1,500)	($1,500)	($1,500)	($4,500)
Total SDI Budget (new) per year	**$700**	**$2,910**	**$4,000**	**$35,250**	**$42,860**
Total Cost (incl. existing resources)	**$700**	**$4,410**	**$5,500**	**$36,750**	**$47,360**

Primary actions and test planning (FY11):

- Complete the SDI Management Proposal
- Complete a Test Plan for laboratory testing for crushed salt in the laboratory to measure thermomechanical behavior across a variety of temperature, stress, and porosities
- Initiate laboratory tests on crushed salt
- Develop an NQA-1-compliant Quality Assurance Program Document and associated procedures
- Complete the F&OR document for the field test

Test planning, initial mining and laboratory studies (FY12):

- Begin elevated temperature tests on intact salt in the laboratory to measure thermomechanical behavior across a variety of temperatures and stresses
- Continue the laboratory tests on crushed salt
- Develop and review the detailed field test plan with equipment lists, instrumentation and borehole layouts, data quality objectives, etc.
- Comprehensively evaluate existing and available information from past thermal experiments
- Develop the criteria for the underground test design and layout
- Begin mining the underground access drifts to the test bed location
- Begin installing ventilation control and power distribution
- Write a test plan for laboratory studies of water liberation and brine migration in salt
- Begin measuring the thermodynamic properties of brines and minerals at elevated temperatures in the laboratory
- Develop a test plan and begin measuring the effect of temperature on radionuclide solubility in the laboratory
- Develop a test plan and begin studying repository interactions with waste container and constituent materials in the laboratory
- Evaluate and use coupled multiphysics modeling capability for field test configuration and analysis

Initial studies (FY13):

- Continue development of fully coupled TM(H) code and model for field test analysis.
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Develop test plan for intact core testing in the laboratory
- Procure test equipment and instrumentation for the field test
- Develop work control and safety basis for the field test
- Complete mining of the underground access drifts
- Develop the documented safety analysis for the field test
- Mine the field test bed

Field test implementation (FY14):

- Core instrumentation boreholes
- Implement the field test equipment, including data collection equipment and fiber optic communication equipment
- Investigate salt properties of test bed location
- Preparedness assessment for field test start and baseline measurements
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Continued development of fully coupled THMC code and model for field test analysis

Conduct the proof-of-principle field test (FY15 - 20)

- Heating start on field test – FY 15
- Investigate thermal effects on intact salt in situ
- Develop a full-scale response for dry crushed salt
- Observe and document fracture healing in situ
- Track moisture movement and vapor phase transport in situ
- Complete laboratory thermomechanical testing and chemistry experiments
- Complete laboratory studies of water liberation and brine migration
- Cool-down of field test by FY 19
- Post-test forensics, mine-back and post-test coring in FY 19 and FY 20
- Complete the final test and data reports
- Develop calibrated, coupled TM(H) model

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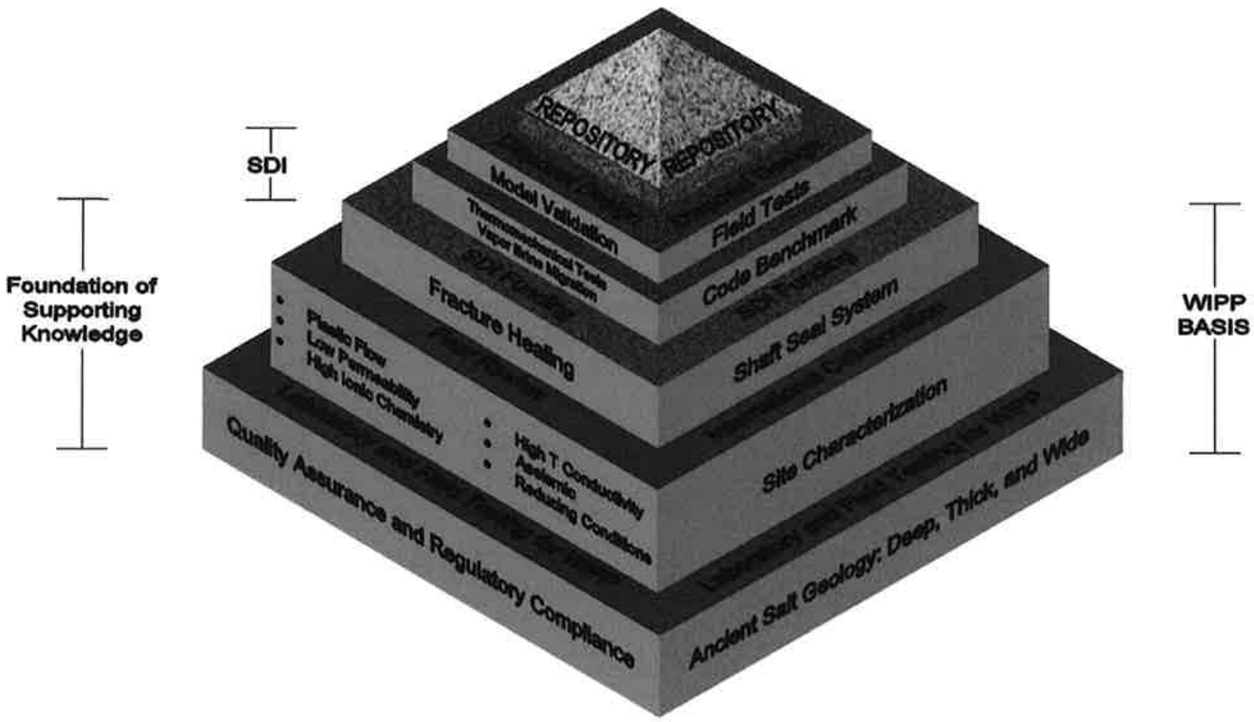
1. PROJECT INTRODUCTION

Long-term decay storage and permanent deep geologic disposal of heat-generating nuclear waste (such as high-level waste [HLW]) in salt lie at the intersection of research on repository performance, waste form behavior in different geologic formations, and public acceptance of the U.S. Department of Energy (DOE) Office of Environmental Management – Office of Nuclear Energy (EM-NE) Initiative for Waste Disposal Research. Public understanding and confidence in decayed storage or permanent isolation of radioactive waste in salt have improved as a result of more than a decade of successful disposal operations at the Waste Isolation Pilot Plant (WIPP). EM-NE-directed research can leverage this positive experience by reducing uncertainties regarding thermally driven processes involved with decay storage and disposal in salt, and therefore further increasing technical understanding for those potential missions. This point is explicitly included in the Memorandum of Understanding between the two offices on the topics of Used Nuclear Fuel and Radioactive Waste Management and Processing Research and Development (DOE, 2011). In collaboration with international salt repository programs, laboratory experiments, and simulated heat-generating waste/salt interaction tests, the next few years will answer remaining questions and more fully inform future repository programs. The proposed work will build upon a foundation of excellence in salt repository applications that began almost 50 years ago.

Bedded salt formations in the United States hold great promise for solving major disposal issues for thermally and radioactively hot waste currently managed by DOE EM. This management proposal involves non-mission-specific testing to evaluate the efficacy of bedded salt for thermally hot nuclear waste. The research, development, and demonstration contained in this proposal will advance the technical baseline for disposal in salt and could significantly inform future nuclear waste repository decisions.

Figure 1-1 illustrates how this management proposal builds upon an enormous base of knowledge from early test programs, many of those at WIPP (e.g., see Table 1-1, historic listing in Appendix B, and Hansen and Leigh. 2011), and that, with a relatively small and achievable incremental amount of modeling, laboratory testing, and field demonstration testing, new paths toward waste disposal designs and a future repository in salt can be realized. Information derived from the proposed field test, laboratory tests, and modeling activities will be transferable to other salt sites. Transferability of experimental and analogue information forms a fundamental scientific tenet, and has been recognized in repository programs, including salt, for decades.

Figure 1-1: Science Based Foundation for TRU and HLW Disposal in Salt



The Challenging Waste Issue

DOE-EM currently manages the defense HLW from reprocessing over 160,000 tons of used nuclear fuel (UNF) in the states of Washington, Idaho, and South Carolina. Figure 1-2 compares the surface exposure rate of defense remote-handled transuranic (TRU) waste (currently being disposed of at the WIPP) and defense HLW. The defense HLW processing system in place today reflects a set of baseline technologies that, among other things, presupposed the co-disposal of DHLW (as borosilicate glass waste forms) and UNF at Yucca Mountain. A recent NAS study on waste form technology options (NAS, 2011) concluded that there is still time to improve upon the current path forward by incorporating scientific advances into the defense cleanup program to maximize efficiencies. The study highlighted the potential opportunities of developing more efficient waste form production methods, and stressed the need to match a waste form and accompanying engineered barriers to the disposal environment. The issues driving the development of waste forms have traditionally included waste loading, radiation tolerance, and long-term durability in an environment in which contact with water leads to radionuclide mobilization and transport through the natural environment. Salt is unique as a disposal medium in that, for an appropriately selected site, the amount of water contacting the waste under undisturbed conditions is expected to be minimal. This feature could be exploited by adopting more efficient, safe, and cost-effective processes upstream of HLW emplacement in the repository by relaxing the requirement that the waste form be exceptionally durable in the presence of water. Thus, research to confirm or disprove critical hypotheses on the efficacy of salt as a disposal medium for thermally hot waste is a logical next step that could lead to a viable disposal concept and to more efficient upstream options for defense waste streams.

The Nuclear Waste Policy Act and its amendments legislate that HLW eventually be emplaced in a national waste repository. However, the national repository is also intended to be a retrievable storage site during the operational phase and possible disposal site for UNF from the commercial nuclear power industry, now representing about 60,000 metric tons (MT). These two waste forms (defense HLW and commercial HLW) are radically different in radioactivity, future value, and many other attributes. Additionally, if UNF is reprocessed in the future, it is potentially limiting to connect UNF storage with either decayed storage or the deep geologic permanent disposal of HLW fractions from recycling. With the new administration's intent to rethink the issue of long-lived radioactive waste disposal in America, it is prudent that DOE research other possible geologic disposal solutions that do not directly link UNF retrievable storage with defense HLW disposal. If retrieval is less important, permanent isolation in salt potentially emerges as a robust geologic solution.

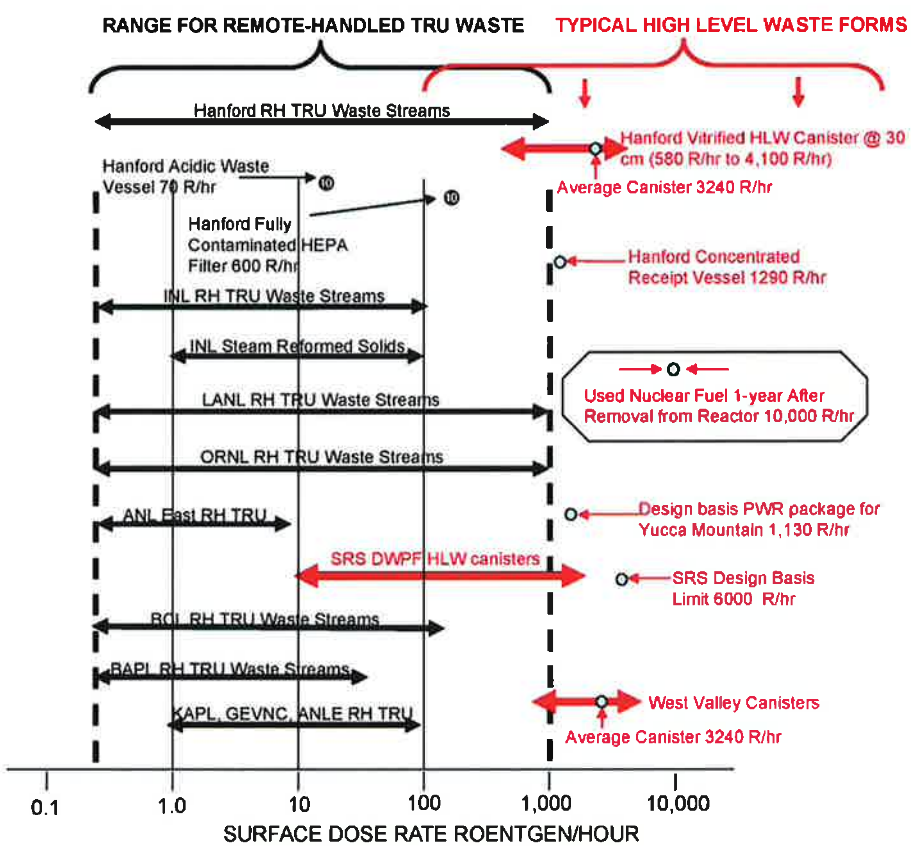
Note that retrievability to maintain ready access to a potentially valuable material is a different concept than maintaining the ability to reverse a decision to bury waste because of a flaw discovered in the safety case after disposal operations have begun. An NAS study on "adaptive staging" of repository programs (NAS, 2003) advocated retrievability from the standpoint of ensuring that decisions can be reversed, even to the extent of being able to remove wastes placed in the repository until permanent closure of the facility. In this context, retrieval of waste from a salt repository is technologically feasible, if necessary due to safety considerations, by a process of locating the waste package and re-mining to recover it. Thus, recovery of waste to reverse a decision due to safety concerns would be achievable, whereas retrieval for the purpose of recovering a valuable resource should not be considered as a viable option for salt. Therefore, the issue of retrievability should not be viewed as an impediment to proceeding with a research program for HLW disposal in salt.

The preliminary views from the subcommittees of the Blue Ribbon Commission (June 2011) noted that regardless of the future nuclear fuel cycle chosen, a geologic repository will be needed. At this point in time it is not possible to categorically state that such a future repository will be loaded with only HLW or only UNF, and it is quite likely that both waste types will be disposed of even if reprocessing is used to intercept new UNF at some future time. It is also premature to categorically state whether or not defense/government/commercial wastes will be segregated for disposal or will be disposed of together. This makes it prudent to study the disposal of disparate waste type characteristics for the higher volume wastes that may be expected. Therefore, for this proposal, the range in higher volume waste characteristics will be bounded by current descriptions of high-burnup UNF and HLW currently being produced (SRNL) and slated to be produced (Hanford) in the near term.

With respect to civilian nuclear waste, there is no technical issue related to safety or adverse environmental impact that creates an urgent need to identify a permanent disposal option. Storage in spent fuel pools and in dry casks is deemed to be an appropriate technological solution for at least 60 years beyond the licensed life of operation (U.S. NRC, 2010), and applied R&D could be conducted to enhance the technical basis for even longer storage periods. Long-term storage, with UNF stored either at reactor sites, or as recommended in a recent MIT study (MIT, 2011), in a centralized storage facility, would provide the time needed (several decades by most estimates) to assess various fuel cycle technology options before choosing the most appropriate, sustainable fuel cycle for the future. If during that period, it is determined that reprocessing would be desirable, the country would be faced with the need to dispose of a variety of waste streams, including HLW. To prepare this HLW for disposal, many of the unit operations and waste forms generated in a civilian UNF reprocessing future would be similar to those already being executed to handle DHLW. This process knowledge would be put to use should the nation decide that reprocessing of civilian UNF is desirable. Extending that concept to repositories, the proposed studies would have direct relevance to future disposal of HLW from reprocessed UNF, potentially by identifying a viable, highly cost effective disposal system. Even if it is ultimately decided that civilian UNF should be disposed of in an open fuel cycle without reprocessing, the proposed studies would provide important information on the behavior of salt under thermal loads that would be relevant to the assessment of salt as a disposal medium for UNF.

This management proposal drives directly to key technical issues common to EM-NE initiatives in waste disposal research. The program described here will vastly improve disposal options, assess waste form performance in salt, and promote public confidence — all key building blocks of the EM-NE initiative. Salt Disposal Investigations (SDI) will move forward with a science-based research program on multiple fronts, laboratory research in hydrology, chemical, and material studies, laboratory thermomechanical salt behavior, directed field testing of simulated waste/salt interaction, and full integration and collaboration with similarly motivated research centers in Europe. Deliberations on the future of nuclear energy directed toward decayed storage and disposal of commercial HLW fractions from recycling will also benefit from research proposed to resolve the key questions about thermal salt storage. This work leverages off earlier work and the substantial knowledge base concerning HLW storage and disposal in salt.

Figure 1-2: Comparison of Surface Exposure for RH TRU Waste (Being Disposed at Waste Isolation Pilot Plant) and Defense HLW



Overlapping Range of HLW (including UNF) and RH TRU Waste Dose Rates

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Why Bedded Salt?

Ten years of successful operation of the WIPP have demonstrated the fiscal, operational, and compliance efficiency of salt mining and defense TRU waste disposal. Salt investigations in the United States and Germany support the concept of salt disposal for heat-generating waste as well; however, there are some gaps in our knowledge base for the mechanical behavior of salt and the hydrologic and chemical behavior of brine at higher temperatures, as well as how salt interacts with waste constituents at higher temperatures. Heat management is an overriding consideration in repository layout, and the very act of balancing the heat load underground creates ample volume for disposal of non-heat generating wastes such as greater than class C and low-level radioactive waste. Furthermore, depending on the results of this testing program and accompanying performance assessment analyses, direct disposal of calcined or other mineralized forms of waste, or other cost-effective changes to upstream processing, might be found acceptable.

The positive attributes of salt that make it an effective medium for disposal and isolation of hazardous, toxic, and radioactive materials have been recognized for over 50 years (NAS. 1957). As briefly discussed below, the attributes of salt are collectively important to its isolation capability and provide the safety basis for isolation of embedded materials.

1) **Salt can be mined easily.** Salt has been mined for millennia. A wealth of underground experience, including TRU waste disposal operations at WIPP, ensures that large-scale, safe mining can be conducted in salt.

2) **Salt flows around buried material and encapsulates it.** Salt will slowly deform to surround other materials, thus forming a geologic barrier that isolates waste from the environment. Creep or viscoplastic flow of salt has been well characterized for many applications. Research in the United States, coupled with international collaborations, has played a significant role in development of this technical understanding.

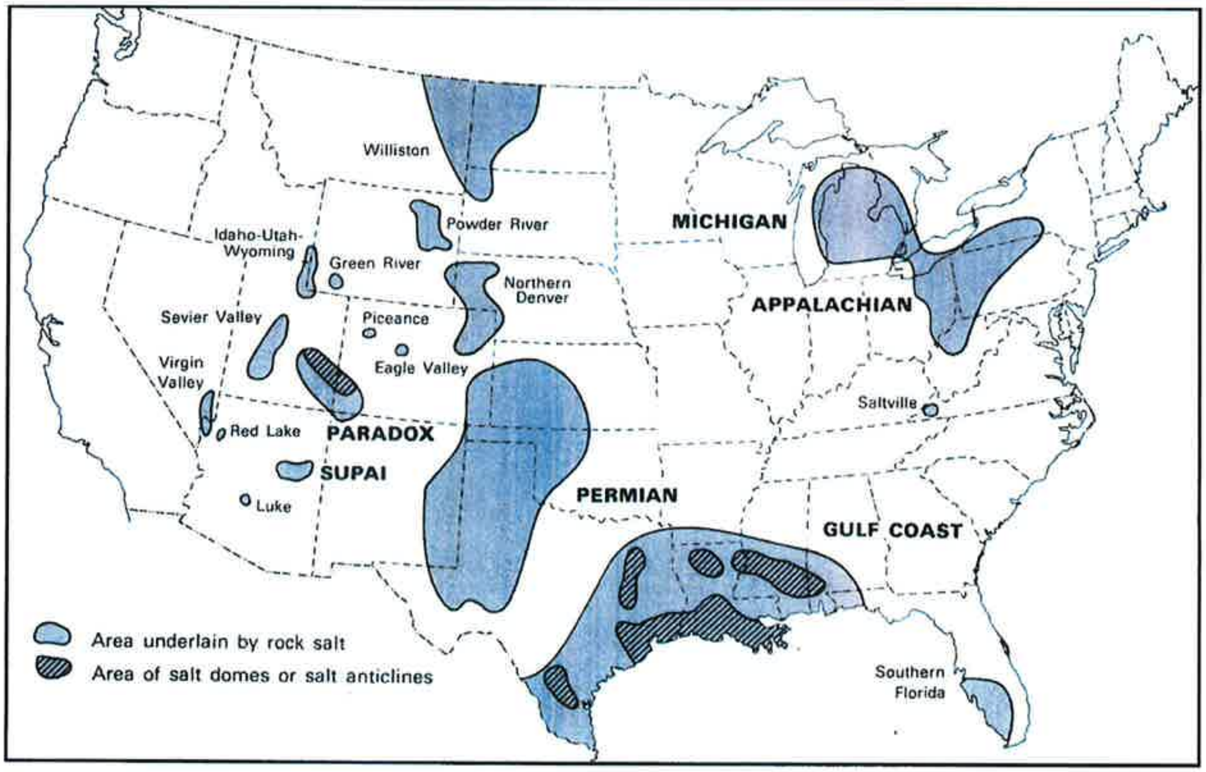
3) **Salt is essentially impermeable.** The very existence of a salt formation millions of years after deposition is proof that water has not flowed through the formation. The established values for permeability of intact salt come from many industry applications, such as the large-scale storage of hydrocarbon product in solution salt caverns. The undisturbed formation permeability of salt is essentially too low to measure using traditional hydrologic and reservoir engineering methods. In undisturbed and healed salt, brine water is not able to flow to waste at rates that would lead to significant radionuclide mobilization and transport.

4) **Fractures in salt are self-healing**. In terms of disposal, one of the most important attributes of salt as an isolation medium is its ability to heal damaged areas. Damage recovery is often referred to as "healing" of fractures. The healing mechanisms include microfracture closure and bonding of fracture surfaces. Evidence for healing of fractures in salt has been obtained in laboratory experiments and through observations of natural analogs. Fracture healing can readily restore salt to a low permeability, as noted above.

5) **Salt has a relatively high thermal conductivity**. Thermal conductivity of natural rock salt under ambient conditions is approximately 2 to 3 times higher than granite or tuff. A relatively high thermal conductivity is a positive attribute in a salt repository for nuclear waste because the heat is rapidly dissipated into the surrounding formation.

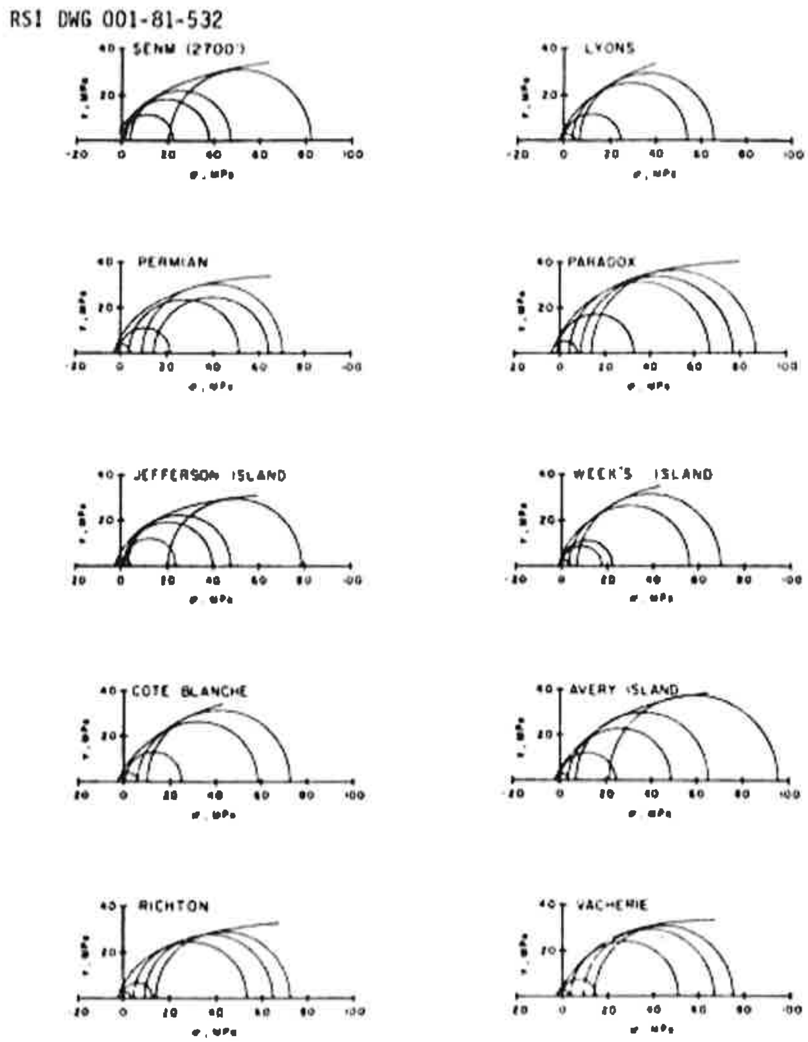
6) **Suitable salt formations exist in wide geographic distributions.** There are multiple locations with stable geologic salt formations within the 48 contiguous states (see Figure 1-3) that could host a repository. Bedded salt is preferred over domed salt due to the inherently larger areas contained in the bedded geologic salt formations, which leads to flexibility in accommodating potentially long periods of repository operations. In addition, salt formations have existed for millions of years in non-seismically active areas.

Figure 1-3: Stable Geologic Salt Formations within the 48 Contiguous States



Salt formations were actively studied for repository applications from the late 60's until the NWPA amendment removed the bedded salt site in the panhandle of Texas from consideration as the civilian repository for spent nuclear fuel and high level waste. In a global sense salt mechanical, thermal, and hydrological properties are fundamentally similar. In the early years of site investigations, basic properties of many salts were measured. For example, in Figure 1-4, the failure envelopes for ten natural salts including both bedded and domal formations with a variety of impurities show the similarity of strength and pressure sensitivity (Hansen et al., 1980). Some of the other basic phenomena, such as dilatant response and plastic deformation mechanisms, have commonality across a wide range of natural salt. These points are made to emphasize that the fundamental studies encompassed in the SDI will be applicable to all salt repository studies.

Figure 1-4: Mohr's Circles of Stresses at Failure for Ten Rock Salts at Room Temperature



Why Study Bedded Salt at Higher Temperatures?

Laboratory and field studies of intact salt and crushed salt and the chemical interactions of salt with waste packaging, waste forms, and waste constituents received a considerable amount of attention in the 1980s. However, the upper temperature limit for the thermomechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests have been conducted predominantly at room temperature. These past studies have been more than adequate to demonstrate that disposal of TRU waste in salt is safe and efficient. However, for thermally hot waste there are gaps in the experimental data that are addressed in this management proposal. The proposed research, development, and demonstration of salt efficacy for the safe and efficient disposal of thermally hot waste proposed here will provide the basis for a single repository that can readily isolate large quantities of nuclear waste material, a key component of a safe and secure nuclear future for the nation.

The main goals for conducting this work are:

- **Demonstrate a proof-of-principle concept for disposal in salt.** WIPP experience has demonstrated that placing waste in a pre-drilled borehole is cumbersome and difficult. This disposal concept — proposed as a result of previous DOE-funded work (Carter et al. 2011 – see section 3.5.1) — obviates the need for pre-drilled holes, as well as the difficult phase of waste alignment and insertion into the pre-drilled hole. The proposed disposal concept is simple, safe, and expedient. The outcome of this proposed testing, in concert with the WIPP and analogue repository experience, will allow a more objective evaluation and optimization of proposed future repository designs.

- **Bound the salt thermomechanical response.** This test will push the envelope in terms of individual canister heat load and the average bulk salt temperature, thus ensuring that the thermomechanical phenomena experienced in the test for disposal in salt encompasses all likely thermal loads associated with future disposal.

- **Apply laboratory research to intact and crushed salt.** The fundamentals of high-temperature intact salt response and hot, dry reconsolidation will be studied in the laboratory. Information derived will inform field test planning and underpin the coupled process models of the large-scale response.

- **Investigate thermal effects on intact salt in situ.** Elevated temperature in the near-field environment will give rise to salt decrepitation (bursting caused by expansion of trapped brine) in addition to stress-induced fracture. Note that these phenomena may be negative or positive in terms of long-term performance, depending on the fate of liberated water and the ability of fractures in salt to heal. High temperatures, fracture states, and brine liberation drive important performance phenomena that will be investigated at repository scales in the field test.

- **Develop full-scale response for dry, crushed salt.** Whereas the reconsolidation processes of ambient crushed salt with a small amount of moisture are well understood mechanistically (e.g. Brodsky et al. 1996), the large-scale reconsolidation of hot and dry salt is less well documented. Understanding crushed salt reconsolidation in this setting is essential to establish room closure response, thermal conductivity, and near-field temperatures.

- **Observe and document fracture healing in situ**. Fracture healing is an important attribute for disposal in salt. This experiment will allow evaluation of creation and healing of a disturbed rock zone.

- **Characterize and understand brine liberation and migration.** Small amounts of brine exist in natural bedded salt, trapped there since its ancient deposition, millions of years ago. The brine exists in three forms: fluid inclusions, grain boundary brine, and hydrous minerals. Laboratory experiments will be conducted to quantify brine migration and characterize mineral reactions relevant to the water budget.

- **Track moisture movement and vapor phase transport in situ.** Because brine is considered a key to the evolution of the disposal setting, its movement in this testing milieu will be documented. Liberated brine will derive from the disturbed rock zone as enhanced by the thermal pulse. Samples of various materials associated with the full-scale test will allow determination of what chemical reactions and transport might take place with the brine movement.

- **Measure the thermodynamic properties of brines and minerals at elevated temperatures.** Precise measurements of the pressure, volume, and temperature (PVT) properties of brines are required for coupled process and performance assessment models.

- **Study repository interactions with waste container and constituent materials.** Evaluation of the chemical interactions of a broad range of materials (see Table 3-4) and waste forms in the laboratory will provide a scientific basis to evaluate waste form strategies and engineer waste forms and packages to limit or preclude the migration of radionuclide species in a salt based repository.

- **Measure the effect of temperature on radionuclide solubility in brine.** Radionuclide solubility will control the source term of any thermally hot waste repository for scenarios in which water contacts the waste. These studies will quantify the magnitude of the temperature effect on radionuclide solubility (U, Th, Tc, and Cs) and both guide and focus future performance assessment work.

- **Develop a validated coupled process model for disposal in salt for high heat load wastes**. Iterative field observations and model development will lead to a model that can be used with confidence in future repository design and performance assessment analyses.

- **Evaluate environmental conditions post facto**. After the heating cycle is complete, the test will be allowed to cool sufficiently to allow for the performance of forensic studies of the healed fractures, the consolidated salt, and corrosion coupons as the heaters are disinterred.

Underlying the research is the hypothesis that heat-generating waste may be advantageous to permanent disposal in salt. Under the conceptual model leading to this favorable result, the approximately 300-year thermal pulse introduced by the defense HLW would dry out a moisture halo around emplaced waste and thereafter accelerate entombment by thermally activating the creep processes. Note also that the thermally hot UNF recycling fractions (notably cesium (Cs)-137 and strontium (Sr)-90) will simply decay away in approximately 10 half-lives or 300 years. Thus, thermal decay storage in salt of these elements, which might otherwise be separated and stored, would favorably affect the disposal environment for the remaining very long-lived isotopes. These long-lived isotopes would be permanently encapsulated in a geologic formation that is demonstrably hydrologically inactive for hundreds of millions of years, thereby potentially precluding the need for engineered barriers in a repository design. As an example, a currently proposed engineered barrier is vitrification, a waste form modification for HLW.

The directed research will inform, guide, and ultimately validate capabilities for the next generation of coupled multiphysics modeling. The current state-of-the-art models will be instrumental for layout of the large-scale in situ field tests and continue to provide bases for performance assessment in the future. Next generation coupled TM(H) codes developed concurrently with the planning phase of the field test would then be benchmarked against current codes and validated using the field test data. This research will identify specific requirements for a viable long-term decay storage and deep geologic disposal concept in salt. These key elements would translate into parameters and phenomena to be measured in a proof-of-principle field test. The validated conceptual and numerical models resulting from the effort can then be used in future design calculations or performance assessment analyses. Appendix B, written as a short memorandum in June 2010, provides a brief recap of some of the reasons that salt research is timely and of national interest.

The investigators are well aware of the significant challenges to established boundaries presented in this proposal. The very reason for this proposal is that this work substantially advances the basis for the design, analysis, and validation of disposal in salt. The work embodied in this proposal is transformative. It is not proposed to repeat what others have done before; from the existing body of knowledge, the intent is to push forward the technical basis for disposal in salt. Cognizance of the scientific baseline has allowed the proposal team to establish the limits identified in this work, which will further the scientific limits in the address of unanswered questions. Because this is a science-based research proposal, which explores and advances the substantial foundation of salt science, the work, by necessity, rests at the forefront of technology, knowledge, and experience. This work is proposed because it explores the frontier and addresses questions that when answered, will set the future direction for disposal options in salt for the nation. Execution of elements of this management proposal, therefore, presents daunting challenges. Laboratory thermomechanical testing, for example, will include tests at high temperature and pressure, because understanding the physics under these conditions is vital to operational concepts, design, safety, and long-term isolation.

One of the important field test design criteria is high thermal loading. If the field test goes forward at a design thermal load of 40 W/m^2, the test bed may experience temperatures in excess of 160°C in the salt mass (see section 3.4.1), above where most data have been acquired to date. Steady state creep rate of WIPP horizon salt accelerates one order of magnitude for each increase of approximately 12°C. The affected salt near the heater is expected to flow rapidly and perhaps decrepitate. Upon review of the field test plan, the team may modify the very aggressive temperature limit, decide to modify the test temperature, or otherwise adjust the test and instrument arrangement. These considerations will be informed early by the laboratory testing and modeling. Experimentation in the laboratory will also present significant technical challenges in terms of instrumentation survival and data acquisition. As the laboratory thermomechanical testing proceeds in advance of the field test, laboratory experience will greatly inform the field-test team.

Applicability of this proposed work to other salt sites

There is a solid foundation of work conducted in salt, both for thermally cool and thermally hot wastes, providing confidence that a directed research program could lead to an expeditious path forward for thermally hot HLW disposal. This foundation, summarized in Hansen and Leigh (2011) and embodied in the WIPP technical basis documents, consists of 1) WIPP site-specific characteristics such as the geology of the Salado Formation (the salt host rock for the WIPP repository), the hydrochemistry of the repository fluids, the hydrogeology of the adjacent formations, and seismic stability; and 2) fundamental physical processes such as salt creep behavior, rock salt damage due to the mining operation, the hydrologic characteristics of intact and damaged salt, the healing of fractures in salt, radionuclide solubility and speciation in high-ionic-strength solutions, and the ambient-temperature consolidation of crushed salt (studied extensively in the context of the WIPP shaft seal system design).

At this stage of development of a HLW repository in salt, site-specific considerations in item 1 that enable the WIPP safety case to be made are not relevant because the science gaps being addressed in this management proposal are basic issues that are independent of any specific site. However, inasmuch as studies conducted at the WIPP site contribute greatly to the foundational knowledge of salt repositories, the rock characteristics and processes studied at the WIPP site are relevant, especially given that the logistically optimal next step for field testing would be to conduct in situ experiments at the WIPP facility. Because the location of a future repository will likely be based on a voluntary siting process (as suggested by MIT, 2011, among others), science-based investigations conducted before site selection must be focused on addressing fundamental issues that will be present at any potential salt repository site. Information gained from *in situ* studies must be transferable to other sites, either through direct analogy or through the use of validated numerical models. Furthermore, the observations made at the specific field study site should provide information useful to the site selection process by highlighting the properties and conditions that are either conducive or deleterious to repository performance. In suggesting the need for testing in an underground research laboratory (URL) at this stage, this proposal draws upon a long precedent in international repository programs (e.g. IAEA, 2001) for an approach involving research at URLs in advance of or in parallel with a site selection process, including the Swedish Aspo Hard Rock Site (Lundqvist, 2001) the Grimsel and Mont Terri sites in Switzerland (McKinley et al., 2001) and the Asse salt mine in Germany; the wisdom and efficiency of this approach appears to be borne out in the successful progress of the Swedish program.

With respect to this effort, the proposed research and development will build upon a foundation of excellence in salt repository applications that began with the 1957 National Academy of Science recommendation to use salt for permanent isolation of radioactive waste from the biosphere. As summarized in Table 1-1, various programs at different times and places have shared their results, which accounts for the large foundation for understanding salt properties over a wide range of applications. The proposed SDI will further add to the scientific basis for disposal in salt.

Table 1-1 summarizes the history of in situ salt thermal tests both in the U.S. and internationally over the past 50 years. The need for additional, science-based testing to fortify the technical baseline supporting HLW disposal builds upon a considerable data base deriving from historical experiments. For example, field heater tests in salt were conducted in Project Salt Vault in Kansas in the 1960s and in WIPP in the 1980s. Building upon past experiences and taking advantage of advanced technology allow the formulation of a solid, task-oriented, progressive proposal to address the remaining issues for HLW disposal in salt.

Table 1-1: Summary of In situ Salt Thermal Tests

Year	Project	Location	Description
1965-1969	Lyons mine, Project Salt Vault	Lyons, KS	Irradiated fuel & electric heaters
1968	Asse salt and potash mine	Germany	Electric heaters
1979-1982	Avery Island	Louisiana	Brine migration
1983-1985	Asse (U.S./German Cooperative)	Germany	Brine migration under heat & radiation
1984-1994	WIPP	Carlsbad, NM	1) DHLW mockup 2) DHLW over-test 3) Heated axisymmetric

It is worth noting that the heated experiments conducted at WIPP were undertaken after the agreement was made not to place heat-generating waste at WIPP. The collective science community agreed that the results obtained at WIPP would be applicable to the civilian program, which was investigating salt in the Texas panhandle. Thus, the justification for continuing field tests at WIPP was recognition of the transferability of information. The basic material properties, effects of stress and temperature, and phenomenology at a field scale were thought to be applicable and transferable between sites (see Figure 1-4, for example). In addition, salt programs have collaborated internationally for the purpose of understanding the fundamental physics. Indeed, the transferability of salt investigations reaches across the ocean, as the US civilian program sponsored brine migration experiments at the Asse mine in Germany. The salt science community has been building the technical baseline collectively for decades, utilizing lab and field test results from many different sources (Sandia National Laboratories. 2010. US/German workshop http://www.sandia.gov/SALT/SALT_Home.html.).

The following synopsis includes field experiments that started as early as 1965 with Project Salt Vault near Lyons, Kansas, as well as nearly contemporaneous field testing and demonstration at the Asse salt mine in Germany.

In situ field tests to study the effects of HLW in bedded salt were initiated at an underground salt mine in Lyons, Kansas in 1965. By 1968, elevated-temperature HLW field experiments had begun at the Asse salt mine in Germany. In situ tests for brine migration resulting from heating were conducted at the Avery Island salt mine in Louisiana beginning in 1979. Soon after, an extensive suite of field thermal tests were initiated at the WIPP site near Carlsbad, New Mexico. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits.

These field tests imparted a relatively modest thermal load in a vertical borehole arrangement and did not use crushed-salt backfill or explore reconsolidation of salt. These tests were primarily focused on the mechanical response of the salt under modest heat load. Although the results can be used, for example, to validate the next-generation high-performance codes over a portion of the multiphysics functionalities, the SDI disposal concept is intended to explore the interactions created by higher heat loads, a horizontal placement and crushed-salt backfill. The Heated Axisymmetric Pillar test conducted at WIPP in the 1980s (Matalucci. 1987) involved an isolated, cylindrically shaped salt pillar and provided an excellent opportunity to calibrate scale effects from the laboratory to the field, as well as a convenient configuration for computer model validation over a small part of the thermomechanical range of interest. These experiments were conducted at temperatures that are at the lower temperature range than that of which the SDI investigations are expected to test.

The very concept of analogues for repository performance is predicated on transferability of information from one site to another. Analogues are used in all geologic repository programs, regardless of the geology. Considerable qualitative support for permanent isolation in salt derives from pertinent analogues. For example, the unique sealing capability of salt has been dramatically demonstrated by containment of nuclear detonations in salt horizons, one at the Gnome Site near WIPP and two at the Salmon Site at Tatum Dome in Mississippi (Rempe. 1998).

In addition to anthropogenic evidence from mining experience and nuclear detonations, nature itself showcases the encapsulating ability of salt formations penetrated by high-temperature magmatic dikes. Salt formations in New Mexico and Germany have been intersected by magmatic dikes. Despite the severe nature of such magmatic intrusions, there are only very thin alteration zones at the contact between the high-temperature igneous intrusion and the salt. No evidence of significant fluid (inclusion) migration toward the heat source has been reported from field observations. Analogues over a wide range of conditions provide qualitative evidence that salt formations have the capacity to permanently contain a wide variety of severe conditions. This type of analogue information is commonly used in repository sciences and transferability of such observations is a fundamental tenet of the safety case.

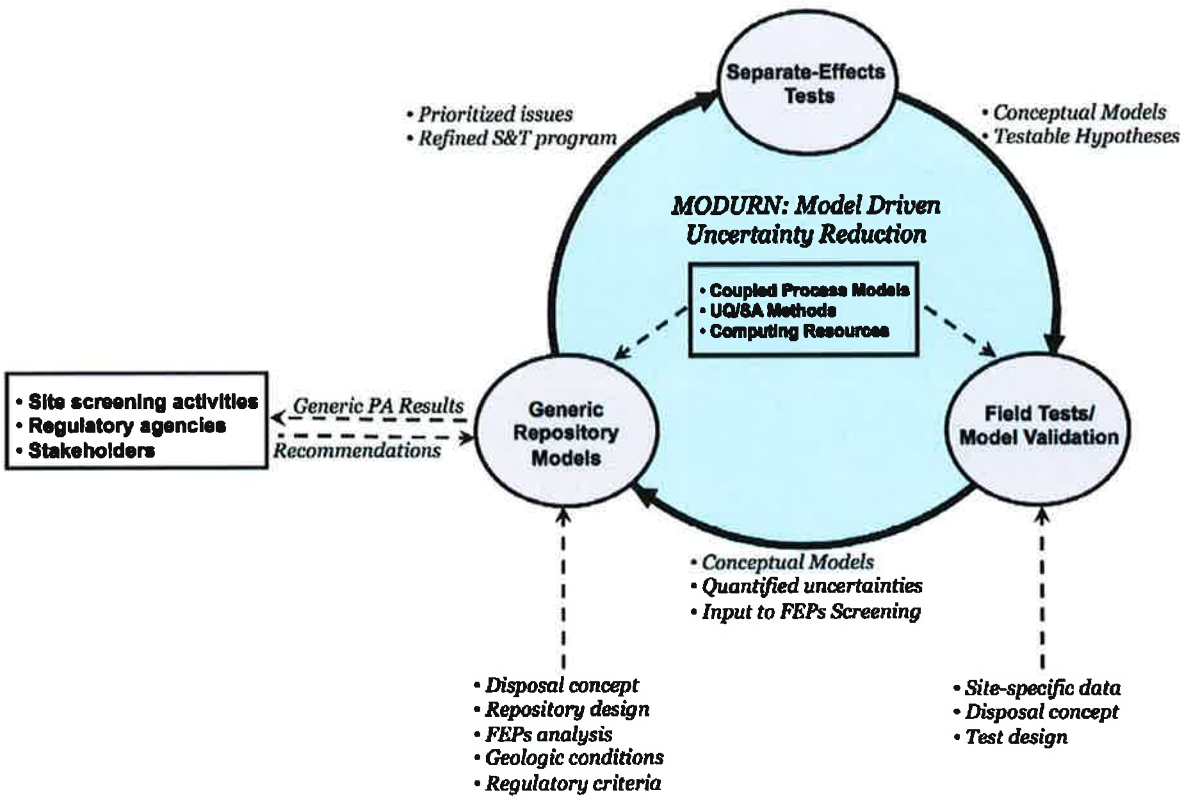
It is for these reasons that SDI investigations, as defined in this management proposal, will further add to the scientific basis for disposal in salt and that these proposed studies at WIPP are applicable to other salt sites.

Relationship of this Work to Broader Repository Science Efforts

After the Presidential decision to eliminate Yucca Mountain from consideration as the host site for a U.S. High-Level waste and spent nuclear fuel repository, the U.S. needs to rethink its approach to the disposition of defense high-level waste and civilian used nuclear fuel. The Presidentially appointed Blue Ribbon Commission for America's Nuclear future is chartered to "*conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities.*" (DOE, 2010). The likely outcome of such an evaluation is a set of recommendations regarding potential technological and policy alternatives that would provide direction for the U.S. in its efforts to deal with legacy nuclear waste, hopefully putting the U.S. on a path that enables cleanup of legacy waste sites and the sustainable utilization of nuclear energy to meet our growing need for low-carbon energy sources. Thus, there is a need to develop a logical set of research and development activities, informed by knowledge of the current national need, which would help the nation to craft a robust repository program. To that end, a set of scientific investigations that will provide clarity regarding the strengths and limitations of the use of salt as a host medium for the deep geologic disposal of high-level and other classes of radioactive waste is identified herein. In reaching this conclusion, no attempt to perform a comprehensive trade study is made, and it is probable that there are other technically viable choices for permanent geologic disposal available to the nation. Nonetheless, it is believed that the research program advocated herein, which proposes to address gaps in the knowledge of the behavior of salt as a disposal medium for thermally hot waste, represents one promising direction with both near term and long term benefits.

To understand our long-term perspective, consider Figure 1-5, which illustrates the role of field tests for model validation in the context of a broader set of investigations required to build a science-based safety case for disposal. The schematic is generic: it is not specific to any disposal concept or host medium, nor does it presuppose that a site has been selected for suitability investigations. The core concept is the systematic reduction of uncertainty in models through the iterative process of model development, experimental studies, and repository modeling to assess geologic disposal viability. Separate-effects tests, which typically study one or a few processes in great detail under controlled conditions, are re-examined in an integrated fashion in an underground research laboratory (URL), and models of the field test are developed. No matter how faithful an in situ test is to an actual disposal concept, it is still only a test of limited duration and spatial extent, rather than an actual repository. Therefore, residual uncertainties propagated through a generic model of a repository must be quantified, bringing in other relevant considerations and processes (e.g. scenario development, regulatory criteria, subsystem models) in order to fully define a Performance Assessment analysis. These results, vetted at regular intervals with stakeholders, are used to inform modification of the science program as new knowledge is incorporated and critical uncertainties are identified. Models are central to this vision, and are used to drive a process of systematic learning, adaptation, and communication that is the recommended path to ultimate success of a repository program (e.g. NAS, 2003). This figure depicts the process at the relatively early stage of development that the U.S. program currently finds itself, in advance of site selection. As the process evolves, site screening would be replaced by site-specific investigations, including field tests at a proposed repository site, PA analyses would no longer be generic, and interactions with stakeholders and regulators would become more regular and formal.

Figure 1-5: Conceptual Schematic of Model-Driven Process for Repository Investigations



Note: Figure Acronyms: FEPs – Features, Events, and Processes; PA – Performance Assessment; S&T – Science and Technology; SA – Sensitivity Analysis; UQ – Uncertainty Quantification.

Successful implementation of this process requires a suite of modeling capabilities, from coupled thermal/mechanical/hydrologic/chemical process models to higher-level systems models of repository performance. The current U.S. program, through the Used Fuel Disposition campaign, has efforts underway to develop repository performance assessment modeling systems, and general-purpose subsurface modeling and simulation capabilities that will significantly enhance our capabilities in the future. Meanwhile, a combination of existing codes and incremental model development will enable us to implement this process.

The understanding of different geologic media and disposal concepts is at different levels of maturity. In the U.S., salt is one of the most mature, with the iterative loop of Figure 1-5 having been traversed in the past through the combination of laboratory scale experiments (called "separate-effects tests" in the figure), field investigations under ambient conditions, PA modeling of the WIPP repository, and field-scale heater tests. As opposed to other media and disposal concepts, the current needs and requirements of a research program for salt are well known and quite specific, and can be satisfied through an integrated program of laboratory experiments, model development, and a validation field test to fill gaps in knowledge for assessing for the disposal concept presented herein. Separate-effects tests include thermal/mechanical studies on crushed and intact salt to extend the range of temperatures for which phenomena are known to approximately 300°C, and brine migration, mineral dehydration, and phase transformation reaction studies to investigate the potential fate of water. Additional laboratory investigations relevant to repository modeling (i.e. inputs to the "Generic Repository Models" portion of Figure 1-5) include studies of interactions of fluids with typical engineered materials at repository temperatures, solubility, speciation, and redox states of key radionuclides in high-ionic strength solutions at elevated temperatures. In other words, a field-validated thermal model of salt behavior relies on thermal/mechanical/hydrologic lab studies, whereas the generic repository modeling performed to put the field results into context for the purpose of building a repository safety case requires additional data inputs related to radionuclide and engineered materials behavior in the repository environment.

Armed with this additional suite of separate-effects tests, a thermal test conducted in the field (represented by the "Field Tests/Model Validation" portion of the figure) is required to complete another iterative loop of the R&D cycle to reduce uncertainties associated with the disposal of HLW in salt. To better understand the rationale for this statement, consider that the behavior at the repository scale is governed by a complex set of interrelated processes at multiple scales. For example, water movement is tightly coupled to the mechanical behavior of the rock as well as the thermal evolution of the decay heat in the waste form, crushed salt backfill, and surrounding salt, both damaged and intact. On the one hand, there is an impressive set of scientific studies which will be used (and additional laboratory studies are proposed) to understand the processes that might control the behavior of salt as a disposal medium for thermally hot waste. However, in the case of repository modeling, different small-scale effects (each of which are relatively well understood) interact with and influence one another, and their impacts on large-scale observables wax and wane over time as the system evolves. Fundamentally, in a complex system, emergent behavior is likely to arise when individual processes interact in this way. The reductionist approach of studying individual processes or characteristics of a salt specimen at the laboratory scale is insufficient to allow, for example, the prediction of the thermal-mechanical evolution of the rock mass and the fate of liberated water. Only through integrated tests are the operative controlling mechanisms able to be fully assessed; large scale, in situ measurements in a repository disposal setting are required to build confidence in a disposal concept, repository design, and safety case.

While the relative merit of conducting this work versus performing R&D in other media is beyond the scope of this management proposal, these proposed activities fit nicely within the broader goal of reconsidering multiple options for permanent geologic disposal. The fact that the logical next step involves field testing is a consequence of the large investments made by the U.S. to study salt for TRU waste disposal, and previously when salt was considered as a host medium for HLW before Yucca Mountain was chosen for intensive investigation. Taking an international perspective to the nuclear waste disposal issue, granite and clay disposal concepts are at a similar stage of development to salt, in that field investigations are being conducted and generic and site-specific activities are being pursued, in many cases in advance of site selection. If the U.S. program follows suit by initiating its own field investigations in salt, and aggressively pursues international collaborations in salt and other media, ongoing repository science activities around the world will be maximally exploited the for the purpose of defining future options for disposal of U.S. wastes. Furthermore, establishing a U.S.-based URL for repository science in salt will help facilitate international collaborative R&D, and will maintain and enhance a critical capability to perform large-scale, subsurface R&D or repository science that was established in the Yucca Mountain and WIPP projects.

2. PROJECT MANAGEMENT, QUALITY ASSURANCE, AND SAFETY

2.1. TEST MANAGEMENT STRUCTURE

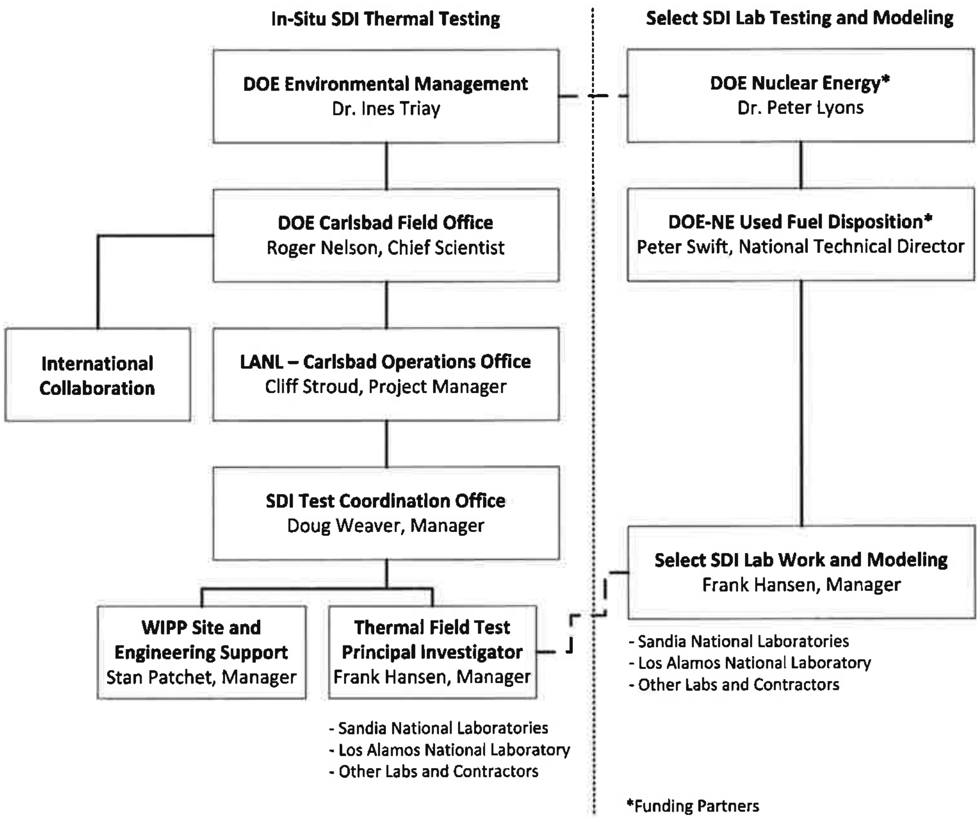
The overall management of the work proposed within this SDI project will be through the CBFO. The CBFO defines quality requirements through a QAPD similar to that used for the WIPP program. The SDI QAPD describes an NQA-1-2008 compliant QA program for the science-based studies concentrating on high thermal loading effects in bedded salt. DOE-NE will manage work packages designated in fiscal year 2012 for select laboratory testing and modeling efforts (see reference 22). DOE-EM is funding efforts largely related to the planning, design, and initial construction of the in situ thermal test at WIPP (see Table 4-2 for specific budget breakdown).

LANL-CO will function as the project management organization, responsible for day-to-day test management and coordination, similar to a successful model used at the Nevada Test Site and the Yucca Mountain Project, ensuring that all test-related information and data activities are consistent and focused. In its management capacity, LANL-CO will report to the CBFO Project Manager. SNL, LANL, and potentially other scientific entities, will provide Principal Investigators to inform and advise test management to ensure the testing program is as productive, integrated, and efficient as can be achieved. Those portions of the SDI investigations funded by Used Fuel Disposition Campaign (UFDC) of the DOE-NE will be managed according to the judgment of the UFDC management team.

WTS, the WIPP Management and Operating Contractor, will provide engineering, construction, and test support labor to provide for the test bed (e.g., drift mining, borehole coring, electrical, and ventilation) and aid in test installation.

Participants in this research will include personnel from LANL, SNL, and WTS. Personnel at these organizations bring many years of direct salt repository experience and have conducted decades of salt research and thermal testing, both in the laboratory and the field. Experience directly relative to the types of field and laboratory activities described in this management proposal include field work at the Nevada Test Site, large in situ thermal tests at Yucca Mountain Nevada, and experimentation at WIPP. Additionally, the primary collaborators bring the experience of many years of public interactions, which sharpen an appreciation for public understanding. Public outreach will be integrated with our international collaborators and build upon elements of their success as well. Appendix C provides a list of key contributors to this management proposal and a summary of related experience. Figure 2-1 illustrates the organizational structure of this testing program with the funding partnership between DOE-EM and DOE-NE.

Figure 2-1: SDI Organizational Structure with Funding Partnership



2.2. QUALITY ASSURANCE AND SAFETY

CBFO, in support of this project, developed an SDI QAPD modeled after the highly effective and time-proven CBFO QAPD. The SDI QAPD describes an NQA-1-2008 compliant Quality Assurance Program for the science-based studies concentrating on high thermal loading effects in bedded salt. Existing WIPP procedures are adapted as appropriate to accommodate the SDI program, thereby taking advantage of the existing mature and audit-tested programmatic and technical processes established for the repository program.

Each program participant assigned responsibility for performing the SDI work described in this proposal (primarily LANL, SNL, and WTS) is currently working under and maintaining compliance with the CBFO QAPD for WIPP activities. The CBFO, for current WIPP work, is responsible for defining quality requirements and applicability, developing appropriate plans and procedures to attain quality, and supporting project participants in pursuit of quality. Where applicable, project participants are responsible for developing and following plans and procedures that effectively implement the requirements described in the CBFO QAPD. Project participants are also responsible for compliance with requirements contained in other relevant CBFO planning documents. Those elements of the SDI funded by DOE-NE will be performed consistent with requirements of the Fuel Cycle Technology QAPD, which governs Quality Assurance for research under DOE-NE.

The combined experience and track record of the national laboratories, WTS, and CBFO in successful implementation of rigorous QA programs in a regulatory environment are exceptional. The primary national laboratories expected to participate in this work (LANL and SNL) have extensive NQA-1 experience in repository sciences associated with WIPP. Each has participated in the successful compliance certification (and two 5-year recertifications) of WIPP with the U.S. Environmental Protection Agency (EPA) as a regulator and the Resource Conservation and Recovery Act (RCRA) permit issuance and recent 10-year renewal by the New Mexico Environment Department (NMED).

Additionally, as with quality assurance, each proposal participant has extensive experience and an exemplary record of safety related to field and laboratory work activities, including a culture and value structure that promotes safety in the workplace. Each listed participant will conduct work safely and responsibly; ensure a safe and healthful working environment for workers, contractors, visitors, and other on-site personnel; and protect the health, safety, and welfare of the general public. This is done through institutional frameworks and processes that align with the principles and functions of Integrated Safety Management.

2.3. WIPP REGULATORY COMPLIANCE CONSIDERATIONS

The WIPP may only dispose of the nation's defense-related transuranic radioactive waste, however, there are processes to evaluate the use of WIPP for underground experiments. The use of the WIPP underground for the field test portion of SDI is based on saving costs by avoiding the development and installation of mining infrastructure at some other existing salt or potash mine of similar depth. There will be some costs to perform the tests in WIPP. However, the area to the north of the access shafts (and far north of waste disposal operations) is already configured with electrical power and fiber optic cable to service basic science experiments. An existing trained workforce, mining infrastructure, nuclear safety bases, and an NQA-1 quality assurance program already in place will make the field test part of SDI cost less than bringing these essential elements of a field test to another commercial mine.

The cost effective and efficient use of WIPP for the field tests is offset by the need to gain regulatory approval to conduct the tests there. WIPP's compliance envelope is complex, with multiple state and federal agencies involved. The two most important regulators that are involved in WIPP operations are the NMED and the EPA. In addition, DOE itself must ensure that any tests performed at WIPP are in compliance with the National Environmental Protection Act (NEPA).

In response to multiple basic science inquiries made by researchers across the country after WIPP opened, DOE conducted an Environmental Assessment (EA) under NEPA guidelines in 2001. That EA analyzed impacts from a variety of possible experiments that might be performed using the unique underground setting at WIPP. One of the bounding experiments was a test very similar to the scope of the proposed SDI. That potential experiment involved using electrical heaters in specially mined alcoves to measure the response of the salt medium to the effects of heat-generating materials emplaced for disposal in salt. A Finding of No Significant Impact (FONSI) was reached as a result of the EA, and this management proposal assumes that no additional analyses are necessary under NEPA to allow the SDI field tests to be performed in WIPP (Marcinowski to Triay. 2003).

The NMED regulates the disposal of hazardous waste at WIPP under the provisions of the RCRA. Much of the transuranic waste destined for disposal in WIPP also contains hazardous components regulated under RCRA. However, none of the specific actions proposed in the SDI field test will involve hazardous materials. Therefore, no modification of the permit issued to WIPP by NMED should be necessary. However, since the SDI tests will use the common infrastructure that is regulated under the permit for waste disposal, DOE will inform and consult with NMED as the tests are designed and conducted.

WIPP's primary purpose is the permanent isolation of transuranic waste resulting from defense activities. EPA's regulations promulgated under 40 Code of Federal Regulations (CFR) Parts 191 and 194 require that DOE ensure isolation and compliance with the standards for a 10,000-year period. The conduct of SDI field test is unrelated to waste emplacement operations (other than the use of common infrastructure) and will not change the characteristics of the overall disposal system within the land withdrawal area for WIPP. DOE will prepare analyses that demonstrate the effects of the additional mining and heating of the test area footprint (well north of the waste disposal operations) will not compromise long-term repository performance. These analyses will be submitted to EPA under a Planned Change Notice for their review and concurrence, similar to the process both agencies have successfully used for other basic science experiments that have been, and continue to be, conducted in the north part of the WIPP underground. This review and approval process has typically required about 3-6 months to complete and will be initiated in mid FY 2011 to support the start of mining.

2.4. INTERNATIONAL COLLABORATION

CBFO will establish a program that will re-engage research and operating entities in Germany and other European Union (EU) member nations. This proactive re-engagement with primarily European counterparts will enhance the DOE's scientific program and protect against loss of knowledge and personnel from salt repository enterprises. Elements of the international outreach will provide consistent support for workshops devoted to repository research topics, which will provide a forum for documenting technical advances that accompany an expanded publication effort.

Salt disposal remains a leading permanent disposal option and it is well established internationally. (Sandia National Laboratories. 2010. US/German Workshop on Salt Repository Research, Design, and Operation, May 25–27, 2010. <http://www.sandia.gov/SALT/SALT_Home.html>). As one of the most advanced repository options in the world, the science community has a definitive grasp of what has been done and what still needs to be done. Much of the experience gained from United States repository development, such as seal system design, coupled process simulation, and application of performance assessment methodology, helps define a clear strategy for a heat-generating nuclear waste repository in salt. The authors worked closely with German salt repository scientists and engineers to identify the research challenges ahead of us.

The recent summary of the US/Germany workshop proceedings issued by Forschungszentrum Karlsruhe GmBH (KIT. 2010) acknowledges that implementation of a repository for heat-generating waste in rock salt is feasible. This German agency supports research and development in rock salt that parallels the work identified in this proposal. Full-scale field studies in the United States include Project Salt Vault at Lyons, Kansas; the Avery Island, Louisiana, heater tests; and WIPP thermal structural investigations. Salt repository programs in Germany include a proposed HLW site at Gorleben, the research facility at the Asse Mine, the nuclear waste storage facility at Morsleben, and a bedded salt storage facility for chemotoxic wastes at Herfe-Nerode. In today's environment, large-scale salt studies have been pursued by EU members. Collaboration with EU countries (with Germany, in particular) would avail technical staff of the latest international developments in salt repository sciences. Possible goals for international collaboration include:

- Create collaboration and technical alliances between CBFO and international partners (first Germany, then other EU member nations).
- Preserve and advance technical applications of salt sciences, specifically focusing on international interests that compliment U.S. interests.
- Perform fundamental research into areas where understanding deformational behavior of salt is incomplete.
- Partner with EU countries (Germany and Poland as a start), through the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, to support a working group on "Safe Disposal of Long-Lived Radioactive Waste in Rock Salt as Repository Host Rock Formation" (Salt Club).
- Develop position papers on vital salt repository issues, such as brine and vapor transport.
- Utilize technology and instrumentation developed and demonstrated in salt applications in Europe.
- Provide an educational basis for and knowledge transfer to next-generation researchers.
- Transfer methods and tools for salt storage facilities and mining operations to ensure safe, secure, long-term functionality of the underground structures.
- Expand existing international collaboration with Karlsruhe/INE on actinide speciation in brine.
- Make technology available to support the nation's future energy supply and infrastructure needs.
- Afford technical experts access to the latest international developments in salt mechanics sciences.
- Develop a central library of acquired salt data and other information, with broad access provided via the Internet.

3. PROPOSED RESEARCH PROGRAM

The proposed research program describes areas that would substantially enhance our knowledge of the behavior of thermally and radioactively hot nuclear waste in salt and would provide fundamental data for the evaluation of concepts for disposal in salt. The program has been divided into the following major elements:

1. Functional and Operating Requirements and Test Planning (including Project Management, QA, Safety and Regulatory Compliance activities as described in section 2.0)
2. Laboratory Thermal and Mechanical Studies to Support the Field Test
3. Laboratory Hydrologic, Chemical, and Material Studies
4. Coupled Process Modeling
5. Field Test Installation and Operation
6. International Collaboration (described in section 2.4)

The first task establishes the functional and operational requirements for the field test. The experimental investigations are divided into laboratory testing, modeling, and in situ testing. Laboratory research in support of the field test includes thermomechanical and hydrologic testing of intact and crushed salt and chemical and physical properties of the brine as a function of temperature. Chemical and material studies consistent with salt repository performance will also be pursued in the laboratory. Some of these areas received a considerable amount of attention in the 1960s to 1990s; however, the upper temperature limit for the thermomechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests were predominantly conducted at room temperature. The laboratory studies will build upon previous work and enhance these efforts by reinvigorating international collaborative research. Furthermore, the proactive reengagement with primarily European counterparts will enhance our scientific program and protect against loss of knowledge and personnel from salt repository enterprises. A carefully designed field test in bedded salt will serve as a proving ground for concepts of disposal in salt and provide data for modeling validation and refinement that is needed for a repository design or performance assessment model. The in situ heater test in out years will provide a full-scale mock-up of a generic salt repository design concept and will provide data (temperature, deformation, and environment) for thermomechanical calculation confirmation, backfill consolidation, moisture movement, and waste form/brine chemical interactions. Forensic analyses of the re-mined material after the in situ heater test will provide performance validation and confirmation in years beyond the current proposal. All of this information will be used to support an integrated modeling and simulation effort for the evaluation of concepts for disposal in salt.

Elements of this management proposal are technically integrated and build a solid science basis for disposal options. The proposed testing and modeling will be conducted under a QA program. The QA obligation includes development of test plans, calibrations, and record capture and storage.

3.1. FUNCTIONAL AND OPERATIONAL REQUIREMENTS AND TEST PLANNING

This task will be determining F&OR for a field test. CBFO will collaborate with the technical team in the development of the F&OR, as well as assuring the appropriate breadth of scientific studies is included. The F&OR document will be a deliverable to CBFO in late FY 2011 and will be used to provide the basis for the test bed location, layout, and operational requirements such as specifics related to providing proper ventilation, power, and access. Test-specific requirements such as instrumentation characteristics, precise borehole placement, instrumentation calibration requirements, data quality objectives, and other detailed test information will be provided in a field test plan to be developed, reviewed, and delivered in FY 2012. Laboratory testing and modeling activities will have specific test plans scaled to the level of activity complexity, in accordance with the applicable QAPD. As part of these detailed test plans, existing and available information from past thermal experiments in salt will be comprehensively evaluated.

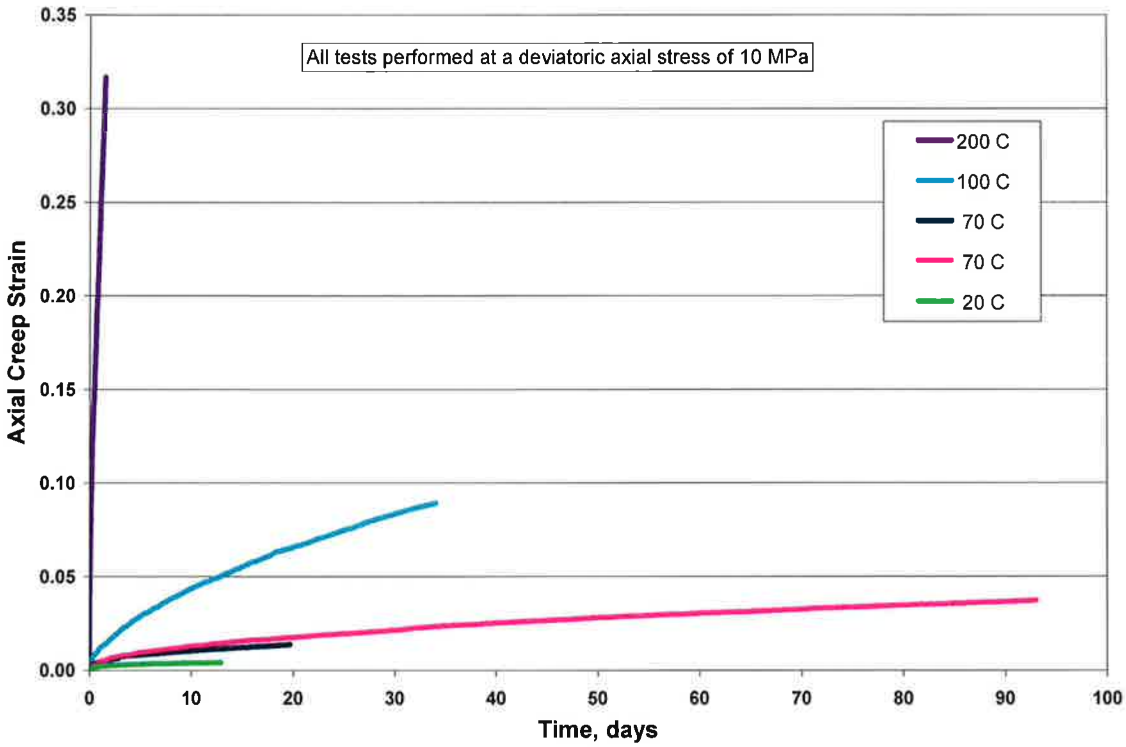
3.2. LABORATORY THERMAL AND MECHANICAL STUDIES

Laboratory studies of salt are proposed and described in the following sections. The laboratory studies are intimately related to the needs of the modeling program. Experiments to evaluate consolidation of hot, dry, run-of-mine salt, will yield a stress/temperature/porosity function needed for modeling the disposal proof of principle. In addition, an assessment of thermal conductivity as a function of porosity is needed to properly account for the transient evolution of the disposal area. Deformational phenomenology of exceptionally hot intact salt tested uniaxially is fundamentally important before the final design parameters are assigned for the disposal concept field test. These thermomechanical (TM) laboratory results are essential for modeling and therefore need to be conducted as early in the program as possible. These TM inputs are used directly for modeling the proof-of-principle disposal concept, which includes liberation of accessible brine.

Laboratory studies on WIPP salt are designed to provide a phenomenological examination of intact salt at high temperatures and stress states that the near-field salt is expected to experience. Consolidation of hot, dry crushed salt will provide important data for performance and detailed modeling of the disposal concept. Salt immediately surrounding a simulated waste package (heater) will consist of run-of-the-mine salt (backfill) used to bury the heater. Both laboratory experimental programs involve mechanical compression at temperatures as high as 200°C to 300°C to observe the change in deformational behavior as the temperature increases. Earlier Office of Nuclear Waste Isolation (ONWI) and WIPP experience and knowledge of salt's thermomechanical response provide an initial basis for this applied rock mechanics work. The personnel performing these studies will share information with international collaborators.

For purposes of the field test, it is anticipated that the underground salt environment will be heated to temperatures well above those for which current salt experimental data exist. In a general sense, the thermally driven response of salt is the controlling element of the concept of disposal in salt. Elevated salt temperatures will cause accelerated salt-creep deformation, which leads to a more rapid encapsulation of the waste. Therefore, these laboratory-based intact-salt studies will provide key field-test information for evaluating the disposal concept and testing the hypothesis that the thermal pulse imparted by the waste leads to this rapid encapsulation.

Figure 3-1: Strong Influence of Temperature on Creep of Natural Rock Salt



Salt deformation is dominated by plastic behavior at elevated temperatures. Figure 3-1 illustrates strain-versus-time curves for creep tests on rock salt performed at the same stress condition but at different temperatures. Temperature has a dramatic influence on the creep rate of intact salt specimens owing to thermally activated deformation mechanisms. Relatively little elevated temperature mechanical testing has been conducted for crushed salt consolidation, an important element of the concept of disposal in salt. Crushed salt testing has two parts. First consolidation testing will derive a relationship between temperature, stress states and porosity. The second test series will determine thermal conductivity as a function of porosity and temperature.

3.2.1. Intact Salt Studies

All testing will be performed under an approved test plan developed in accordance with appropriate QA requirements discussed earlier in this management proposal. A preliminary test matrix is identified here for schedule and cost estimates. Test conditions described push the threshold of laboratory experience on natural salt. The Principal Investigator will reserve flexibility in the test plan to change the preliminary test conditions if results warrant it. The intact salt will be tested in an unconfined condition at a constant axial strain rate using solid cylinders. Uniaxial stress loading will continue until the specimen exhibits either failure or extreme deformation (~20% strain). It is well known that salt deformation, even at room temperature, is dominated by plastic deformation mechanisms. Crystal plasticity will be greatly enhanced as temperature increases, such that extensive plastic deformation will accompany fracture formation. As a preliminary basis of estimate, a total of nine tests (Table 3-1) will be conducted comprising a triplet of tests at each of three temperatures: 200°C, 250°C, and 300°C.

Inelastic creep processes will dominate the deformation of the specimens even in a quasi-static load application, with the creep response being ever more pronounced as the temperature increases. Rather than specimen failure, extreme deformation is expected to cause the tests to be stopped.

Table 3-1: Uniaxial Compression Test Matrix

Test Number	Salt Type	Test Type	Temperature	Loading Condition
9,10,11	Intact	Uniaxial stress	200°C	Constant Strain Rate
12,13,14	Intact	Uniaxial stress	250°C	Constant Strain Rate
15,16,17	Intact	Uniaxial stress	300°C	Constant Strain Rate

The tests at 200°C will overlap with historical databases and provide a point where predictive models based on those databases can be checked for the current work. The tests at temperatures above 200°C will provide new data so that extrapolation outside the actual test database will not be necessary. The field test (and actual alcove disposal) is expected to involve temperatures much greater than 200°C (at the heaters), thus this high-temperature research is needed for the design and evaluation of the in situ experiment. An assessment of the need to run triaxial experiments at these temperatures will be made based on the results of these uniaxial tests. The schedule and budget do not include triaxial testing.

3.2.2. Crushed Salt Studies

The laboratory tests on crushed salt include consolidation as a function of stress and temperature and thermal conductivity as a function of bulk density and temperature. Here "crushed" salt means run-of-mine salt that is sieved to separate out large aggregate. Consolidation of the sieved run-of-min salt can be performed in two ways: either using an oedometer arrangement or an isostatic pressure vessel. Thermal conductivity of the backfill salt will be measured on reconsolidated salt specimens produced during the consolidation studies. The thermal properties will be measured over a temperature range from the mine temperature to 300°C and at a variety of porosities.

Because of greater opportunity for experimental control, most consolidation research will be done using an oedometer. Oedometer consolidation involves uniaxial compression of circumferentially constrained granular salt within a hollow steel shell. The large scale apparatus for consolidation under heat and load will have to be fabricated. Consolidation is measured using axial displacement measurements, and the measured change in volume represents the reduction of pore space in the run-of-mine salt and an accompanying increase in bulk or fractional density. A total of eight individual tests (as listed in Table 3-2) are proposed. Two replicates will be performed at each of four temperatures: 100°C, 150°C, 200°C, and 250°C. The stress application and deformation of these tests is expected to be short term; however, the pre-test heating and the post-test observational work (petrographic analyses) will require additional time.

Table 3-2: Oedometer Consolidation Test Matrix

Test Number	Salt Type	Test Type	Temperature	Loading Condition
1,2	Backfill	Uniaxial compaction	100°C	Biaxial Stress
3,4	Backfill	Uniaxial compaction	150°C	Biaxial Stress
5,6	Backfill	Uniaxial compaction	200°C	Biaxial Stress
7,8	Backfill	Uniaxial compaction	250°C	Biaxial Stress

The consolidation of granular salt will also be examined using hydrostatic (uniform triaxial) compression. In this style of testing, stress control is provided by two independent systems: an axial loading ram and fluid pressure applied radially to the specimen. The loading ram is a standard hydraulic actuator driven by a servo valve, and either the ram position or the load on the ram can be used as the feedback control variable. Fluid pressure in the vessel is controlled by a constant-pressure intensifier, which also functions as a dilatometer, making it possible to measure volume changes of samples.

The isostatic compression method can be modified to produce deviatoric compression where the axial and confining pressures are not equal. This test condition is a more realistic representation of the consolidation expected in alcove disposal, where the roof-to-floor closure is expected to be faster than the rib-to-rib closure. A series of deviatoric consolidation tests will be performed to compare to the isostatic and oedometer consolidation results.

Thermal conductivity tests will be performed over a temperature range from room temperature to 300°C at known values of fractional density (porosity). The specimens for the thermal conductivity tests will be created in a manner similar to the way uniaxial consolidation tests are conducted. The major difference in the thermal conductivity specimen creation test will be that the test will be terminated at specific targeted values of fractional density. Additionally, the specimens might have to be sized differently than the mechanical test specimens for thermal conductivity test purposes.

The thermal conductivity test method will most likely be the comparative cut-bar method (ASTM E1225, Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique) to measure axial thermal conductivity. In this test, the crushed salt specimen is placed between two sections of a material with known thermal properties, and then a heat flux is passed through the assembly. Comparison of the temperature gradients is then used to determine the thermal conductivity of the test specimen. Depending on specimen size requirements for run-of-the-mine crushed salt and the anticipated relatively low values of thermal conductivity compared to the value for intact salt, the guarded hot plate method (ASTM C177, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus) may be used for some crushed salt thermal conductivity measurements. This method is more commonly used for materials requiring large specimen sizes with low thermal conductivity values.

The individual thermal conductivity tests to be performed in this initial laboratory effort are outlined in Table 3-3. The tests will be conducted on a range of porosity values from 35% (estimated mine-run value) to porosities approaching those of intact salt. The thermal conductivities will be determined at average specimen temperatures of mine temperature, and at 50°C degree increments from 100 to 300°C — shown as 25°C–300°C in Table 3-3.

Table 3-3: Thermal Conductivity Test Matrix

Test Number	Salt Type	Test Type	Porosity (%)	Six Temperatures
1–6	Backfill	Steady-Flow Conductivity	35	25°C–300°C
7–12	Backfill	Steady-Flow Conductivity	30	25°C–300°C
13–18	Backfill	Steady-Flow Conductivity	25	25°C–300°C
19–24	Backfill	Steady-Flow Conductivity	20	25°C–300°C
25–30	Backfill	Steady-Flow Conductivity	15	25°C–300°C
31–36	Backfill	Steady-Flow Conductivity	10	25°C–300°C
37–42	Backfill	Steady-Flow Conductivity	5	25°C–300°C
43–48	Backfill	Steady-Flow Conductivity	~1	25°C–300°C

Design, development, fabrication, and qualification of test equipment and techniques are included in the estimates found in Table 4-1. Each testing program would be conducted under a reviewed and approved test plan. Test conditions may be changed by the Principal Investigator as research progresses; however, the test matrix provided sufficiently defines the research effort for proposal purposes.

3.3. LABORATORY HYDROLOGIC, CHEMICAL, AND MATERIAL STUDIES

During the field test, it is anticipated that the underground salt environment will be heated to temperatures for which current experimental data do not exist. Two interrelated components of the system involve the nature and fate of brine as well as the geochemical interactions of the salt/brine/engineered materials/radioactive waste.

Understanding the mobilization of native brine is essential to establish the evolution of the underground setting of the disposal concept. Migration of small amounts of water present in fluid inclusions within the intact salt, as well as the potential liberation and transport of brine derived from dehydration of hydrous minerals within the interbeds of a halite deposit, must be characterized in order to assess such parameters as the basic amount of brine available to the system and its ability to influence deformational processes such as fracture healing and granular salt consolidation. In addition, as the potential carrier of radionuclides, the brine source and transport represent essential components of the repository source term for scenarios in which brine-waste interactions are evaluated.

Closely related to the source and transport of brine is the chemical and material behavior of the brine/salt/engineered materials/waste form system. Laboratory studies on salt and brine will build upon the scientific basis developed for WIPP, and bounding brine and salt formulations will establish the key factors that control radionuclide solubility and mobility at elevated temperatures (as discussed in the chemistry sections of this proposal). The data obtained will be used to fill knowledge gaps in models for radionuclide release for the range of hypothesized intrusion conditions that could be encountered in the disposal of thermally hot waste (such as EM defense HLW) in a salt repository. In addition, material interaction data from both the laboratory studies and the field test site will be analyzed, providing data that could be used to assess the compatibility of various waste forms, if warranted.

The next two subsections present the laboratory brine liberation/migration tests and chemical/material studies proposed to fill gaps in data needed to support the field test and model development. In each area, a detailed test plan will be written, reviewed, and approved prior to initiating the laboratory experiments. Thus the concepts put forward below are consistent with the science basis for disposal in salt and will be rigorously reviewed in the process of implementation.

3.3.1. Hydrologic Studies

The foundational data needed to assess the sources, rates, and migration mechanisms for brine fall into two categories: brine migration in intact (or dilated) salt, and water liberation from accessible brine, such as hydrous minerals or grain boundary brine. These two experimental investigations are detailed below.

Brine Migration

The fate of water trapped as inclusions within salt crystals and in hydrous minerals present along with the halite is important to understand when assessing performance of a salt repository. Typical quantities of water present in salt fluid inclusions is on the order of 0.1 to 1% in bedded salt (e.g. Permian salt from the WIPP site ranged from <0.1% and 1.7% and is highly spatially variable – Roedder and Belkin, 1979a), and much lower in domal salts (e.g. on the order of 0.003% in several Louisiana salt domes – Knauth and Kumar, 1981; Knauth et al., 1980). Historically, fluid inclusions in salt have been used forensically to study the paleoenvironments relevant to the location of petroleum reservoirs. Pursuit of the concept of using salt for nuclear waste disposal led to a series of investigations employing fluid inclusions in geologic studies to shed light on the environment and subsequent evolution of the salt deposit, as well as to consider the possibility that this water might negatively impact repository performance (Roedder, 1984). A recognized and well-studied mechanism by which salt can potentially migrate up a temperature gradient toward the nuclear waste canister is the process of dissolution of salt on the high-temperature side of the inclusion, solute diffusion within the fluid to the low-temperature side, where deposition occurs from the supersaturated solution. The net effect of this process is migration of the inclusion from lower to higher temperatures. If significant water contacts the waste canisters, corrosion could occur, including the possibility of exposing the waste to direct contact by water should a portion of the repository later become inundated due to natural processes, failure of repository seals, or an inadvertent human intrusion episode. Beyond these potential failure mechanisms, the role of water in facilitating fracture healing must be understood in order to predict the evolution of permeability and rock deformation properties in the DRZ. Relatively steep gradients of the order of 2°C/cm or higher are required to mobilize fluid inclusions in salt.

U.S. Geological Survey (USGS) experiments (Roedder and Belkin, 1979; 1980) indicate that an increase in ambient temperature and/or gradient increased the inclusion mobilization rate, in approximately direct proportion. The migration rates for inclusions in different parts of a given sample, however, were found to vary by a factor of three, for as yet unknown reasons. The three major controlling variables seem to be inclusion size, ambient temperature, and temperature gradient. Theoretical considerations and some experimental studies suggest that the migration rate may also be related to the fluid composition, the presence (and volume) of a gas bubble, the gas pressure in such a bubble, mechanical strain in the host salt, dislocation abundance and nature, and crystallographic direction.

While numerous laboratory studies have been performed to investigate the mechanisms by which fluid might mobilize and contact waste canisters, significant uncertainties remain. The details of movement of fluid inclusions even within a single salt crystal are very complex, depending on temperature gradient, inclusion size and shape, the presence or absence of a gas bubble, stress, and surface tension effects within the inclusion (see Carter and Hansen, 1980 for a summary discussion). Furthermore, the fate of brine at grain boundaries is also complex and variable: in many cases, migration of inclusions is observed to cease at grain boundaries, with the fluid spreading into microcracks at the boundary. However, in some instances, the inclusion is observed to traverse the grain boundary (Jenks and Claiborne, 1980) and continue to migrate within the adjacent grain. Decrepitation has also been observed to liberate relatively large quantities of water from inclusions (Roedder and Belkin, 1979a). As temperature rises, water from either inclusions or mineral dehydration reactions that is present in microcracks and other discontinuities in the rock mass will tend to be mobilized through vapor transport, at rates that are proportional to the permeability of the fractured salt medium. This permeability will, for some period of time, be orders of magnitude higher than that of intact salt; it will exhibit directional dependence (e.g. Beauheim and Roberts, 2002); it will depend on distance from the mined opening (Hansen and Leigh, 2011); and it will vary in time as fractures undergo stress-induced healing (Pfeifle and Hurtato, 1998). The nature of this interplay of various processes is currently unknown and requires further study, starting with laboratory tests and progressing to examination of the integrated effects in the field.

To perform these essential experiments, these rather extreme conditions shall be examined in the laboratory by way of some innovative tests on both natural intact and disturbed salt. Laboratory thermal gradient testing could address the possibility for brine migration with the following approach: 1) impose a thermal gradient on natural salt cores (both intact cores and with a mechanically stressed zone within the core) to promote brine migration and 2) allow liberation of brine from the core as a function of stress state and deformation. There are several important aspects to this approach. First, the temperature and stress states could be controlled independently, starting with a temperature gradient and no applied stresses. Observational microscopy could document fluid inclusion migration relative to the gradient and grain boundaries. Second, an appropriate stress state could be imposed while thermal gradients are maintained. In both cases, the liberation of moisture will be estimated from both weight loss and fluid capture, while the phenomenology of brine inclusion migration will be documented using microscopy techniques. The fundamentals of brine migration and vapor transport, especially at the intact/disturbed rock zone interface, are identified as central to building the case for disposal in salt. Brine migration studies will be reinitiated in the laboratory for a specific range of conditions diverse set of conditions (temperatures, gradients, and levels of damage, which will be measured as volumetric strain) in order to further develop the conceptual model for brine migration behavior.

Clay Dehydration and Phase Transformation Studies

Hydrous minerals, in particular clay, produce the most brine at WIPP. Clay interbeds in the Salado Formation (repository layered salt horizon at WIPP) can attain a thickness of up to one meter. Therefore, in the process of the thermal gradient testing described above, the weight loss of the clays will be examined specifically. Clays (smectite/illite layered phyllosilicates) are important in a repository environment as their volumes, water contents and stability can be affected by even small variations in temperature and partial water pressure, thereby resulting in changes in water amount in the environment and potentially in the host rock strength, porosity and permeability. In a repository, emplacement of waste will increase temperature and thus will change the water vapor pressure. In such a geological system, the partial water pressure is typically lower than the total pressure and dehydration of clays might occur below the boiling point of water (Koster van Groos and Guggenheim. 1986). Different behaviors are expected depending on whether the rocks are unsaturated (disturbed salt) or saturated (intact salt).

The thermal behavior of clays may involve several phenomena: 1) reversible collapse/expansion of the smectite layers due to loss/gain of interlayer water at water vapor pressures < 1 atm (Wu, et al. 1997); 2) irreversible collapse of the smectite layers due to loss of interlayer water and migration of interlayer cations into the layers (Meunier, et al. 1998); 3) irreversible reduction of the osmotic swelling capacity of smectites in a steam atmosphere (Koster van Groos and Guggenheim. 1986); and 4) inhomogeneous transformation of smectites into interstratified illites/smectites at temperatures > 300 °C (Mosser-Ruck et al. 2010). Of these four types of thermal reactions, reversible collapse and collapse in a steam environment probably play more important roles in a repository environment. Such dehydrations may create transport pathways as those volume contractions are accommodated under in situ conditions.

For clay dehydration, because there are gaps and discrepancies in experimental data, the partial dehydration of clays over the relevant temperature and partial water pressure range will be quantified, clay phases analyzed and characterized, and the potential impact on the water source term and stability of the altered minerals assessed. Along with geochemical modeling and thermodynamic constraints (Vidal and Dubacq. 2009), the phase transition from smectite to illite will be mapped out in repository P, T space. Because data will be provided from basic measurements and to close gaps in knowledge, the data would then be incorporated in coupled THMC models to properly account for the impact of these mineral reactions on water liberation and migration. The high pressure experimental lab at LANL (presently performing research on geothermal tracers, carbon sequestration, and natural analogue nuclear waste forms) is well suited to perform such experiments in Dickenson autoclaves and cold seal assemblies at potential repository maximum temperatures (350°C) and lithostatic pressures (600 bar). Furthermore, the LANL experimental lab is now certified to the new DOE pressure standards.

3.3.2. Chemical and Material Studies

This overall approach encompasses experiments and fundamental research that identify and analyze the components and characteristics of the waste that could impact repository performance. The work will be divided into five tasks:

1. ***Measure the thermodynamic properties of brines and minerals at elevated temperatures.*** Precise measurements of the pressure, volume, and temperature (PVT) properties of brines are required for hydrologic and chemical benchmark modeling and future development of performance assessment models.

2. ***Study repository interactions with waste container and constituent materials.*** Evaluation of the chemical interactions of a broad range of materials and waste forms with a salt-based repository will provide a scientific basis to evaluate waste form strategies and engineer waste forms and packages.

3. ***Measure the effect of elevated temperature and ionizing radiation on brine chemistry.*** The results of these experiments will bracket the potential changes in brine chemistry due to temperature and radiolysis, as well as provide a measure of the extent that these changes are controlled by waste package constituents.

4. ***Measure the effect of temperature on radionuclide solubility in brine.*** Radionuclide solubility will determine the source term of any thermally hot waste repository for scenarios in which brine contacts the waste. These studies will quantify the magnitude of the temperature effect on radionuclide solubility in brine and both guide and focus future performance assessment work.

5. ***Measure radionuclide oxidation distribution and redox control at elevated temperatures.*** The lower oxidation states of key radionuclides (U(IV) and Tc(IV)) will be less soluble, and it is important to establish the effects of elevated temperature and ionizing radiation on the processes that generally lead to the creation of a reducing environment in a salt repository.

The motivation for these tasks is discussed in more detail below. Details regarding the laboratory apparatus, experimental techniques, and ES&H requirements will be described fully in detailed test plans written upon commencement of the laboratory testing program.

3.3.3. Measure the Thermodynamic Properties of the Brines and Minerals at Elevated Temperatures

PVT properties of brines are required for both radionuclide source term model and benchmark model development. Precise, specific heat capacities of brines from the site are required to predict the thermal history of brines according to different thermal loading scenarios. These properties for complex brines are not available in the literature. To determine the range of conditions under which thermodynamic properties are required, both undisturbed conditions in which the intact salt is under lithostatic load will be considered, and disturbed conditions in which the presence of the mined opening or, for example, a borehole being inadvertently drilled through the repository, will be considered. Under the undisturbed scenario, the lithostatic pressure (brine pore pressure) for a salt repository at a depth of 650 meters is about 15 megapascals (MPa). In such a case, the pressures for the brines at elevated temperatures will be dominated by the brine pore pressures. Under the disturbed scenarios, the pressures for the brines at elevated temperatures will be the saturated vapor pressures, which are a function of both temperature and brine composition.

For purposes of this management proposal, the host rock is the Salado Formation. The following tests will be performed on samples from the Salado Formation:

1. ***Determine the saturated vapor pressure of brine in equilibrium with halite–polyhalite–anhydrite at temperatures up to 300°C.*** Saturated vapor pressures of complex brines at elevated temperatures are not known. This property is important for calculating the pressure dependence of chemical equilibrium.

2. ***Determine the PVT properties of brines up to 300°C at constant pressures (1 to 20 MPa) and saturated vapor pressures.*** The ultimate goal of this subtask is to produce adequate experimental data to develop equations of state for brines.

3. ***Determine viscosity and thermal conductivity of brines up to 300°C.*** These fluid properties will affect the heat and mass transport processes affecting brine movement at the pore scale, and therefore must be known under a wide range of conditions.

3.3.4. Study Interactions with Waste Container and Constituent Materials at Elevated Temperatures

Laboratory tests specifically targeting the disposal field test proposed (see section 3.5) are shown in Table 3-4 and will provide laboratory data under controlled conditions that will be used to interpret the results obtained on coupons placed in the in situ heater tests. The test matrix is focused on a broad range of materials and waste forms that might be considered for a salt-based repository disposing thermally hot waste and will provide a scientific basis to evaluate waste form strategies and material selection in waste package design. The key test parameters are:

- Temperatures from 25°C to 300°C
- Humidity, low brine-inundated conditions
- Presence and absence of air/oxygen
- Brine composition
- Pressure, ambient to 20 MPa
- Ionizing radiation

Table 3-4: Test Matrix for Alcove-Specific and Bounding Material Interaction Tests

Material	Environmental Conditions			
	Temperature	Humidity	Atmosphere	Ionizing Radiation (γ)
Actual In Situ Heater Test Container Materials	25°C - 300°C	Low, moderate, and high humidity	Air and Inert at 1 and 20 MPa	0 - 10,000 rad/h
Salt and Interbed Material from the Site	25°C - 300°C	Low, moderate, and high humidity	Air and Inert at 1 and 20 MPa	0 - 10,000 rad/h
Possible Repository Metals	25°C - 300°C	Dry, low, moderate, high humidity; brine inundation	Air and Inert at 1 and 20 MPa	0 - 10,000 rad/h

These tests will build on past studies in salt (German HLW canister underground tests, U.S. ONWI program, and WIPP) to provide a more robust understanding of material performance in salt for the range of environmental conditions possible in a repository where thermally hot waste is disposed.

The expectation in salt is that it is not necessary to design a container or waste form as a barrier against radionuclide transport so it is not the intent in this proposal to give the impression that these materials are required or that additional containment is necessary. There are advantages to using certain materials, such as iron or stainless steel, for maintaining a reducing environment which can provide defense in depth against transport. The use of steam reforming, vitrification, or encapsulation in glass can reduce solubility of the waste matrix but it is the contention, when burying in salt, that none of these are required. The plan is testing the materials that make up defense HLW.

A wide range of analytical techniques are available to establish the reaction products and overall reactivity. G-values (i.e., the number of molecules produced per 100 eV of ionizing radiation absorbed) for gas generation in the salt irradiations will be established by measuring gas composition and pressure as a function of time. Water content will be determined as a function of the experimental conditions for materials that initially contain water (e.g., salt, some waste forms). For the inundated tests, changes to the brine chemistry will be determined to establish the appropriate range of brine chemistry for the radionuclide source term studies.

The temperature range up to 300°C was chosen as a bounding value for the temperature in the bulk salt formation. This temperature is used for the brine studies and the material interaction studies. Temperatures near the canister heater could exceed this value and the lab test may be modified through the test plan to reflect the higher temperature. Local temperatures near the canister would be expected to gradually decline by the time significant quantities of water could possibly contact the canister and the waste.

3.3.5. Measure the Effect of Elevated Temperature and Ionizing Radiation on Brine Chemistry

High temperatures and levels of ionizing radiation present in thermally hot waste will affect brine chemistry. Increased temperature will lead to changes in the solubility of the major cations and anions present in brine, causing compositional changes in the brines at the point of saturation, as well as shifts in the system redox potential (Eh) and acidity-alkalinity (pH). These compositional changes could impact radionuclide solubility. Radiolysis could lead to the buildup of oxidizing and/or reducing species that would change the redox potential of the brine system. Gamma irradiation using self-contained Cs source cells will be used in the laboratory to establish general radiolytic trends that tie into the existing literature of established redox trends. The most important potential impact of these radiolytic effects is on the redox distribution of radionuclides. The proposed experiments to study and understand these effects are outlined in Table 3-5.

Table 3-5: Test Matrix for the Effects of Temperature and Radiation on Brine Chemistry

Brine	Environmental Conditions			
	Temperature	**Ionic Strength**	**Atmosphere**	**Ionizing Radiation**
NaCl	25°C -150°C	0.1 M - 5 M	anoxic	0-10,000 rad/h (γ) Variable isotope (α)
$MgCl_2$	25°C -150°C	0.1 M - 5 M	anoxic	0-10,000 rad/h (γ) Variable isotope (α)
Simulated* Brine A	25°C -150°C	Alone, Excess Salt, Waste Package Materials	anoxic	0-10,000 rad/h (γ) Variable isotope (α)
Simulated* Brine B	25°C -150°C	Alone, Excess Salt, Waste Package Materials	anoxic	0-10,000 rad/h (γ) Variable isotope (α)
Simulated* Brine C	25°C -150°C	Alone, Excess Salt, Waste Package Materials	anoxic	0-10,000 rad/h (γ) Variable isotope (α)

*Brines A and C are "bracketing" simulated brine formulations that cover the range of expected brine compositions; Brine B is an intermediate formulation brine. Final detailed compositions will be provided in the test plan for the laboratory work.

For all experiments proposed, changes in the brine chemistry (cation/anion composition, Eh, pH) will be monitored as a function of temperature and irradiation condition. The results of these experiments will bracket the potential changes in brine chemistry due to temperature and radiolysis, as well as a measure of the extent that these changes are overwhelmed by waste package constituents. Recovered precipitates will be analyzed to establish their elemental and phase composition.

The thermal model performed for the generic salt repository (Carter et al. 2011) produced peak bulk salt temperatures of approximately 150°C. This is the value that formed the basis for the temperature selection for the chemical studies since the higher temperatures are localized near the canister.

3.3.6. Measure the Effect of Temperature on Radionuclide Solubility

The oxidation-specific solubility of key radionuclides will be established as a function of temperature, using oxidation state-invariant analogs. This overall approach has been used successfully in room temperature studies at WIPP and avoids the experimental complexity of uncontrolled changes in oxidation state during the experiments. The overall goal of this study is to establish the magnitude of the temperature effect on radionuclide solubility to guide future performance assessment models. These data would become important in any repository scenario in which water contacts the waste and mobilizes radionuclides. It is likely that in any future repository program, these scenarios will need to be investigated regardless of how robust the scientific evidence is for encapsulation of the waste by the deforming salt medium.

The test matrix for the radionuclide solubility experiments is given in Table 3-6. Waste package materials will be included in some experiments to account for sorption effects and solid/liquid interface interactions.

Table 3-6: Test Matrix for the Effect of Temperature on Radionuclide Solubility in Brine

Radionuclide	Environmental Conditions			
	Temperature	Brine	Atmosphere	Waste Package Materials
U(VI)	25°C - 150°C	Brine A, B, C	anoxic	Fe, Glass, TBD
Th(IV)	25°C - 150°C	Brine A, B, C	anoxic	Fe, Glass, TBD
Tc (IV)	25°C - 150°C	Brine A, B, C	anoxic	Fe, Glass, TBD
Cs	25°C - 150°C	Brine A, B, C	anoxic	Fe, Glass, TBD

3.3.7. Measure Radionuclide Oxidation Distribution and Redox Control at Elevated Temperatures

Radionuclide speciation under the conditions possible in a high thermal load, salt-based repository has not been studied extensively, and further research is needed. There is currently very little empirical data on the speciation of many radionuclides for the range of pH conditions likely to occur in these subsurface brines. For a salt-based repository that will experience elevated temperatures, it is especially important to obtain data on the effects of temperature on redox distribution and radionuclide speciation.

Some key actinides (uranium (U), neptunium (Np) and plutonium (Pu)) and fission products (technetium (Tc)) can have multiple oxidation states in brine depending on the redox potential of the brine system. The lower oxidation states of these key radionuclides (U(IV), Np(IV), Pu(III/IV) and Tc(IV)) should be less soluble. It is important to measure the effects of elevated temperature on the processes that generally lead to the creation of a reducing environment in an anoxic salt repository, which keeps these radionuclides in lower oxidation states.

The central objective of this subtask is to measure and quantify the effect of elevated temperature on processes known to establish reducing conditions at room temperature. The most important of these processes are pH/Eh variations, bioreduction, and reaction with reduced metals (e.g., iron, manganese, others). The overall experimental approach is to prepare the radionuclides in their higher-valent oxidation state, establish anoxic conditions in a range of brine systems, and evaluate the effectiveness of reduction as a function of temperature and self-irradiation effects (auto-radiolysis). The test matrix for these experiments is given in Table 3-7.

Table 3-7: Test Matrix to Establish the Key Factors that Control Radionuclide Oxidation State

Process	Environmental Conditions			
	Temperature	Brine	Atmosphere	Components
Varying pH	25°C - 150°C	Brine A, B, C	anoxic	U and Tc will be evaluated
Fe reduction	25°C - 150°C	Brine A, B, C	anoxic	U and Tc will be evaluated

3.4. COUPLED PROCESS MODELING

Prediction of the thermomechanical and hydrologic response of the in situ experiment will initially be made by benchmarking calculations using the best-available codes and models. It is anticipated that at least the two major national laboratories will participate in the benchmark calculations, and the international collaborators will be invited to model the benchmark as well. Benchmarking computational capability is common practice in repository programs, and was done on the WIPP program many years ago, on an international parallel calculations exercise, and more recently by the European Commission for calculations on the BAMBUS II experiment. The benchmark parameters will be established by a technical team. The benchmark modeling cases will assume that the initial modeling structure and the parameter values are understood and certain. However, it is known that there are differences in the constitutive models adapted for the state-of-the-art codes. The performance will be assessed in the benchmark exercise. The benchmark model will be used to inform the field test personnel with regard to placement of instrumentation and sample coupons, as well as establish the data quality objectives for the main test parameters.

The benchmark models will be refined (validated/calibrated) using field test data to match and predict the behavior of the actual system at the alcove scale. This work proposes to benchmark and then refine calculational capability for design and analysis of a salt repository. Because there is no current unified predictive model for thermomechanical, hydrologic, and chemical behavior in bedded salt, the modeling will be performed in two separate tasks, defined in the subsections below.

3.4.1. Thermomechanical Benchmark Modeling

The overall objective of this modeling effort is to inform the field test design and to assess the current capabilities of the thermomechanical computational codes available to solve several complex initial/boundary value problems, which represent heaters, excavations, and back-filled crushed salt of the in situ experiment.

This benchmark exercise will use codes that are appropriate for application to salt repository calculations. Hopefully, several of the most developed constitutive models for thermomechanical behavior of salt can be brought to the benchmark studies through our proposed international collaborations. The advanced salt mechanics codes used by research centers in Germany that are being considered for these analyses are summarized in the *Final Individual Report Joint Project: Comparison of Current Constitutive Laws and Procedures Using 3-D Model Calculations for the Mechanical Long-Term Behavior of Real Underground Rock Salt Mines* (FZK 02C1587, 2010).

The calculations will be explicitly defined, such as a benchmark analyses of the Room H test conducted at the WIPP horizon. Code-specific details (such as mesh refinement, error bounds on iterative processes, and time step sizes) will be left to the modeler's judgment. The type of output requested would include temperature distribution, deformation at certain locations, and stress states. With the addition of the crushed salt constitutive model and porosity-specific thermal conductivity relationship, these models will be applied to specific numerical aspects of the field test.

Fully coupled thermomechanical modeling will provide information on temperature distribution and room and drift closure. These calculations require constitutive laws for deformation of intact salt, reconsolidation of granular, mine run salt, and thermal conductivity of granular salt as a function of porosity. The state of the art to perform these calculations will be assessed. Constitutive models will be enhanced by the thermomechanical testing previously described. This management proposal acknowledges that an essential part of the field test is to determine, at full scale, the liberation processes and fate of the native brine. Therefore, a module for these processes will be added to the coupled thermomechanical code. Considerations include evolution and devolution of the disturbed rock zone, temperatures experienced in the disturbed zone, permeability creation and healing, reduction in permeability of crushed salt as density increases, and temperature distribution at a large enough scale to ascertain if a condensation zone is possible. The fate of accessible brine is fundamental to chemical considerations.

A preliminary assessment of the disposal concept has already been completed by Sandia SIERRA Mechanics (Stone et al., 2010). These example calculations used the SIERRA Mechanics code suite that is comprised of application codes that address specific physics regimes. The two SIERRA Mechanics codes which are used in thermal-mechanical coupling are Aria and Adagio (Stone et al., 2010). The suite of physics currently supported by Aria includes the incompressible Navier-Stokes equations, energy transport equation, species transport equations, as well as generalized scalar, vector and tensor transport equations. A multiphase porous flow capability is a recent addition to Aria. Aria also has some basic geochemistry functionality available through embedded chemistry packages. The solid mechanics portion of the thermomechanical coupling is handled by Adagio which solves for the quasistatic, large deformation, large strain behavior of nonlinear solids in three-dimensions. Adagio has some discriminating technology that has been developed at Sandia involving the use of matrix-free iterative solution algorithms that allow extremely large and highly nonlinear problems to be solved efficiently. This technology also lends itself to effective and scalable implementation on massively parallel computers. The actual thermal-mechanical coupling is done through a flexible solution controller within SIERRA Mechanics called Arpeggio. Additional features that need to be added include the temperature, stress, reconsolidation model for the hot run-of-mine salt and a relationship between thermal conductivity and porosity, both of which are elements of this proposal described earlier.

Fully coupled thermomechanical models involve three-dimensional details that will allow prediction of the expected field test results. As improved modules for reconsolidation and thermal conductivity are developed in the early stages of this proposed research, very informative calculations can be executed. As noted in this management proposal, the state-of-the-art codes and models, including SIERRA Mechanics, will be evaluated for their ability to simulate the concept of disposal that will be demonstrated in the field test. Preliminary examples of output are shown in the following Figures 3-2 and 3-3, which are very similar to the results discussed by Stone et al. (2010). These preliminary calculations show temperature distribution and run-of-mine salt consolidation that simulates the alcove disposal configuration (thermally activated creep deformation enhanced by an 8.4 kW canister). These calculations were run with a second canister of hulls and hardware (approximately 10 meters from the back of the alcove) in addition to the high-level waste canister located at the back of the alcove. Because the canister of hulls and hardware produces no heat, it is not planned to be included in the SDI thermal test.

Figure 3-2: Preliminary Temp Distribution for the Proof-of-Principle In Situ Field Test

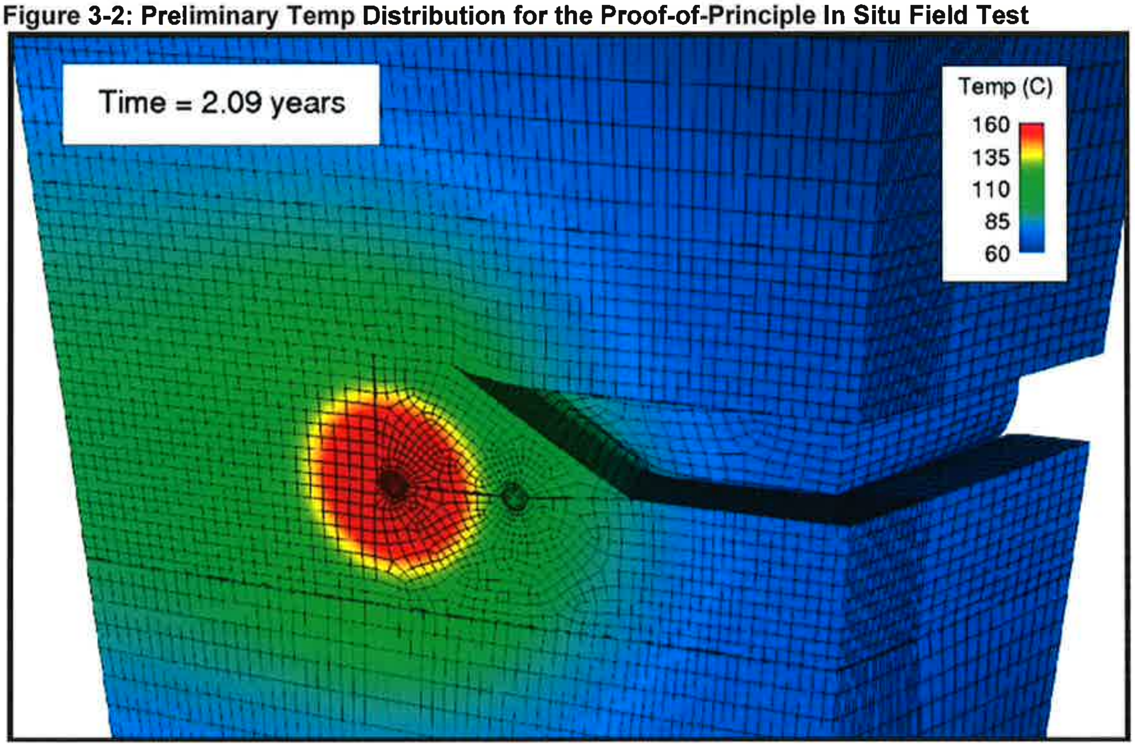
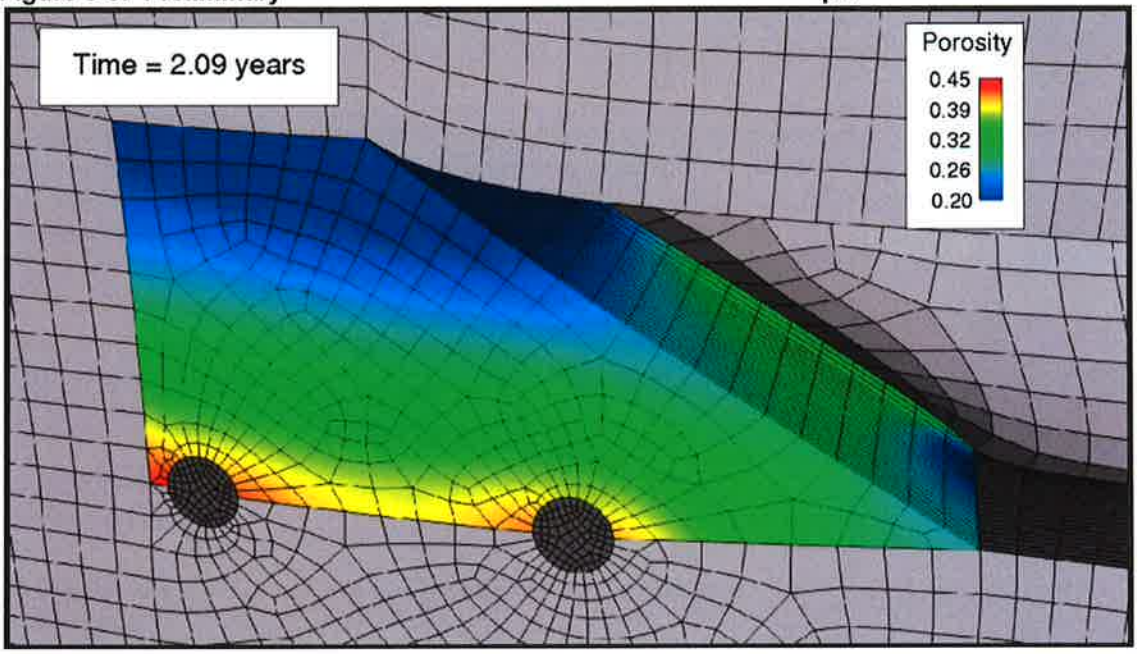


Figure 3-3: Preliminary Reconsolidation Calc for the Proof-of-Principle In Situ Field Test



As noted, the primary focus of the benchmark calculations is to inform the field test design personnel with regard to expected full-scale in situ results. This information will be useful for placement of gauges and density of coverage for certain measurements. The benchmark calculations simultaneously allow ongoing assessment of the state of the art for models and codes, while providing preliminary results that guide field testing. To model the proof-of-principle field test as accurately as possible, the initial testing of intact core at high temperature and the tests associated with reconsolidation need to be completed and evaluated. The modeling process will involve continued refinement as field and laboratory results are acquired, which will allow for improved modeling capability. These results will be periodically reported in technical publications as the project collects information. At the completion of the field test, a general model of the thermomechanical behavior of the field test will be calibrated and published.

3.4.2. Hydrologic and Chemical Benchmark Modeling

Prediction of the thermal, hydrologic, and chemical conditions of the in situ experiment will be made by benchmarking calculations using the best-available codes and models. The overall objective of such a study would be to assess the current capabilities of the thermal-hydrologic-chemical computational codes available to solve several complex initial/boundary value problems, which represent idealizations of real drifts/rooms and waste/backfill of the in situ experiment.

This benchmark exercise will use codes that have been developed for other thermal, hydrologic, and chemical applications and apply them to salt repository calculations. The calculations will be explicitly defined. Code-specific details (such as mesh refinement, error bounds on iterative processes, and time step sizes) will be left to the modeler's judgment. The type of output requested might also be much different from that typically requested for drift design calculations and, in fact, the output data requested will include specific numerical aspects of the field test application.

This task will also seek to refine a modeling capability to predict the brine chemistry and associated radionuclide solubility/concentration in high ionic strength brine systems at the elevated temperatures expected in a high thermal load salt repository. The overall modeling approach will extend the approach used at WIPP and will rely heavily on the extensive experience gained from the WIPP and Yucca Mountain projects. The empirical nature of this modeling approach makes it challenging to accurately predict the effects of temperature without the availability of experimental results over the temperature range of interest (25°C -150°C). Initially, simulation of the behavior of high ionic strength solutions will be conducted using the best available databases and information. An assessment will be made to determine if there are significant gaps in the available data, and if so, the uncertainties will be parameterized and considered in the subsequent modeling exercises. Then, as the project progresses, the prediction of radionuclide solubility/concentration will rely heavily on the data collected in the laboratory studies and temperature data from the in situ test. As a result of these efforts, a modeling approach that accounts for higher temperature and a wide range of brine composition will be configured. This model will provide needed concentration data to define the radionuclide source term in subsequent transport and release calculations, which may be required for future performance assessment calculations.

As noted, the primary focus of the benchmark calculations is to inform the field test design personnel with regard to expected full-scale in situ results. The hydrochemical calculation might be useful for placement of gauges and density of coverage for certain hydrologic and chemical measurements. The benchmark calculations are exercises that simultaneously allow ongoing assessment of the state of the art for models and codes, while providing preliminary results that guide field testing. Also as noted, the modeling process will involve continued refinement as field and laboratory results are acquired, which will allow for improved modeling capability. These results will be reported in technical publications as the project collects more and more information. At the completion of the field test, a general model of the thermal, hydrologic, and chemical conditions of the field test will be calibrated and published. Assuming that a fully coupled THMC modeling capability is available during the project, this code would also be employed for this purpose.

3.5. FIELD TEST PROOF OF PRINCIPLE

This section describes a preliminary, high-level plan to conduct a field test in salt to evaluate its behavior under thermal loads representative of those that would be experienced if HLW were disposed in salt. To set the stage for this proposed field test program, first, the motivation and the basis for selecting the geometry and conditions of the test is described. One of the most important elements affecting the design of a HLW repository is heat management. A disposal safety case, properly conceived and elucidated, relies on well-understood processes attesting to the stability and durability of the geologic barriers to radionuclide migration over geologic time scales. Perturbations caused by the installation of a mined opening or the emplacement of waste must be carefully considered. As such, the decay heat from the waste places limits on the maximum possible areal density of waste, with a significant impact on utilization efficiency of the subsurface facility. Consequently, the management of waste before it is emplaced in the repository, and the configuration of waste packages underground, must be conducted such that critical thermal design criteria are met.

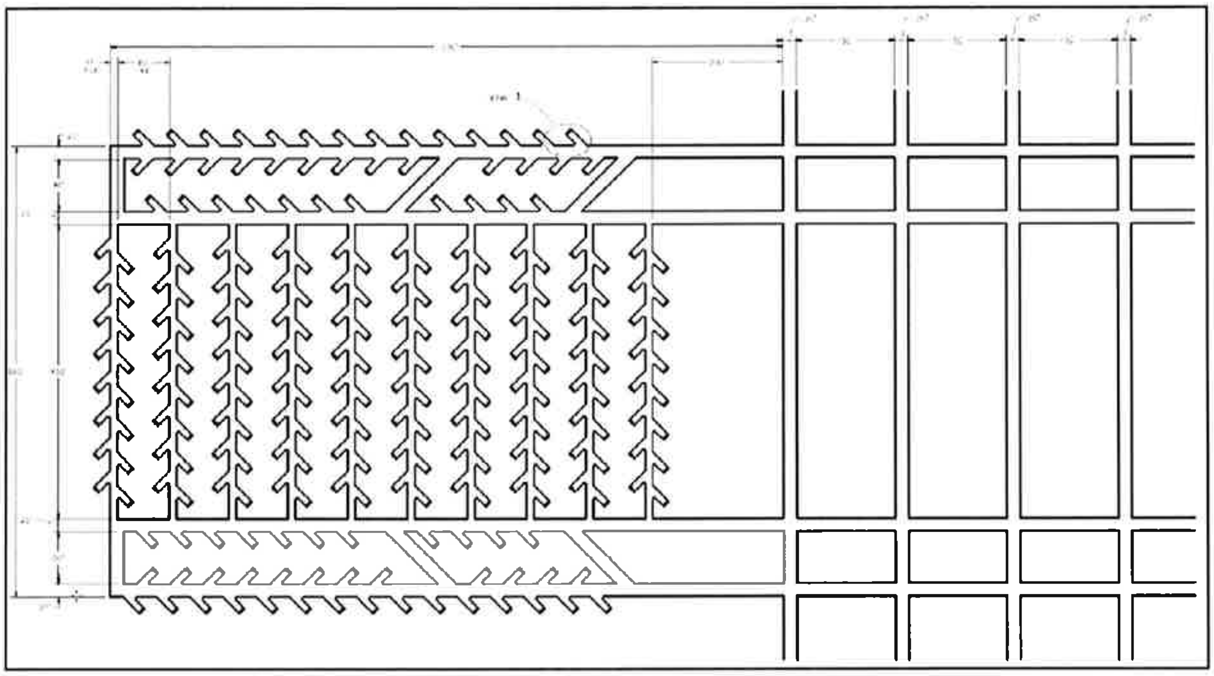
Another requirement affected by heat is that of predictability: models used for repository design and performance assessment calculations must be demonstrated to be valid for their intended purpose, to provide assurance that the repository will perform as expected during operations and in the post-closure period. During operation, the stability of the mined facility and the temperatures and radiation environments to which workers will be exposed must be well understood and operations conducted so as to minimize risk to workers and the public. During operations and after permanent closure, parameters such as the maximum allowable temperatures experienced by the waste form, engineered waste package, and the surrounding medium must be established to ensure that the isolation capability of the repository system is not degraded as a result of decay heat. Because heat is a disturbance from the natural state of the geologic medium, a comprehensive understanding of those changes must be demonstrated, and those changes reflected in validated models of the physical/chemical system, in order to support the safety case for geologic disposal. If it can be shown that salt behaves in a predictable way (as demonstrated by a validated numerical model) and that the waste isolation capability of the salt host medium is not degraded relative to isothermal disposal conditions, then important strides will have been made in expanding the safety case for salt to include disposal of thermally hot wastes.

3.5.1. Preliminary Work: Conceptual Disposal Concepts

To conduct meaningful, focused research in geologic disposal, an appropriate starting point is a disposal concept describing the physical configuration of wastes in the underground, and the operations that would be conducted to load the repository. For salt, the favored approach is to select a disposal concept that is reasonably bounding in terms of local and areal-average heat load, is feasible and efficient operationally, and is likely to result in a solid safety case provided that issues identified as uncertainties are addressed. A study of a generic salt repository for disposal of thermally hot HLW (Carter et al., 2011) documents the basis for the disposal concept adopted in the present study. That study, which proposed a conceptual design of a repository from a future closed fuel cycle producing large quantities of heat-generating borosilicate glass HLW, presented a subsurface and surface facility design and disposal strategy that, in principle, can be practically realized using proven mining operations. The study assumed that waste with significant radionuclide mass loadings, including Cs, Sr, and other heat-generating elements, would be buried with minimal decay storage, thereby providing an aggressive, bounding case with respect to the thermal load.

The design concept is based on a disposal strategy in which a series of repository panels, each of which is a subsurface cell consisting of individual rooms and a total of 236 alcoves, are constructed underground (see Figure 3-4 for the configuration of a single panel). The disposal operation, detailed in the insets in the figure, would consist of placement of one HLW canister at the end of each alcove. Mining operations would be performed on a "just-in-time" schedule such that the waste would be emplaced soon after the mining of a particular area is completed. Carter et al. (2011) determined that, for the assumed repository layout, operating conditions, and waste streams, that HLW from a facility reprocessing 83,000 Metric Tons Heavy Metal of UNF, operating for a period of 40 years, could be disposed of in a repository of 96 panels covering an area of 2.1 by 2.5 miles, or 3,350 acres. In addition, because the layout and linear distances of mined repository are controlled by the need to spread HLW out to distribute the heat load, ample space would also be available to co-dispose of other radioactive waste streams such as GTCC and LLW that would be generated in a reprocessing plant. The HLW package and potentially remote-handled (RH) waste being co-disposed in the same alcove would be covered by crushed salt backfill to provide radiation shielding for workers conducting operations in the vicinity. This strategy is intended to enable a simpler disposal operation than the emplacement methods into the intact salt than those in which boreholes are drilled into the intact salt, making it easier for the disposal operation to "stay ahead of" the heat from previously disposed waste.

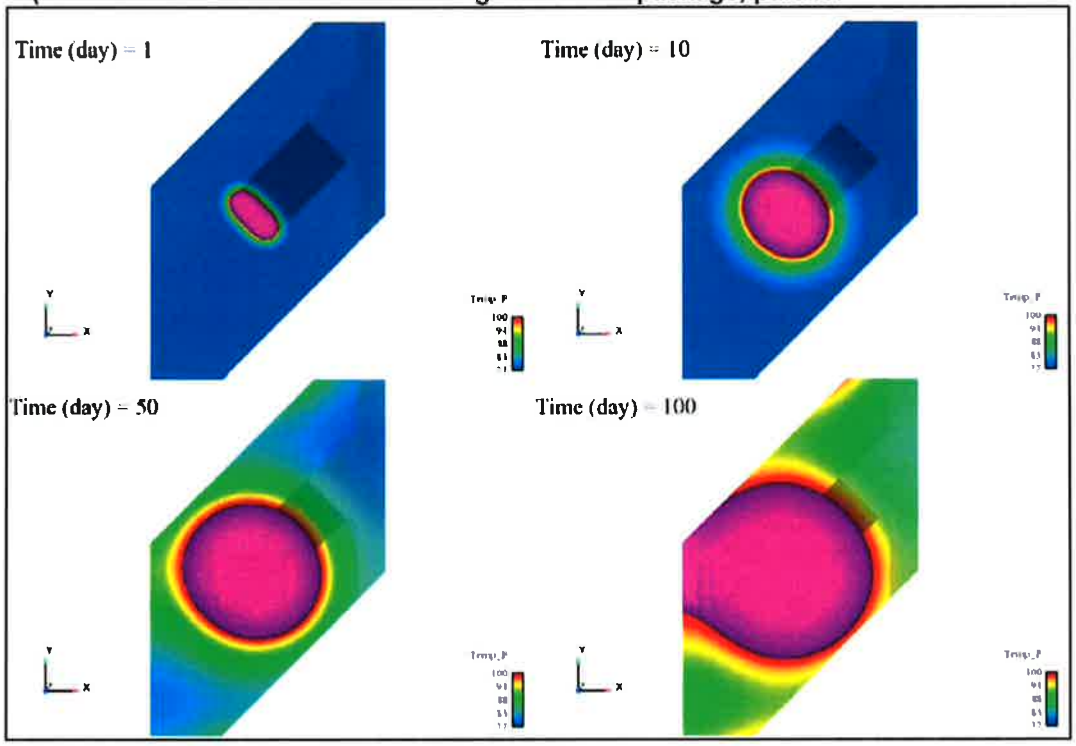
Figure 3-4: Disposal Concept of Carter et al. (2011) Used as the Basis of the Proposed Field Testing Program



Note: Figure reproduced from Carter et al. (2011)

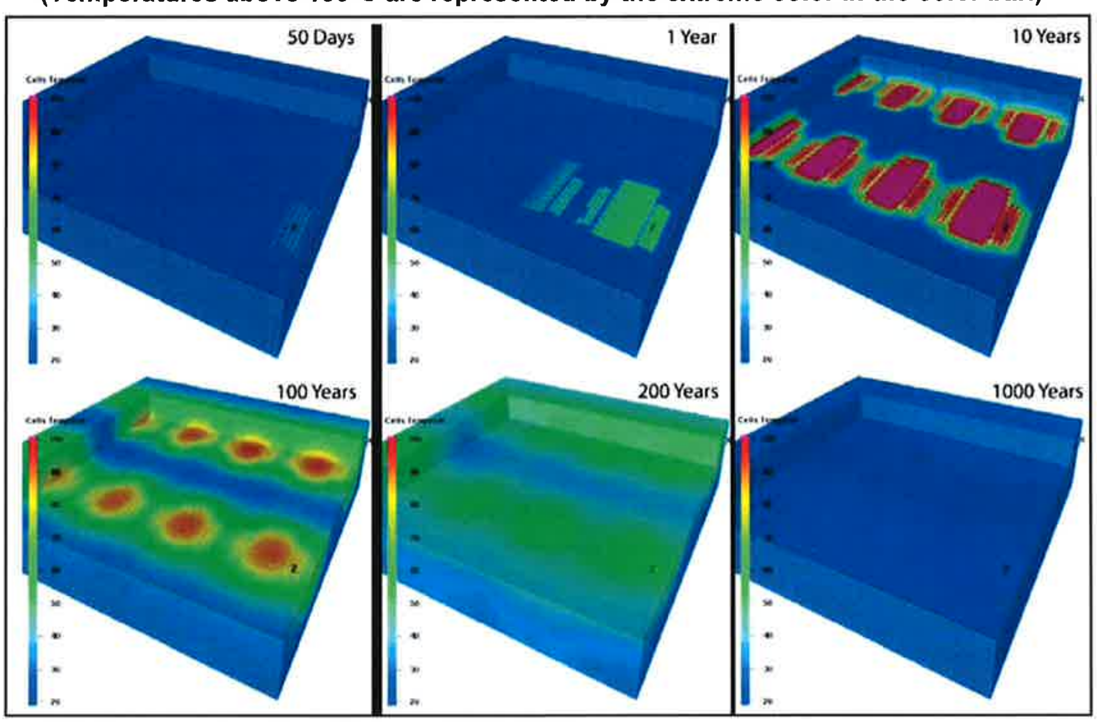
To provide a framework for understanding and addressing thermal issues, modeling studies were conducted (Clayton and Gable, 2009; Gable et al., 2009) to illustrate the likely thermal behavior of the system and to quantify the magnitude of uncertainties, including simulations assessing the level to which uncertainties can be reduced with a thermal field test. These studies reported heat transport modeling results at both the alcove and repository panel scales. The thermal calculations were performed in the absence of direct consideration of mechanical effects. Instead, the potential impact of these effects on temperatures within the waste form and the surrounding medium was assessed indirectly by varying thermal parameters in ranges that reflect the uncertainties brought on by unknown mechanical effects. Given that caveat, results from both the panel-scale (Figure 3-5) and alcove-scale results (Figure 3-6) confirmed that the base case disposal concept as outlined in Carter et al. (2011) is sound from the standpoint of avoiding operational difficulties accompanying the propagation of the thermal pulse to adjacent alcoves, which takes 75 to 150 days, or to adjacent panels, which takes 7 to 12 years. This conclusion is relatively insensitive to details of the thermal and mechanical processes occurring at the alcove scale.

Figure 3-5: Alcove-Scale Thermal Simulation: 100°F Isotherm as a Function of Time. (Plots are for a horizontal slice through the waste package, parallel to the alcove floor.)



Note: figure reproduced from Clayton and Gable (2009)

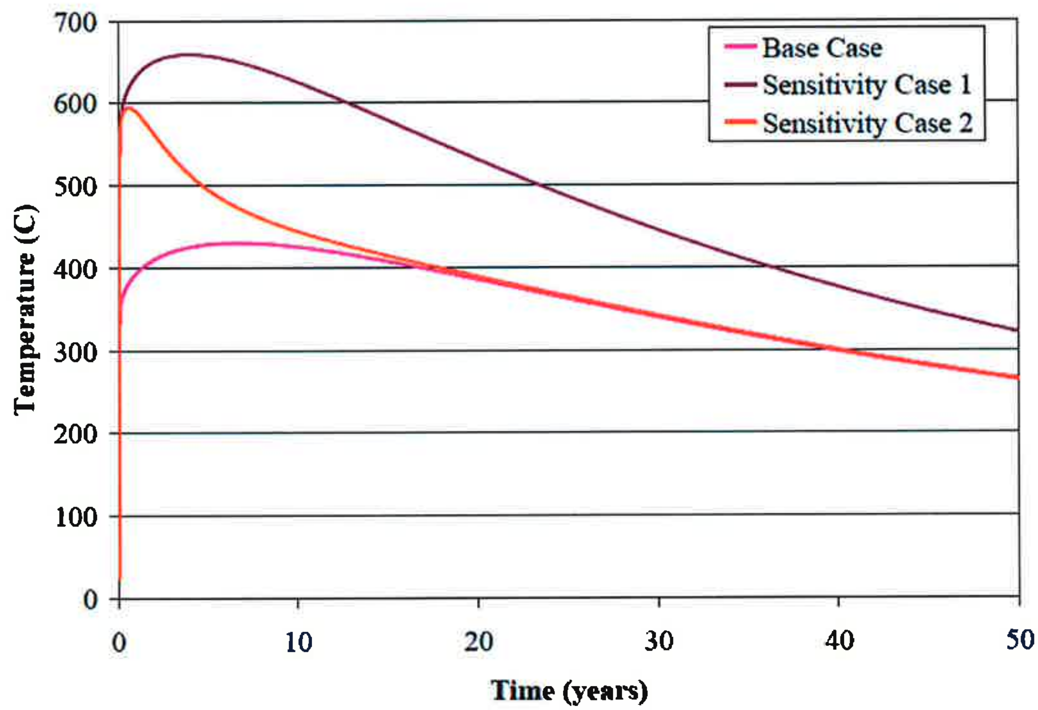
Figure 3-6: Repository-Scale Thermal Simulation. (Temperatures above 100°C are represented by the extreme color in the color bar.)



Note: figure reproduced from Clayton and Gable (2009)

However, details at the alcove scale, including processes for which there is insufficient knowledge, have a strong bearing on the local conditions experienced by the waste and surrounding salt. For example, one hypothesis pertinent to this disposal concept is that the crushed salt will rapidly reconsolidate when compressed due to alcove closure, and that this process will be accelerated due to heat, relative to room-temperature salt creep processes. However, Figure 3-7, reproduced from Clayton and Gable (2009), shows that if the crushed salt reconsolidates either gradually (Sensitivity Case 2) or not at all (Sensitivity Case 1) within the first 50 years after disposal, the average temperatures experienced by the waste would be much higher than if the crushed salt rapidly consolidates and attains the thermal properties of intact salt (the Base Case). Unconsolidated crushed salt has a very low thermal conductivity compared to intact salt, leading to an insulating effect on the waste package and contents until the crushed salt consolidates. Thus, the mechanisms and timing of the crushed salt consolidation process must be understood and incorporated in a model that can be used to iteratively develop a robust repository disposal concept.

Figure 3-7: Average Waste Temperatures Versus Time for Different Assumed Behaviors of the Crushed Salt Backfill



Note: figure reproduced from Clayton and Gable (2009)

Note that slow reconsolidation of the crushed salt would not be a "showstopper" issue: a disposal concept that would mitigate the impacts of insulation of the waste package could be devised that would keep waste temperatures lower, all other things equal. Clayton and Gable (2009) discussed several viable solutions, including: aging the waste; disposing of waste with lower loadings in a greater number of alcoves; or designing the shape of the waste form to facilitate heat transport away from the canister. Nevertheless, answering this scientific question would enable a robust disposal concept design to be devised that supplies a high degree of assurance that the waste would remain within specified limits of temperature.

3.5.2. Conceptual Field Test Design

The alcove waste-disposal concept of Carter et al. (2011) described in the previous section innovatively balances safety, ease of operation, and heat management. This configuration is different than the configurations tested at Lyons, Kansas; Avery Island, Louisiana; or the thermal/structural interaction tests at WIPP. In these earlier tests, live nuclear waste packages (at Lyons) and electrical heaters (at WIPP, Lyons, and Avery Island) were placed in vertical boreholes drilled into the floor of the mine. The proposed field test consists of seven alcoves with five of the alcoves containing an electrical heater to simulate a disposed waste package. Each electrical heater will be placed on the floor near the back of the alcove and covered with crushed salt. Thus, the waste-disposal configuration for the field test is a full-scale mock-up, with heat loads and spacings that are intended to bound thermal conditions for disposal operations. The field test, laboratory tests, and modeling activities will produce data directly applicable to a potential repository, reduce the uncertainty of current predictive models, and allow improvement to the scientific bases of the models.

The test will incorporate measurements of temperature changes imposed on the intact salt surrounding the alcove (roof, floor, and pillars) and mine-run salt placed as backfill over the waste. Closure and entombment processes will be measured directly by various deformation gauges, as well as post facto forensic reconnaissance. Hydrologic effects will be determined through the monitoring of moisture/brine movement in and around the test alcoves, as well as down-drift in the exhaust air. In addition, chemical effects on various metal coupons and radionuclide analog elements will be assessed during the forensics stage. The test bed is expected to see temperatures in excess of 160°C in the salt mass (see section 3.4.1). The alcove tests will be complemented by laboratory tests on dry mine-run salt to determine its deformation characteristics at elevated temperatures (200–300°C) and on intact salt specimens to obtain creep rates above 200°C. The pre-test and post-test chemistry and environmental parameters will also be evaluated and compared to laboratory test results under more carefully controlled environmental conditions. The underground experiment measures the imposed transient temperature field, the accelerated deformation in the intact salt and backfill, and the movement of moisture/brines in the salt. Figures 3-8 and 3-9 illustrate in a perspective view, the general layout and architecture of the field test and a typical heated alcove. Note that Figure 3-8 only shows the thermal test area and adjacent access drifts. It does not show the cross cuts and outer most ventilation and access drifts that are shown on Figure 3-10.

Figure 3-8: Perspective View of the Mining Layout for the SDI In Situ Thermal Test

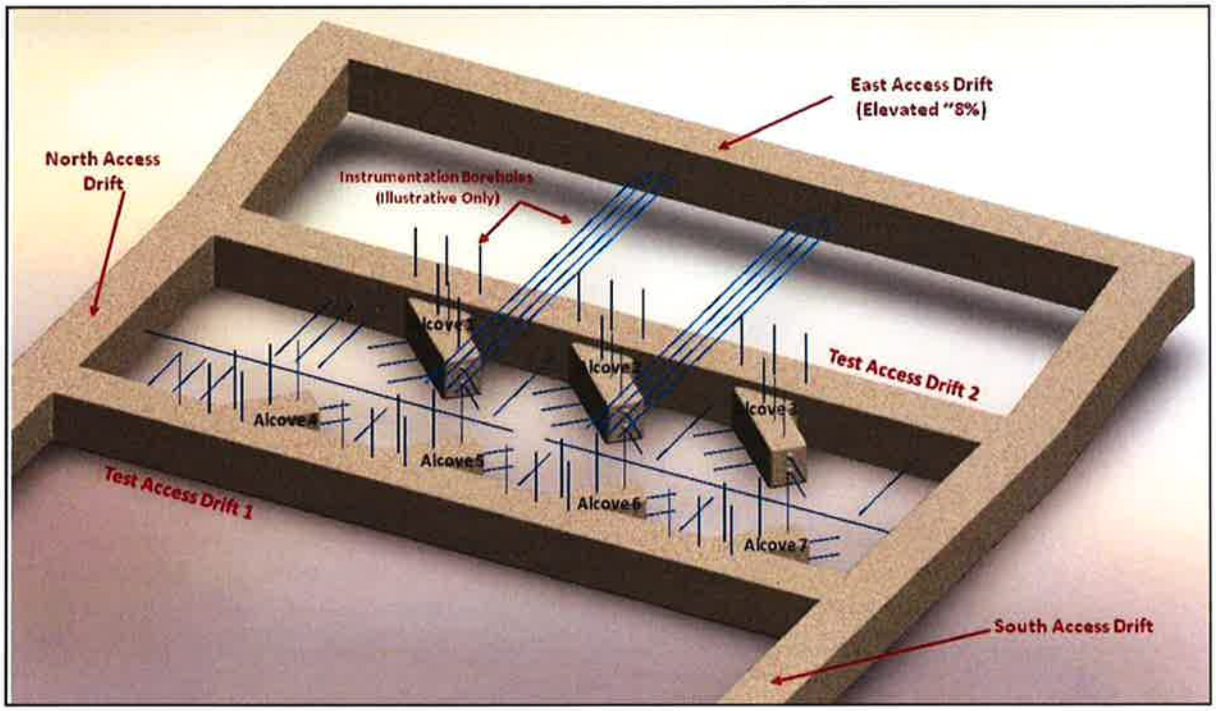


Figure 3-9: Areal View of a Typical SDI Alcove

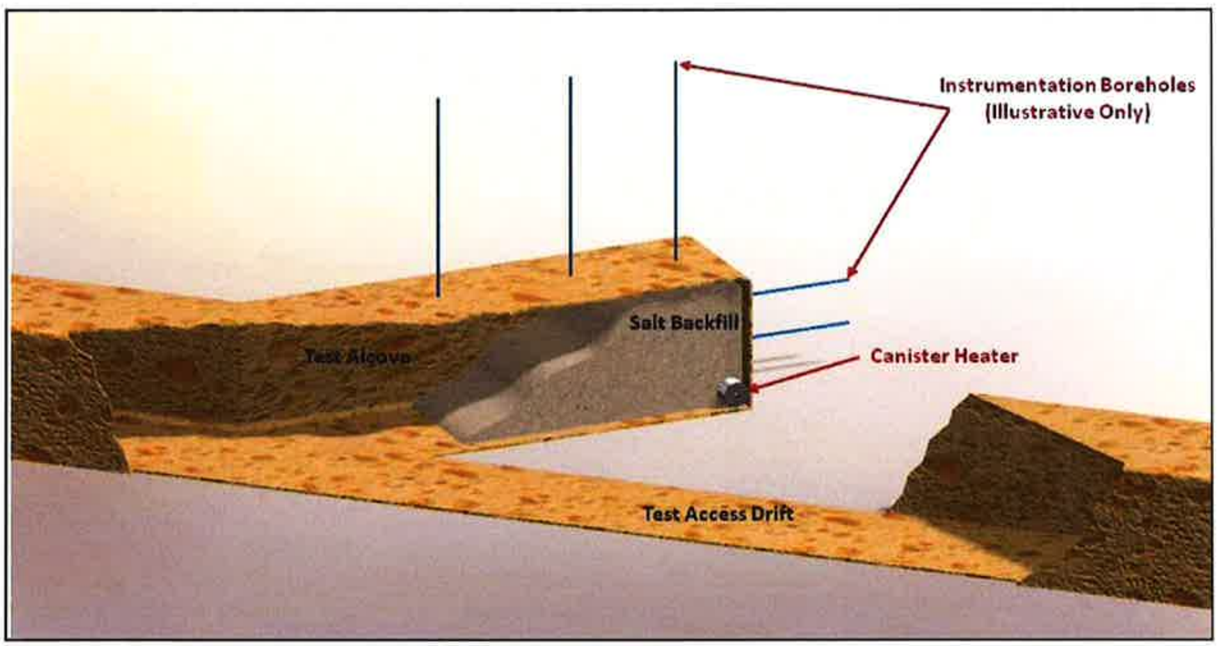


Figure 3-10 illustrates the approximate area within the WIPP that would most logically support the field test. Some of the major considerations to the exact placement of the test within the WIPP are: 1) this test will not interfere with WIPP operations, 2) the test should be located to the north, as far from waste handling operations as possible, and outside the shaft pillar area, 3) the test should not interfere with existing scientific testing occurring in the northern part of the facility, and 4) the test should exhaust directly to the exhaust shaft.

A concept that would address each of these criteria sites the test bed a few hundred feet south of the N-1100 drift in the WIPP facility and outside the shaft pillar area. Approximately 9,500 linear feet of mining would be required to implement this concept. A two-drift access drift, one originating from N-780 and the other from N-1100, with cross cuts would provide ample ingress/egress as well as sufficient controlled ventilation for accelerated forced cool-down of the test bed. The ventilation return would be directly to the exhaust shaft. This arrangement allows for accelerated cooling for access to the test bed to conduct post-test forensics. Additionally, it allows for rapid cooling of the test area if required.

The test will be located in a representative selection of salt, characterized during the early mining stages prior to turn out for the test bed. The test bed would be located approximately mid-way between WIPP Marker Beds 138 and 139 in the facility. Specific details related to test bed criteria and placement will be documented and transmitted to the construction support organization by way of the F&OR document and detailed field test plan.

Figures 3-11 and 3-12 illustrate the general layout of the waste-alcove type salt repository to be demonstrated in the field test. The primary objective of this full-scale demonstration is to provide thermal, structural performance, and hydrological data for the alcove configuration. In detail, the objectives of the in situ heater test are to:

- Measure temperatures to confirm heat transfer calculations.
- Monitor salt movement (alcove deformation) to validate salt creep calculations.
- Impose reconsolidation on the crushed salt to test the salt-reconsolidation model.
- Determine brine and vapor movement for initial information on moisture effects.
- Validate far-field thermal modeling capability by having several interacting alcoves.
- Provide a specific problem and detailed in situ test data for three-dimensional computer code validation and benchmarking.
- Evaluate chemical effects on coupons of various materials placed in proximity to canisters and associated changes in the in-field chemistry and environment.

Details of the in situ heater test will be developed in a formal field test plan based on the F&OR document. After the test plan is written, CBFO will review and provide final acceptance of the test plan. The concepts displayed here are sufficient to allow reasonable estimates for cost and schedule.

Figure 3-10: Proposed Area within WIPP for the SDI Heater Test

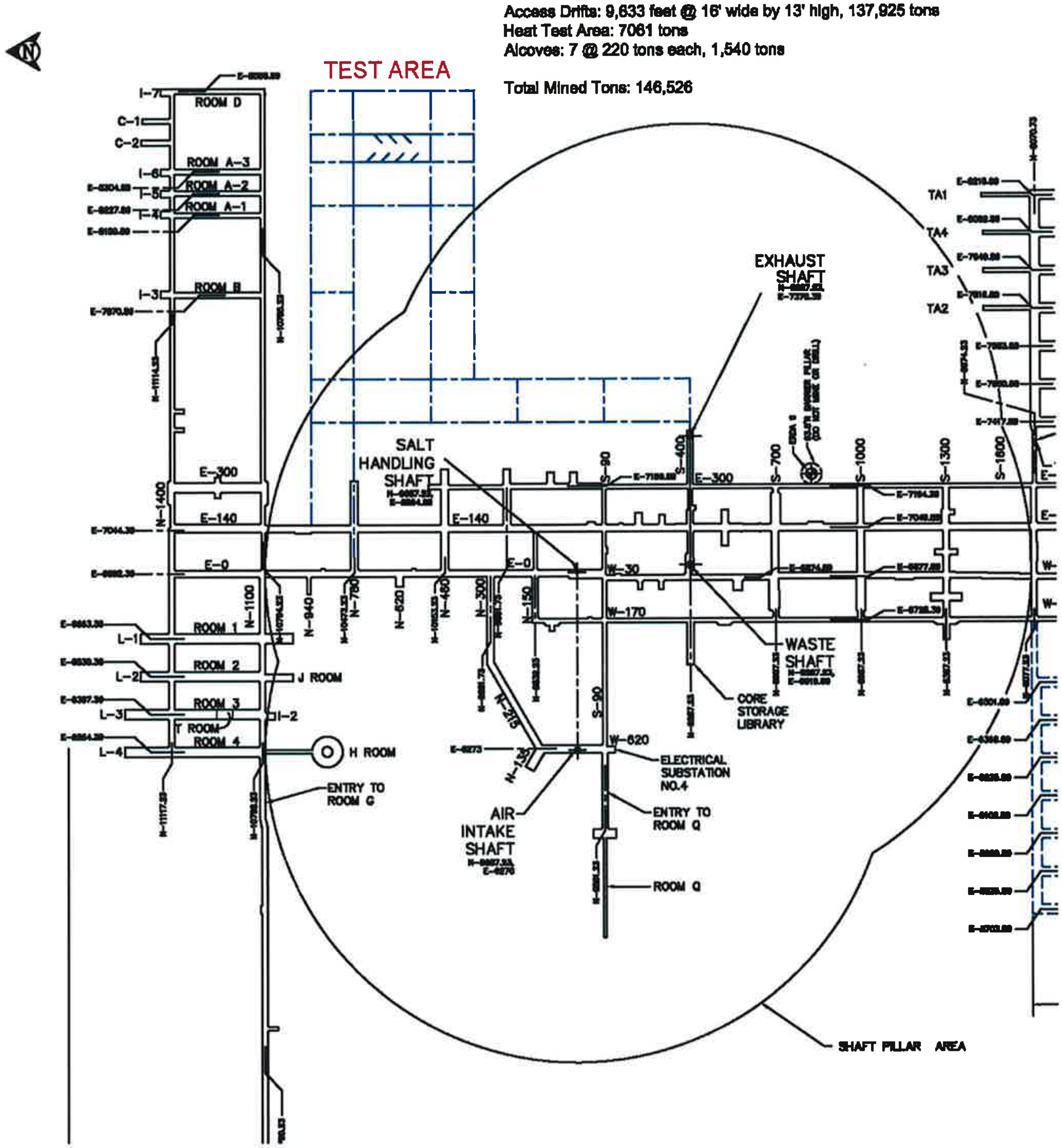


Figure 3-11: Plan View of the Mining Layout for the SDI In Situ Test

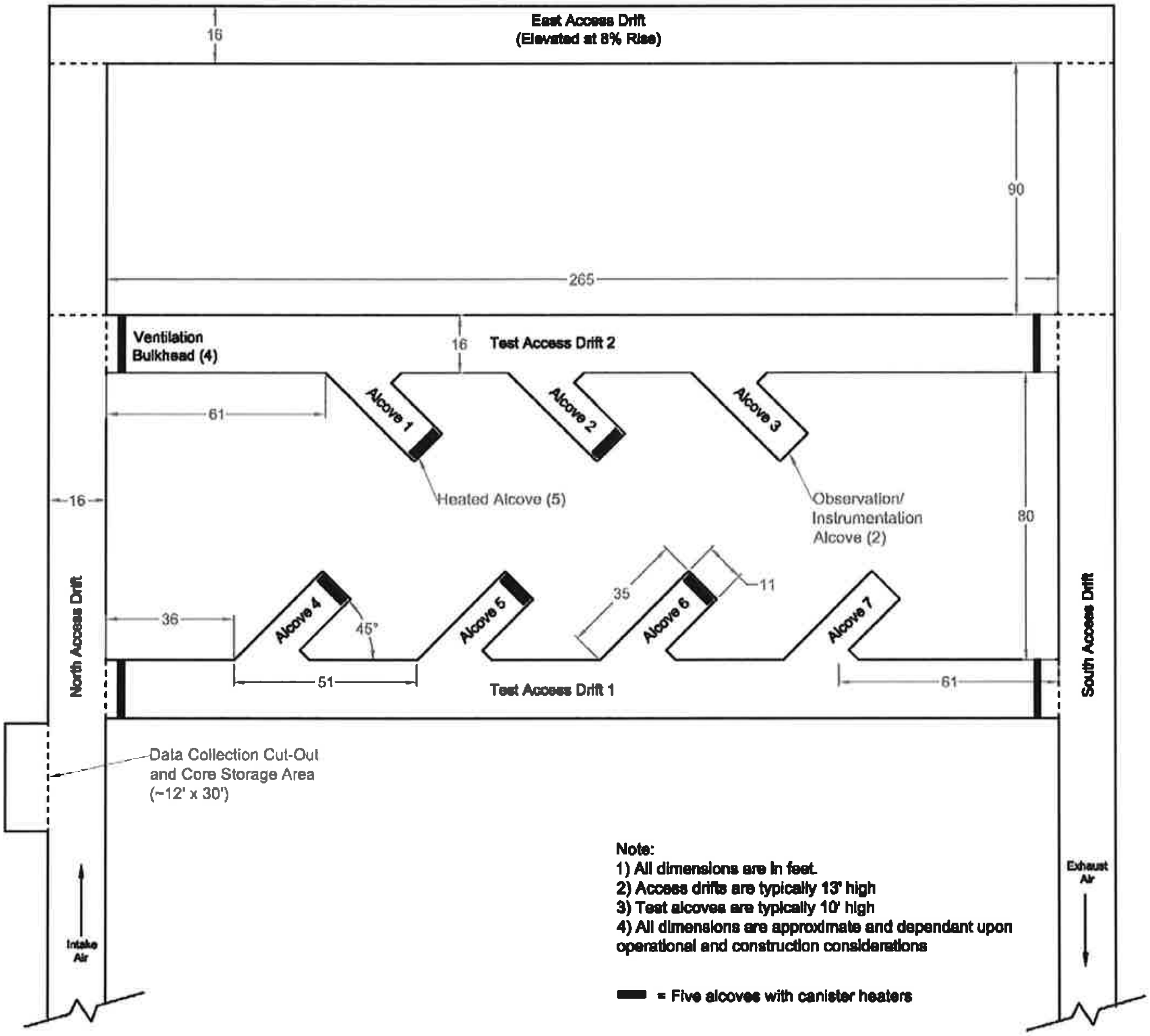
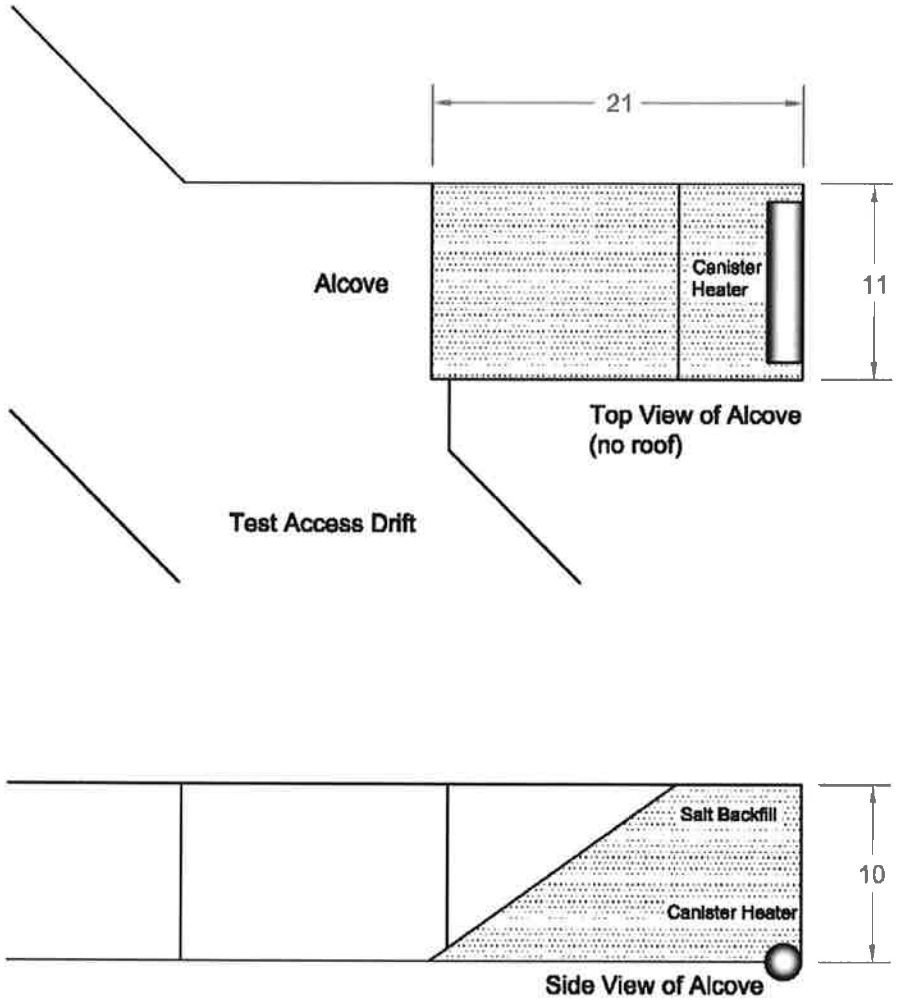


Figure 3-12: Plan and Profile View of a Typical Alcove



NOTE: Dimensions are in feet. Dimensions are preliminary, not to scale, and for planning purposes only. Angle of repose of the salt is for illustration. Exact layout and dimensions will be documented in the F&OR document and the detailed field test planning documentation. Cylinder shown at the back of the alcove is the canister heater simulating the thermally hot waste canister and will be placed in a notch at the back of the alcove for stability and enhanced heat transfer.

Seven alcoves will be instrumented to measure brine and vapor movement, temperatures, deformation, closure in and around the alcoves, pressure in the crushed salt, and ventilation conditions. Because of the large deformations and brine conditions expected during the test, redundant instrumentation from observation drifts as well as from within the test alcoves themselves will be deployed. Robust signal wiring, including wireless signal transmission, will be investigated and deployed if suitable. Geophysical techniques as described in section 3.5.3 will be used to assess test conditions. Remote visual monitoring through high temperature camera systems will also be deployed. The proposal team intends to include our international peers in review of this test arrangement.

The field test will use electrical heaters to simulate the waste packages. The concept at this stage includes 8.5 kW heaters that should bound the thermal output of any waste placed in each alcove. This thermal loading pushes the areal heat density to approximately 40 W/m^2, which will produce temperatures well above 100°C, (temperatures above where most data have been acquired to date) in the nearby undisturbed salt. The heaters will have sealed (welded) ends with high-temperature potted electrical leads. The electrical controller will use a step-down transformer to regulate heater power. These values will be validated and specific heater wattages and areal heat loading values will be specified in the field test plan.

Electrical Heater Stability During Testing

The concept of buoyancy includes the notion that the waste will either "melt" its way downward or float upward, and the heated volume of salt may move upward as a result of its reduced density. The planned field test instrumentation includes surface surveys that are part of the performance confirmation monitoring program for WIPP. Thus, any uplift will be measured from these very accurate surveys. Measurement of buoyancy in situ will be investigated if practical geophysical and instrumentation techniques can be identified.

The movement of canisters containing heat-generating nuclear wastes buried in a salt formation has been hypothesized. The existence of buoyant forces due to thermally produced density differences suggests the possibility of initiating convection cells in a plastic medium like salt. A proper assessment of this motion includes considerations of the temperature dependence of the effective viscosity and thermal conductivity of the salt, as well as the decreasing thermal output of the heat-generating wastes with time.

Analyses performed in the 1970s indicate that very little canister movement will result during the heat-producing life of the waste canisters. The transient analyses show that initially the canister will sink. Then, due to the formation of a convective cell in the salt from heating by the wastes, the canister will rise. Eventually, as the convective cell diminishes, the canister begins to sink again. Predicted displacements are less than a canister length during this process. The steady-state analyses provide upper bounds on the magnitudes of upward velocity possible during heating. In all cases, the velocities are sufficiently small to indicate that very little movement will occur while the canister is capable of producing heat.

Field Cost Estimates

Cost estimates are developed on a "per alcove" basis, using the fully instrumented alcove. There will be modifications to the instrumentation arrangements, particularly in the two alcoves without heaters. And the final design will almost certainly add to and otherwise change some of the detail exhibited here. The precise instrumentation configuration will be developed in a detailed field test plan. Nonetheless, the array of instruments provides a reasonable overview of the in situ test for estimating purposes. Table 3-8 provides a breakdown of the measurement types, measuring devices, and estimated quantities, along with cost estimates for the in situ heater test. Table 3-9 represents the additional total equipment purchase costs for the in situ heater test. Some select instrumentation and equipment will be developed and/or purchased in FY12 and FY13. The data acquisition system, the heaters and controllers, and the remainder of the equipment will be purchased in FY14 in preparation for a heater start in mid FY15.

Table 3-8: Instrument Costs per Alcove for the In Situ Thermal Test

Measurement	Sensor Type	Estimated Number per Alcove	Estimated Installed Cost ($K)
Roof-Floor Closure	One-meter range, spring loaded pull-wire potentiometer, temperature compensated	4	$30
Salt Displacement and Deformation	Multiple Point Borehole Extensometer (MPBX) with invar rods and four displacement transducers	5	$90
Temperature	Thermocouples/RTDs	40	$70
Crushed-Salt (Backfill) Pressure on Heaters	Temperature-compensated load cells between buried loading plates	4	$30
Heat Flux to Salt	Flexible high conductivity heat-flux meter mats with precisely positioned thermocouples	4	$30
Water Vapor Movement	Systems for monitoring of vapor movement within the test bed (e.g., air volume, temperature, humidity, sonic velocity, electrical-resistivity)	1	$40
Estimated Instrument Cost per Alcove			**$ 290**
Estimated Total Instrument Cost for 7 Alcoves			**$2,030**

Table 3-9: Equipment Costs for the In Situ Thermal Test

Equipment & Hardware	Description	Quantity	Estimated Installed Cost ($K)
Heaters with Controller	Rod heaters (redundant leads and elements), 10kW capacity in 24-inch diameter casing, sealed both ends, potted high-temp leads	5	$750
Data Acquisition	Multi-channel DCS	1	$350
Fiber optic communication system	Communications cable data hub and system to communicate data to the DCS and the surface	1	$250
Cameras & Recording	10 digital video cameras and video station	1	$200
Estimated Total Equipment Cost			**$ 1,550**

A 24-month heating interval is anticipated, followed by an 18- to 24-month cool-down period. Information to be gathered after the heating period includes sampling the reconsolidated crushed salt for forensic studies, including optical and scanning election microscopy and limited physical and mechanical testing. The heaters and any attached metal coupons will be recovered and evaluated.

A team responsible for experimental operations consisting of a test coordinator and field testing support staff will be required to perform equipment testing, shakedown, technical operation, monitoring, maintenance, data collection, data reduction, operational assurance, and reporting. Additionally, the Principal Investigators and field test scientific management is required for the duration of the test once it begins heating in FY15.

3.5.3. Mining and Construction Support

The proposed in situ testing effort requires salt mine access. To aid in determining relative costs, a division of responsibilities has been developed for this proposal and as shown in Table 3-10, which delineates the anticipated work breakdown.

Table 3-10: Partitioning of Responsibilities - Construction & Operations Support and Testing

Activity	Pre-Test Planning	Const. and Ops Support	Testing
Prepare mine layout and specifications	X		
Define infrastructure needs (air, electrical, comm)	X		
Develop detailed field test plan	X		
Excavate the defined openings (access and alcoves)		X	
Install ventilation structures		X	
Drill/core instrumentation boreholes		X	
Install instruments in boreholes (e.g., MPBXs, thermocouples)			X
Install data collection system (DCS)			X
Connect instruments to DCS			X
Run fiber-optic cable from DCS to surface		X	
Connect fiber optics to transmitter		X	X
Install electric power distribution		X	
Install electric control panels and heater controllers		X	
Install heaters		X	
Provide underground compressed air		X	
Routine supply delivery (aboveground to test area)		X	
Special equipment delivery		X	
Facility management and science program interface		X	
Test coordination, oversight and facility interface			X
Install ventilation monitors		X	
Install instrumentation			X
Install heaters in alcove		X	
Cover heaters with mine-run salt		X	
Install instruments in mine-run salt		X	X
Daily heater power inspection/regulation		X	
Instrumentation and DCS maintenance			X
Collect and analyze test data			X
End of test forensics, recovery & decommissioning		X	X

The estimates for mining and infrastructure are estimated from direct mining experience at WIPP. The operating WIPP facility provides advantages in terms of operating infrastructure, Mine Safety and Health Administration (MSHA) qualification, equipment, and resources. The field experiment will not interfere with the WIPP operations or the greater WIPP mission.

It is estimated that the savings for mining and infrastructure costs exceed 50% of those in the original proposal from February 2010. The infrastructure at WIPP, as well as mining equipment and machinery, has already been purchased by the DOE. WIPP personnel and equipment would facilitate mining, mucking and trucking, utilities, transport, surveying, craft support, facility operation, and safety. Estimates are shown in Table 3-11. The labor and infrastructure associated with mining and engineering at the WIPP are existing WIPP resources and will not require new SDI budget. However, those total costs are accounted for, but not included in the new SDI specific budget necessary to complete the work. Consumables and equipment (e.g., ventilation control, power distribution, the purchase of a new core rig) are included as direct costs requiring new SDI budget. The cost estimate also includes forensic back-mining in the last year of the project to retrieve coupons, salt samples, and the heaters for laboratory analysis and determination of in situ alcove environmental conditions, mineralogy, and brine chemistry. As before, the total costs are shown, but not included in the roll-up of necessary new SDI budget to conduct the work. As there are no mining or infrastructure costs in FY11, the following table begins in FY12.

Table 3-11: Mining and Infrastructure Costs (in thousands of dollars)

Activity	FY12	FY13	FY14 – FY18	FY19	FY20
Mining, Surveying, Salt Disposal, and Management (existing WIPP resources)	($1,500)	($1,500)			
Core Rig Purchase & Coring			$1,700		
Ventilation Control	$250	$250	$50		
Power Distribution	$200	$200	$600		
Safety Case & Work Control	$50	$50	$50		
Ops Support			$3,000	$700	$500
Test Forensics, Mine Back					($1,500)
Total SDI Budget (new) per year	**$500**	**$500**	**$5,400**	**$700**	**$500**
Total Cost (incl. existing resources)	**$2,000**	**$2,000**	**$5,400**	**$700**	**$2,000**

The total distance mined for test access rooms and alcoves for the basis of estimate is approximately 750 linear feet at approximately 11 feet wide by 10 feet high. Approximately 9600 total linear feet of mining (approximately 16 feet wide by 13 feet high) will be required in the north section of the WIPP in order to gain access and properly ventilate the test area. Each alcove will be backfilled with run-of-mine salt after the heater is placed in the alcove as shown in Figure 3-9. Whereas the detailed field test plan will have exact layouts and dimensions, it can be expected that there will be approximately 20 boreholes per alcove (cored from both inside and outside the alcove). If each borehole were an average of 20 feet long, an approximate total of 4,000 linear feet of precisely placed boreholes will be required to field this test.

The five heaters at 8.5 kW will require a power load of 43 kW. Assuming a 25% load factor, this would be 53 kW of power. The instrumentation, equipment, lighting, and general power will require 10 kW clean 110V/220V single-phase power.

3.5.4. Geophysical Assessment and Monitoring of the Field Test

A key test parameter associated with this experimental work is brine and vapor movement in the salt formation during heating and cool-down. These measurements are generally not as straightforward to make as is monitoring for temperature or ground movement. Additionally, the large ground movements and brine conditions expected to be seen during the test will make it imperative that measurement techniques not dependent upon hard wired gauges down a borehole be used where feasible. As such, new or more advanced techniques are likely to be developed and employed in this field test to measure, at a minimum, vapor and brine movement. These techniques are also anticipated to provide three-dimensional information regarding mechanical changes and physical closing of alcove openings to complement more direct measurement methods.

Geophysical techniques (in addition to the more traditional instrumentation listed in Table 3-8) are expected to be developed, demonstrated, and potentially deployed to monitor salt alcove properties important to the test. These categories of salt alcove properties, features, and behavior may include: 1) fluid migration, 2) alcove interface rheology and structural changes, 3) thermally induced seismicity, and 4) electrical properties. A two-year duration period at the beginning of the time-line is set aside to develop and demonstrate these techniques such that measurement techniques sufficient to monitor salt alcove properties important to the test, in particular for vapor movement, are achieved. All of these methods are proven but are site- and application-specific. They are low risk in that they are well established, but some may not be appropriate for this problem due to such issues as minimum spatial resolution and limited sensitivity to contrasts between solid, fluid and vapor phases. For these reasons, higher risk is associated with applying these techniques to fluid and vapor migration. The demonstration period will be used to develop advancements that address the resolution and sensitivity issues. The following section discusses some of these techniques.

Near real-time (four-dimensional (4D)) interrogation (using repeated active and passive seismic and active resistivity measurements) may be made at sufficiently large standoff distances to avoid the potential damage to the sensor networks that could occur due to high temperatures and major structural changes in and immediately surrounding the test alcoves. Two primary thermally induced physical processes associated with the salt heater test may be monitored: 1) thermomechanical evolution and deformation of the alcoves, backfill, and surrounding formation, and 2) migration of fluids (brine) within and between these same structural components. As with the more detailed description of the thermomechanical instrumentation, the geophysical monitoring layout would be integrated with the field test plan and reviewed by internal technical teams. Stand-off in situ seismic and electrical resistivity experiments are proposed for the salt heater tests to quantify: 1) the thermomechanical evolution of targeted structural components, and 2) the migration of brine within these same structures. The work would also build on and provide support for the point measurements of salt alcove deformation (extensometer) and temperature (thermocouple) outlined in earlier sections by providing full 3D time-lapse measurements of the entire volume surrounding and including the alcove, backfill, and heaters. Furthermore, the seismic and resistivity arrays would survive major alcove deformation or collapse that might damage the extensometer and thermocouples. The following geophysical techniques are proposed.

- **Active time-lapse in situ seismic wave transmission measurements and monitoring.** Active seismic methods are the primary tool that could remotely, noninvasively detect subtle thermal/mechanical changes within the test area. Reflection imaging and transmission imaging could provide complementary information of the test area.

  The velocity at which seismic waves travel through solid material varies with density, temperature, and pressure. The density, wave scattering properties, and energy dissipation of the material also change with temperature. Thus, spatial variations in the travel time, scattering, and attenuation of seismic waves can be used to map changes in seismic wave velocities, material density, heterogeneity, and viscoelastic properties caused by temperature gradients in and around a heated region of salt and/or brine and vapor movement. One method that may be used is known as seismic tomography and is similar to techniques used in medical X-ray diagnostics. Full 3D coverage of the region surrounding heated alcoves with appropriate seismometers or accelerometers would allow detailed 4D tomograms to be obtained using active seismic data acquired at different times, which would illustrate how the spatial temperature profile around the heaters evolves. 3D ray tomography and 3D double-difference waveform tomography are proposed to obtain high-resolution 3D images showing where temperature changes occur. When the source frequency is in kilohertz, the anticipated spatial resolution of 3D images would range from approximately 0.5 m to a few meters (or half wavelength to 2-3 wavelengths), depending on tomography algorithms. It might be possible to attain .25 m resolution or better with higher frequency sources, since the experimental layout is very compact (Schuster, 1996).

- **Passive seismic event monitoring.** The deformation induced by heating the salt will likely result in multiple scales and degrees of brittle failure of the alcove structure and surrounding formation. During initial heating, small-scale deformation might occur along cracks or fracture planes, either by crack growth or by slippage along pre-existing planes of weakness. These discrete events will result in very small microseismic or acoustic emissions. As heating progresses, large-scale fracturing can occur in the salt alcove walls, ceiling, and floor. Data from these events can be used to determine the location, development, and extent of the fractures, as well as the fracture mechanism itself. Performing the passive seismic monitoring will not require additional instrumentation; both passive and active types of thermally induced seismicity can be detected using the same seismometers or accelerometers that would be deployed for the active seismic experiments discussed above. Event location resolution is expected to be about 0.3 m, based on previous work. Further, with sufficient 3D coverage of receivers surrounding the microseismic sources, it would be possible to resolve the type of crack deformation being induced, for example, tensile vs. shear deformation. The microseismic data would provide an important measure of how thermal-induced strains are accommodated discretely in the salt body and how they lead to major structural events. A passive seismic monitoring system will provide insight into the presence and source of brittle phenomena. One might expect flexural tensile brittle processes and possible acoustic emission from proximal anhydrite, because of its stiff rheologic response.

Therefore, a carefully arrayed seismic network will be evaluated for deployment in the field experiment.

- **Active time-lapse seismic reflection imaging and monitoring of alcove interfaces.** Seismic/elastic reflection imaging (migration) techniques produce much higher resolution 3D images of subsurface material interfaces than transmission tomography, from which such interfaces are often invisible. Seismic reflectors are structural interfaces separating two materials with different seismic impedances. The primary interfaces of interest in this study are those between the solid salt alcove walls and the crushed salt backfill, plus the interface between the heater and its surroundings. Seismic reflection signals would be used to produce high-resolution 3D images of interfaces in the vicinity of the heater test (Fehler and Huang, 2002, Annu. Rev. Earth Planet. Sci., 30:259-284.).

- **Electrical resistivity measurements.** Measurement of electrical resistivity is a powerful technique for probing and monitoring geological systems, including rock and salt formations, because the technique is very sensitive to small changes in electrical properties. Repeated in situ measurements of salt resistivity would provide high resolution 3D time-lapse images of temporal changes related to fluid migration. A combination of field and laboratory measurements is proposed to apply electrical techniques to characterizing the moisture movement within the salt. In situ field measurements would be performed to obtain baseline measurements and to characterize electrical resistivity as the salt body warms. Several techniques would be used for imaging electrical resistivity, including electrical profiling (surveying) and transient electromagnetics (EM). Data from individual 2D electrical surveys and electromagnetic soundings can be combined into 3D data cubes. Because resistivity values of salt range from 10 to 1013 ohm-m under ambient conditions, the influence on resistivity of grain size, hydration, temperature, and possible clay content must be determined via laboratory measurements in order to interpret the field data. These measurements would allow for better interpretation of the range of resistivity values that would be observed, as well as for better discrimination among thermal compaction, water content and migration, and clay content. Although electrical resistivity methods are typically less well know by geophysicists, there is a large amount of experience, and many companies which specialize in electrical techniques (e.g., Zonge, www.zonge.com; geometrics, www.geometrics.com; sensors&software, sensoft.ca; fugro airborne services, www.fugroairborne.com, hydrogeophysics, www.hydrogeophysics.com; and Willowstick, www.willowstick.com).

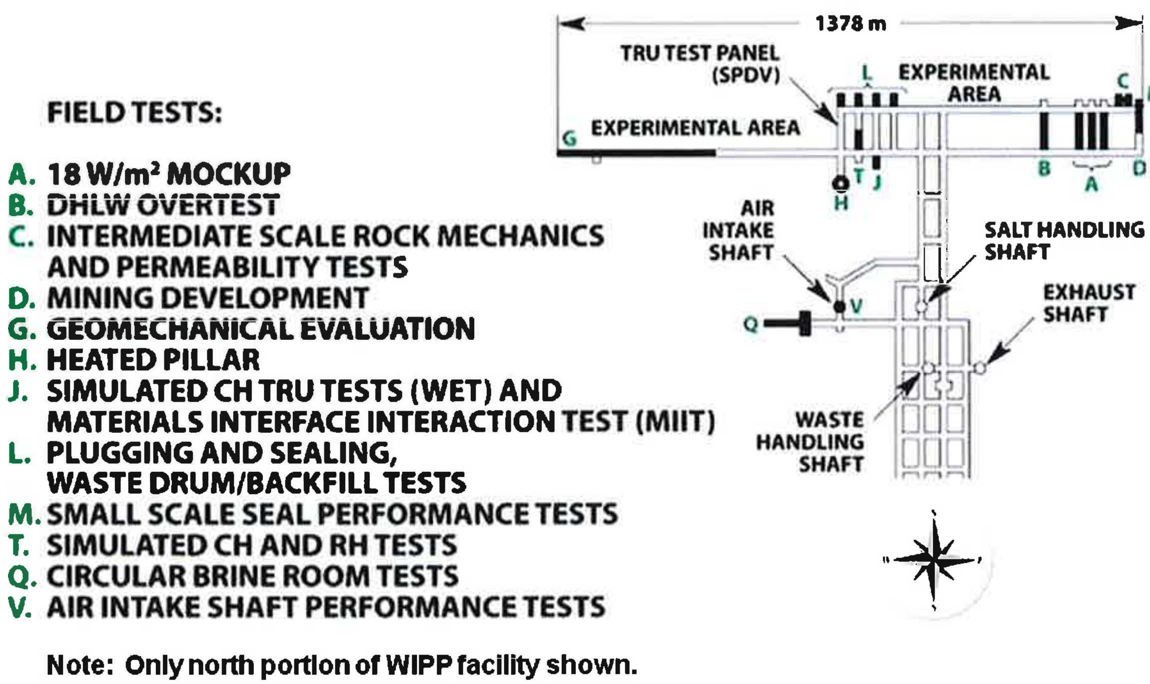
- **Joint Seismic and EM imaging.** Electrical and electromagnetic signals are more sensitive to brine and vapor movement than seismic measurements. On the other hand, the resolution of seismic imaging is much higher than EM imaging. Joint seismic and EM imaging could significantly enhance detection of brine and vapor movement. Joint seismic and EM imaging is proposed for monitoring brine and vapor movement in the salt formation during heating and cool-down processes.

3.5.5. Feasibility of Reentry into the North WIPP Experimental Area

Excavation for siting the SDI field test could potentially allow reentry to the north experimental area, which was abandoned over twenty years ago. The feasibility of this idea will be developed as the SDI work continues and is not currently planned, budgeted, or scheduled. The concept is put forward here because the proposal team recognizes a possible opportunity for forensic reconnaissance of previously heated rooms.

As illustrated in Figure 3-13, heated room experiments were conducted in A and B rooms in the north experimental area. The A room tests were heated at an equivalent of 18 W/m2 mockup. The B room was called the defense high-level waste (DHLW) overtest. These tests were abruptly terminated, and at least some heaters were abandoned in place. At least one heater was overcored and removed, but no examination was made of the reconsolidated salt attached to the heater, the nature of brine migration in the intact salt adjacent to the heater, or of possible corrosion on the heater itself. Other abandoned heaters and the proximal salt may be accessible for examination after more than 20 years in situ. The opportunity and practicality of reentry will be investigated.

Figure 3-13: Location of Past Field Tests Located Within WIPP



4. COST AND SCHEDULE

4.1. COST AND SCHEDULE

Table 4-1 lists the cost (in thousands of dollars) by element for each portion of the proposal by fiscal year. The budget estimates are constrained for the first two fiscal years. Table 4-2 shows a breakdown of the activities by funding organization, both DOE-EM or DOE-NE.

Figure 4-1 shows the expected duration for the test by element under the funding profile. Figure 4-2 shows an accelerated schedule with a heater test start in FY14 if additional funding were provided in the first two years of the test.

The Yucca Mountain Drift Scale Test took approximately 2.5 years (mid 1995 to Dec 1997) to construct and install at a cost of approximately $19 million (including mining, drilling, and engineering costs). The SDI thermal test is estimated to take approximately 3.5 years (Oct 2012 to mid 2015) at approximately $28 million (plus the in-kind costs of construction, drilling, and engineering work). Therefore, based on past experience and comparison with other large underground thermal tests, these cost and schedule estimates are reasonable.

Table 4-1: Cost by Element (in thousands of dollars) - Budget Constraint on the First Two Fiscal Years

SDI Proposal Element	Sect #	Task/Product	Comments	COSTS (estimated) BY FISCAL YEAR ($1,000K) FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	TOTALS
Management, Quality Assurance, and Safety	2.1 - 2.3	Management, Quality Assurance, and Safety		$450	$1,000	$900	$900	$600	$600	$600	$600	$700	$600	$6,950
		Proj Mgmt, QA Support, Performance and Safety Analysis/Approvals	* Includes F&OR document development in FY11 (Section 3.1)	$450	$600	$900	$900	$600	$600	$600	$600	$600	$800	$6,650
		Detailed Test Plan Development	* Development of detailed test plan in FY13		$400									$400
International Collaboration	2.4	International Collaboration		$0	$200	$200	$200	$250	$250	$250	$200	$200	$200	$1.950
Lab Thermal and Mechanical Studies	3.2	Bound Salt Thermomechanical Response	*Test Plan development and early lab testing in FY11	$250	$400	$600	$300	$300	$300	$300	$300	$400	$300	$3,450
Laboratory Hydrologic, Chemical, and Material Studies	3.3	Laboratory Tests in Support of Modeling, PA, and the Field Test		$0	$210	$700	$500	$500	$300	$300	$300	$400	$300	$3,510
Coupled Process Modeling	3.4	Coupled Process Modeling		$0	$300	$700	$500	$200	$200	$200	$200	$300	$300	$2,900
		Thermomechanical-Hydrological Benchmark Modeling			$250									$250
		Process Coupling and Validation			$50	$500	$300	$100	$100	$100	$100	$100	$200	$1,550
		Chemical				$200	$200	$100	$100	$100	$100	$100	$200	$1,100
Field Test Installation and Operations	3.5	Install and Conduct Field Test Proof of Principle	* Heating start FY15 - Accelerated cool down by FY19	$0	$2,300	$2,400	$8,900	$2,500	$2,100	$2,100	$2,100	$2,850	$3,350	$28,600
		Instrumentation, Data Collection, and Testing												
		Alcove Instrumentation Development and Procurement	* 7 Alcove arrays and one redundant set		$200	$200	$1,900							$2,300
		Canister Heaters and Controllers Procurement					$750							$750
		Data Acquisition System Procurement, Shakedown, and Calibration					$350							$350
		Fiber Optic System Procurement and Shakedown for Data Transfer					$250							$250
		Underground Camera System Procurement and Shakedown					$200							$200
		Geophysical Assessment and Monitoring (e.g., vapor movement)			$100	$200	$400	$100	$100	$100	$100	$300	$200	$1,600
		Instrumentation Shakedown, Calibration, and Installation					$1,850							$1,850
		Underground Testing Personnel (e.g. data collection, active measurements)						$1,300	$1,100	$1,100	$1,100	$1,100	$600	$6,300
		Post-test Sample Collection Personnel										$450	$250	$700
		Investigate Salt Properties of Test Bed Location	* Test bed specific investigations at WIPP				$200	$200						
		Field Test Scientific Management (e.g. PIs)						$300	$300	$300	$300	$300	$300	$1,800
		Construction and Ops Support												
		Mining - Access Drifts, Test Bed	* Preservation of mining and hoist crew		$1,500	$1,500								$3,000
		Coring - Core Rig Purchase + Instrument Coring	* Purchase or lease of new core rig				$1,700							$1,700
		Ventilation Control			$250	$250	$50							$550
		Dedicated Power Installation	* New line to test bed area		$200	$200	$600							$1,000
		Safety Case and Work Control			$50	$50	$50							$150
		Ops Support (e.g. access, utilities, heater installation)	* Over 50% infrastructure costs saved at WIPP				$600	$600	$600	$600	$600	$700	$500	$4,200
		Test Forensics, Mine Back, Coring											$1,500	$1,500
			TOTAL SDI BUDGET (*new budget*) NEEDED BY YEAR	$700	$2,910	$4,000	$11,300	$4,350	$3,750	$3,750	$3,700	$4,850	$3,550	$42,860
			TOTAL DISCRETE COST BY YEAR (*including existing WIPP resources*)	$700	$4,410	$5,500	$11,300	$4,350	$3,750	$3,750	$3,700	$4,850	$5,050	$47,360
			DOE-NE BUDGET (*new budget*) FOR THE TEST	$700	$910	$2,000								
			DOE-EM BUDGET (*new budget*) FOR THE TEST	$0	$2,000	$2,000								
			TOTAL DOE-EM COST (*including existing WIPP resources*) FOR THE TEST	$0	$3,500	$3,500								

***** Shared EM-NE costs from FY14 to Completion*****

DOE-NE provided funding: (red)
DOE-EM provided funding: (blue)
Covered with Existing WIPP Labor/Infrastructure: (green)

Table 4-2: Cost by DOE Organization in FY12/FY13 (in thousands of dollars)

SDI Sect #	Task/Product	FY11	FY12	FY13
DOE-NE Provided Funding				
2.1 - 2.3	**Management, Quality Assurance, and Safety**	$450		
3.2	**Bound Salt Thermomechanical Response**	$250	$400	$600
3.3	**Laboratory Tests in Support of Modeling, PA, and the Field Test**		$210	$700
3.4	**Coupled Process Modeling**			
	Thermomechanical-Hydrological Benchmark Modeling		$250	
	Process Coupling and Validation		$50	$500
	Chemical			$200
	DOE-NE BUDGET (*new budget*) FOR THE TEST	$700	$910	$2,000
DOE-EM Provided Funding				
2.1 - 2.3	**Management, Quality Assurance, and Safety**			
	Project Mgmt, QA Support, Performance and Safety Analysis/Approvals		$600	$900
	Detailed Test Plan Development		$400	
2.4	**International Collaboration**		$200	$200
3.5	**Install and Conduct Field Test Proof of Principle**			
	Instrumentation, Data Collection, and Testing			
	Alcove Instrumentation Development and Procurement		$200	$200
	Geophysical Assessment and Monitoring (e.g., vapor movement)		$100	$200
	Construction and Ops Support			
	Mining - Access Drifts, Test Bed		$1,500	$1,500
	Ventilation Control		$250	$250
	Dedicated Power Installation		$200	$200
	Safety Case and Work Control		$50	$50
	DOE-EM BUDGET (*new budget*) FOR THE TEST	$0	$2,000	$2,000
	TOTAL DOE-EM COST (*including existing WIPP resources*) FOR THE TEST	$0	$3,500	$3,500
	TOTAL SDI BUDGET (*new budget*) NEEDED BY YEAR	$700	$2,910	$4,000
	TOTAL DISCRETE COST BY YEAR (*including existing WIPP resources*)	$700	$4,410	$5,500

: DOE-NE provided funding (red)

: DOE-EM provided funding (blue)

: Resources Covered with Existing WIPP Labor/Infrastructure (green)

Figure 4-1: Estimated Schedule for Test Program Duration (Constrained FY12/FY13 Scenario)

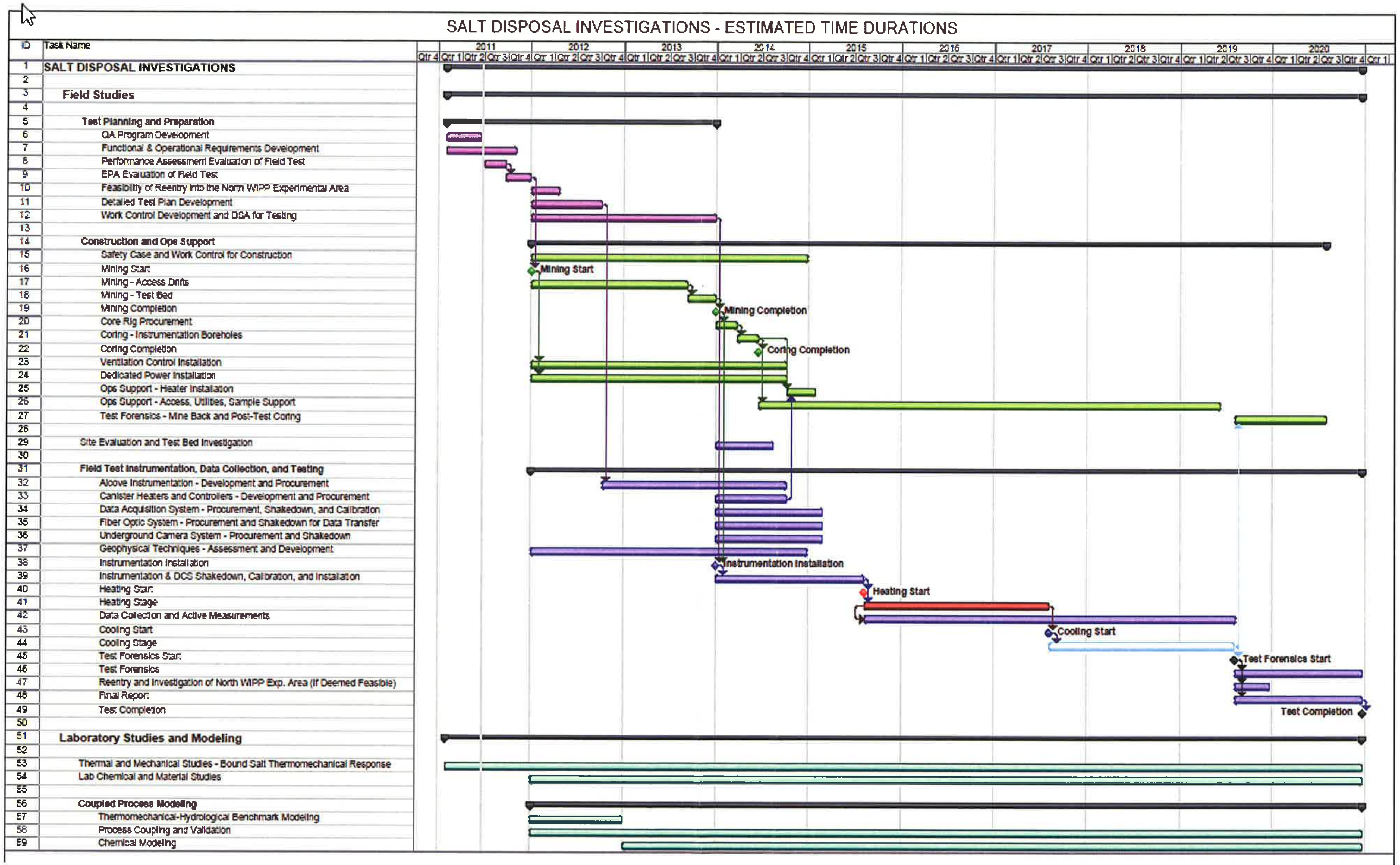
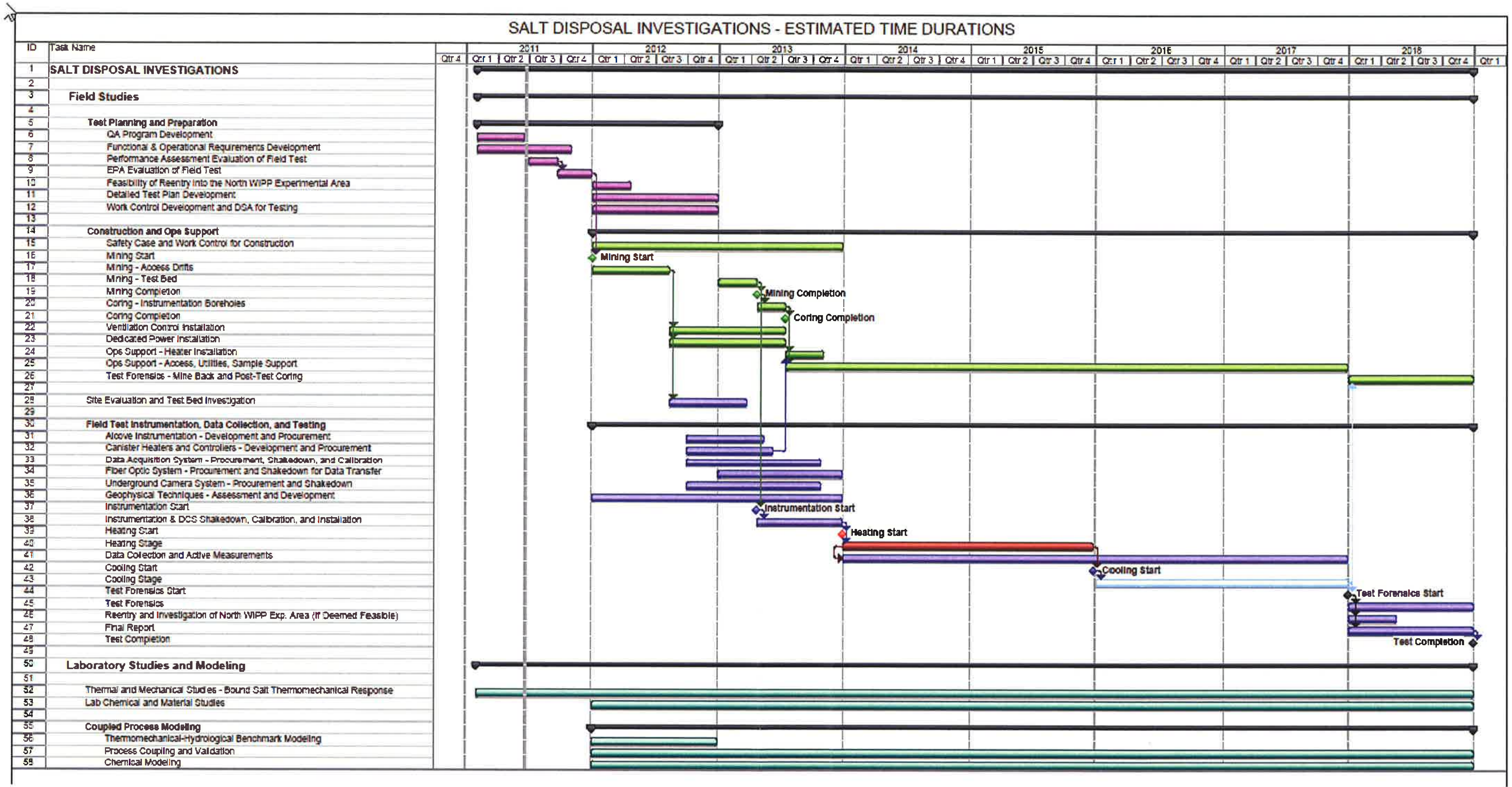


Figure 4-2: Estimated Schedule for Test Program Duration (Accelerated Scenario)



4.2. MAJOR ACTIVITIES AND ACTIONS

Primary actions and test planning (FY11):

- Complete the SDI Management Proposal
- Complete a Test Plan for laboratory testing for crushed salt in the laboratory to measure thermomechanical behavior across a variety of temperature, stress, and porosities
- Initiate laboratory tests on crushed salt
- Develop an NQA-1-compliant Quality Assurance Program Document and associated procedures
- Complete the F&OR document for the field test

Test planning, initial mining and laboratory studies (FY12):

- Begin elevated temperature tests on intact salt in the laboratory to measure thermomechanical behavior across a variety of temperatures and stresses
- Continue the laboratory tests on crushed salt
- Develop and review the detailed field test plan with equipment lists, instrumentation and borehole layouts, data quality objectives, etc.
- Comprehensively evaluate existing and available information from past thermal experiments
- Develop the criteria for the underground test design and layout
- Begin mining the underground access drifts to the test bed location
- Begin installing ventilation control and power distribution
- Write a test plan for laboratory studies of water liberation and brine migration in salt
- Begin measuring the thermodynamic properties of brines and minerals at elevated temperatures in the laboratory
- Develop a test plan and begin measuring the effect of temperature on radionuclide solubility in the laboratory
- Develop a test plan and begin studying repository interactions with waste container and constituent materials in the laboratory
- Evaluate and use coupled multiphysics modeling capability for field test configuration and analysis

Initial studies (FY13):

- Continue development of fully coupled TM(H) code and model for field test analysis.
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Develop test plan for intact core testing in the laboratory
- Procure test equipment and instrumentation for the field test
- Develop work control and safety basis for the field test
- Complete mining of the underground access drifts
- Develop the documented safety analysis for the field test
- Mine the field test bed

Field test implementation (FY14):

- Core instrumentation boreholes
- Implement the field test equipment, including data collection equipment and fiber optic communication equipment
- Investigate salt properties of test bed location
- Preparedness assessment for field test start and baseline measurements
- Continue laboratory thermomechanical testing and chemistry experiments
- Conduct laboratory studies of water liberation and brine migration
- Continued development of fully coupled TM(H) code and model for field test analysis

Conduct the proof-of-principle field test (FY15 - 20)

- Heating start on field test – FY 15
- Investigate thermal effects on intact salt in situ
- Develop a full-scale response for dry crushed salt
- Observe and document fracture healing in situ
- Track moisture movement and vapor phase transport in situ
- Complete laboratory thermomechanical testing and chemistry experiments
- Complete laboratory studies of water liberation and brine migration
- Cool down of field test by FY 19
- Post-test forensics, mine-back and post-test coring in FY 19 and FY 20
- Complete the final test and data reports
- Develop calibrated, coupled TM(H) model

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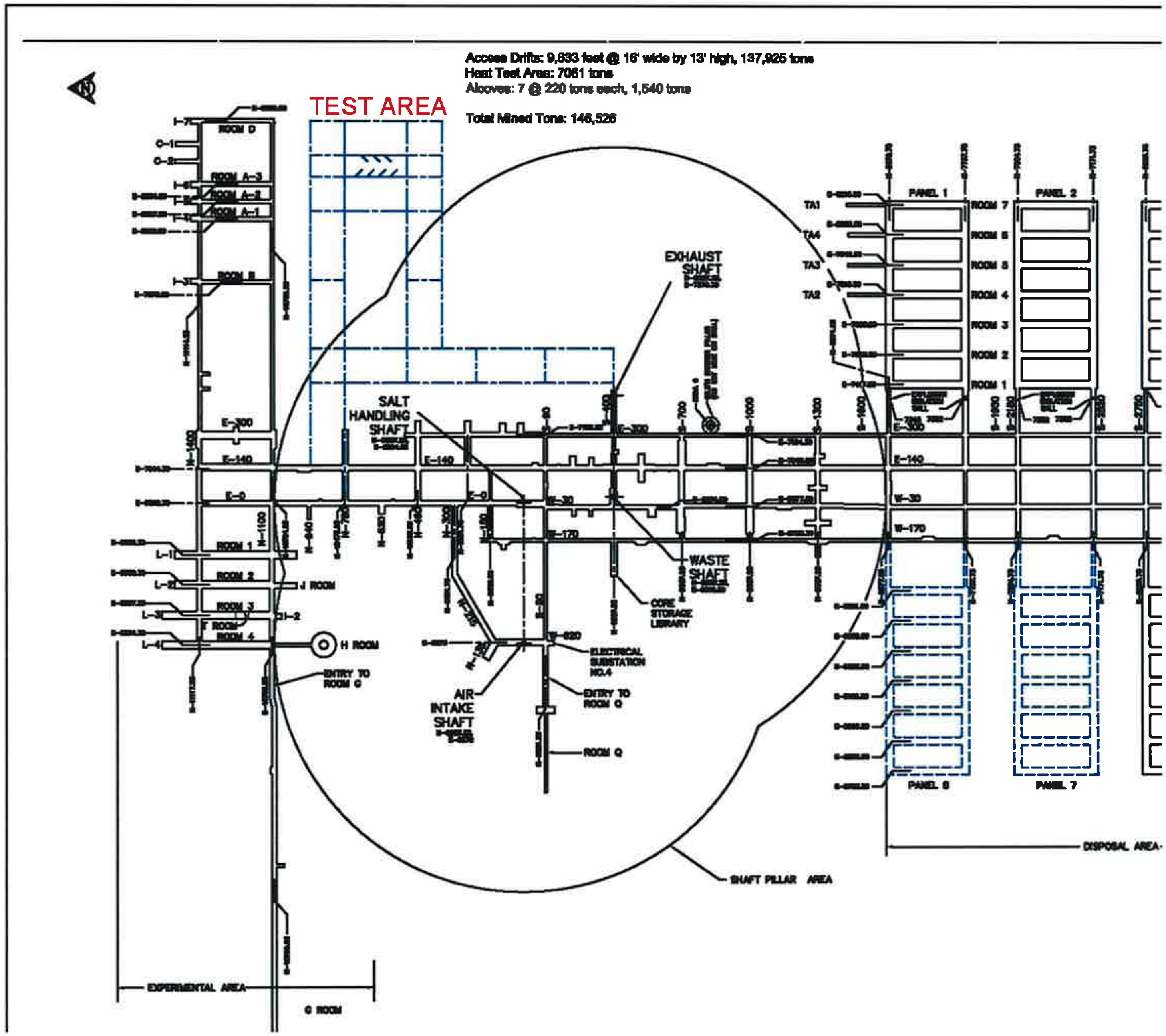
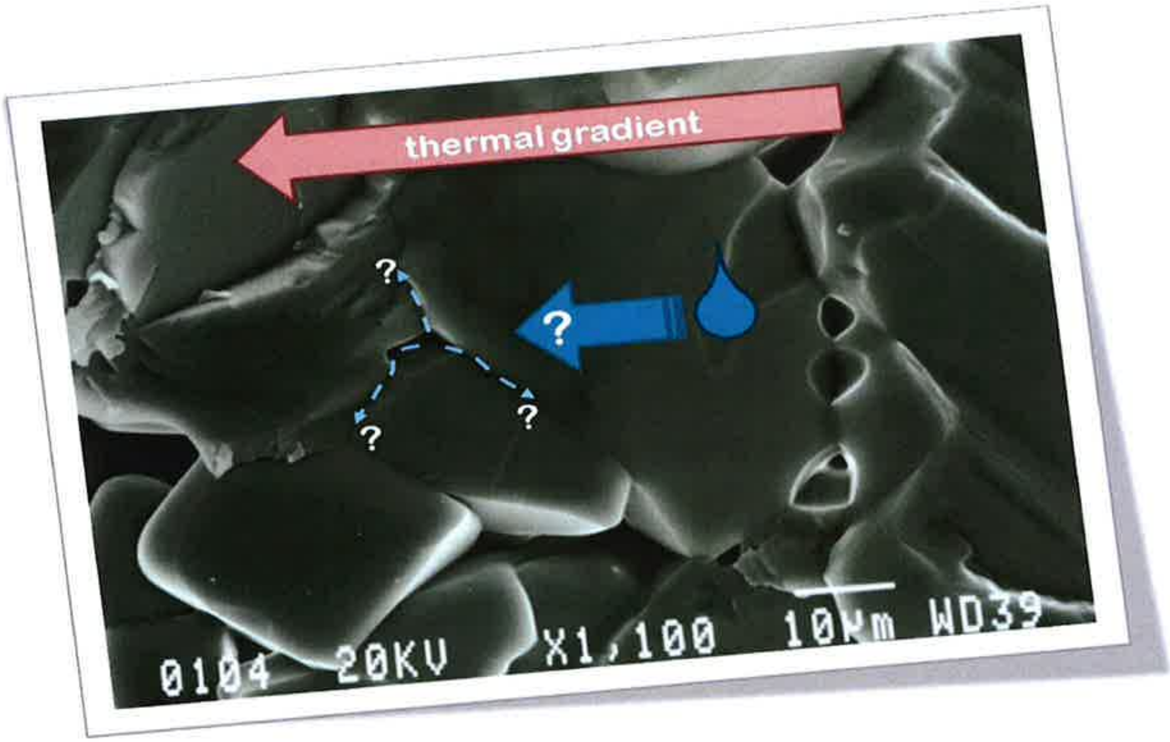
APPENDIX A - PROPOSED AREA WITHIN WIPP FOR THE SDI HE



APPENDIX B –
THE NEED FOR SALT DISPOSAL INVESTIGATIONS AND FIELD TESTS (developed June 29, 2010)



Introduction

> **A science-based research program that will enable DOE to guide America's rational decision on future nuclear waste disposal options**

This brief memorandum recaps some of the reasons that salt research is timely and of national interest. The proposal submitted to the DOE Office of Nuclear Energy (NE) and Office of Environmental Management (EM) senior management in February 2010 outlines a clear process of advancing salt repository science beyond the work done in the 1960s through the 1980s. The United States has not advanced the notion of defense high-level waste (DHLW) disposal in salt since these programs were abandoned more than 20 years ago. Given the current environment in the U.S. regarding future repositories, this missive evaluates historical information, describes the gaps in our knowledge and then advances an argument describing the need for a science-based research program that will enable DOE to guide America's rational decision on future nuclear waste disposal options.

The administration's intent to reevaluate long-lived radioactive waste disposal in America, as evidenced by the recently appointed Blue Ribbon Commission on America's Nuclear Future, has motivated DOE to research geologic disposal solutions that do not directly link spent fuel retrievable storage with the permanent disposal of HLW. Isolation in salt clearly remains a robust geologic solution. Future considerations by DOE on decay and disposal of commercial high-level waste fractions from recycling will benefit from research proposed to resolve the few remaining key questions about thermally hot radioactive waste isolation in salt. These investigations will necessarily leverage earlier work and build on an existing considerable knowledge base about HLW storage and disposal in salt.

Why This Research Is Needed

Public understanding and confidence in permanent isolation of radioactive waste in salt have improved as a result of a decade of successful disposal operations at WIPP. Directed research and collaboration with international salt repository programs can help reduce identified uncertainties regarding thermally-driven processes involved with radioactive decay and disposal in salt and therefore further increase technical understanding for these potential missions. The proposed work will build upon a foundation of excellence in salt repository applications that began with the 1957 National Academies of Science recommendation to use salt for permanent isolation of radioactive waste from the biosphere.

Year	Project	Location	Description
1965-1969	Lyons mine, Project Salt Vault	Lyons, Kansas	Irradiated fuel & electric heaters
1968	Asse salt and potash mine	Germany	Electric heaters
1979-1982	Avery Island	Louisiana	Brine migration
1983-1985	Asse (U.S./German cooperative)	Germany	Brine migration under heat & radiation
1984-1994	WIPP	Carlsbad, New Mexico	1. DHLW Mockup 2. DHLW Over-test 3. Heated axisymmetric pillar test

Table B-1. Summary of in situ salt thermal tests

Table B-1 summarizes the history of in situ salt thermal tests both in the U.S. and internationally over the past 50 years. A more detailed description of each program can be found at the end of this paper. Despite this foundation, there are a number of important gaps in scientific understanding of the thermo-mechanical and hydrologic-chemical behavior of radioactive and thermally hot waste in a salt medium.

Consider the recent interview with a current member of the Blue Ribbon Commission on America's Nuclear Future, on the subject of waste disposal in salt by Scientific American (August 2009, "*What Now for Nuclear Waste*?", Matthew Wald, pp. 46-53):

> *Salt is nice, in some senses, from a geologic perspective. But if the salt is heated, the watery inclusions mobilize and flow toward the heat, so burying spent fuel there would require waiting until the hot waste products cool down a bit—somewhere around the second half of this century.*

This demonstrates one of many misperceptions about disposal in salt. The interviewee states fluid inclusions migrate toward the heat source under a thermal gradient as a fact, yet there remains great uncertainty in brine and vapor transport.

Previous in situ salt tests related to repository issues and operations were sufficient to advance design for safe disposal of non-thermal TRU waste in salt; WIPP licensing and 10 years of operations have confirmed operational and performance expectations. Field heater tests as outlined in Table B-1 have provided significant benefit to our knowledge of salt behavior, however there are gaps that exist in the past experimental data that need to be addressed. Advanced computer modeling and data gathering techniques used today are vastly superior to the tools available 25 years ago. Regulatory and technical rigor is expected and necessary to form defensible conclusions about the efficacy of salt as an efficient and effective disposal media for thermally hot radioactive waste.

Things We Don't Know or Understand

Clearly, laboratory and field studies of the interaction of heat with salt have received attention in the past. However, the upper temperature limit for the thermo-mechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests have been predominantly conducted at room temperature. These past studies have been more than adequate to demonstrate that disposal of TRU waste and moderate areal thermal densities of DHLW in salt are safe and efficient. However, they do not provide the experimental data necessary to form a defensible basis for policy, engineering, and performance assessment of salt outside our experience with TRU waste.

Considering all of the existing experimental data from previous U.S. and German salt investigations, a recent (May 2010) U.S./German Workshop on Salt Repository Research, Design, and Operation began collaborations aimed toward identifying the current state of salt repository sciences. From this workshop, several critical, unresolved issues with regard to salt repositories were identified that should be addressed. The following issues and others will be summarized in the workshop proceedings:

1. Brine migration — Brine inclusions may preferentially migrate up the thermal gradient and corrode waste packages, but the transport process is unclear when inclusions reach inter-grain boundaries, as well as what happens when (if?) vapor phase transport dominates;
2. Buoyancy — Thermally hot waste containers have been postulated to "melt downward," and the entire disposal horizon has been postulated to float upward due to buoyancy;
3. Heat associated with HLW disposal in salt — Heat-generating waste has been characterized in 10 CFR 51 as exacerbating a process by which salt can rapidly deform, which could cause problems for keeping drifts stable and open during the operating period of a repository;
4. Solubility and transport — Radionuclide solubility in high ionic strength brines over wide temperature ranges is much more complex than in unsaturated water, and research is needed to describe leaching and transporting radionuclides;
5. Radiolysis — Further data are needed on the effect of radiolysis and temperature on the speciation of waste constituents, brine chemistry, waste materials, waste packages, and the salt.

A second US/German workshop on geochemistry and radiochemistry in salt repositories will be held in Carlsbad in late summer aimed toward furthering international cooperation and identifying the current state of knowledge and understanding of the chemistry in salt repositories. The product of the two collaborative workshops will guide and support the Salt Disposal Investigations (SDI) direction and focus.

The Salt Disposal Investigations Proposal

The main reason to immediately conduct salt investigations leading up to and including a full scale in situ heater test is that they will provide critical information on the efficacy and flexibility of salt for the deep geologic disposal of thermally hot radioactive waste, building on the momentum of the success of WIPP. As enumerated in detail in the SDI proposal, the specific investigations will:

- Track moisture movement and vapor phase transport in situ.
- Observe and document fracture healing in situ.
- Measure the salt thermomechanical response.
- Investigate thermal effects on intact salt in situ.
- Study repository interactions with waste container and constituent materials.
- Develop full-scale response for dry, crushed salt.
- Demonstrate a proof-of-principle disposal in salt concept.
- Apply laboratory research to intact and crushed salt.
- Measure the thermodynamic properties of brines and minerals at elevated temperatures.
- Measure the effect of temperature on radionuclide solubility.

Summary

Underlying the in situ testing and supporting laboratory research is the hypothesis that heat-generating waste can actually be advantageous to permanent disposal in salt. The ~300-year thermal pulse introduced by spent fuel or high-level waste may dry out a moisture halo around emplaced waste and thereafter accelerate entombment and salt healing by thermally activating the creep processes. At the same time, any very long-lived isotopes also present will be permanently encapsulated in a geologic formation that has demonstrably been hydrologically inactive for hundreds of millions of years, thereby potentially precluding the need for engineered barriers, including vitrification for disposal.

Directed research will inform, guide, and ultimately define requisite capabilities for the next generation of coupled multiphysics modeling, which in turn will be instrumental for development of performance assessment methodology. Building on the impressive performance and knowledge base developed for defense TRU waste disposal at WIPP, this research will identify specific requirements for a potentially viable long-term decay storage and deep geologic disposal concept for HLW in salt. These key elements will translate into parameters and phenomena to be measured in a proof-of-principle field test, which crowns the proposed effort. The proposed research, development, and demonstration of salt efficacy for the safe and efficient disposal of thermally hot waste will provide the basis for a repository that can readily isolate **vast** quantities of nuclear waste material, providing a key component of a safe and secure nuclear future for the nation.

References to Appendix B:

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A. Hull and L. Williams, *Radioactive Waste Isolation in Salt; Geochemistry of Brine in Rock Salt in Temperature Gradients and Gamma-Radiation Fields – A Selective Annotated Bibliography*, Argonne National Laboratory, Argonne, IL., ANL/EES-TM-290, 1985

History of Salt Disposal Research for Thermally Hot Waste

Previous in situ salt tests related to repository issues and operations were sufficient to advance design for safe disposal of non-thermal TRU waste in salt; WIPP licensing and 10 years of operations have confirmed operational and performance expectations. However, disposal of heat-generating waste in salt gives rise to thermally driven processes that require investigation before a concept for disposal of such waste can be confidently developed. The need for additional, science-based testing to fortify the technical baseline supporting HLW disposal builds upon a considerable data base deriving from historical experiments. For example, field heater tests in salt were conducted in Project Salt Vault in Kansas in the 1960s and in WIPP in the 1980s. These field tests provide significant benefit to our knowledge of salt behavior; however, some gaps can be identified that have not been sufficiently resolved. The requisite studies in the SDI proposal derive from two main focus areas: one area comprises equivocal issues and technical gaps arising or remaining from the historical testing, while the other focus area takes advantage of the significant computational tools and capabilities available today that simply did not exist when the field tests were conducted a generation ago. Building upon past experiences and taking advantage of advanced technology allow the formulation of a solid, task-oriented, progressive proposal to address the remaining issues for HLW disposal in salt. The research, development, and in situ heater test demonstration will specifically provide the basis for decision making concerning long-term decay storage and deep geologic disposal of thermally hot radioactive waste in salt.

The following synopsis includes field experiments in salt formations that started as early as 1965 with Project Salt Vault near Lyons, Kansas, and nearly contemporaneous field testing and demonstration at the Asse salt mine in Germany. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits. The following is a brief history of heated in situ testing in salt:

1957 The National Academy of Sciences/National Research Council (NAS/NRC) of the United States published a study on radioactive waste disposal on land, proposing for the first time the use of geological formations, especially rock salt.

1965-69 The first integrated field experiment for the disposal of HLW was performed by Oak Ridge National Laboratory (ORNL) in bedded salt near Lyons, Kansas. This test, named Project Salt Vault (PSV), used irradiated fuel assemblies from the Engineering Test Reactor at Idaho Falls as a source of intense radioactivity, while electrical heaters were placed in boreholes in the floor to simulate decay heat generation of HLW. The tests simulated the heat flowing into the base of the pillar from a room filled with waste with the primary focus on rock mechanics of floor, ceiling, and pillar deformation. These pioneering tests with live spent fuel and simulated electrical heaters produced modest pillar temperatures of less than 50°C. The tests did concentrate on potential structural effects of radiation (there were none). Significant brine accumulation was observed after the electrical heaters were turned off, which initiated the lingering issues of moisture behavior in such a setting. Possible brine inclusion migration and vapor transport phenomena have not been completely resolved by field experiments.

1968 A field experiment with electrical heaters was performed in the Asse salt mine to investigate the near-field consequences of emplaced HLW. These early experiments on the disposal of HLW at Asse evaluated thermomechanical properties of the Stassfurt Halite. Later on, operational options investigated included vertical borehole disposal of steel canisters and horizontal placement of steel casks surrounded with backfill crushed salt. The system was approved by the responsible mining authority. In all, three large-scale "heater" experiments were performed in the Asse mine, which yielded important data for the validation of material and computer models needed to assess the coupled long-term behavior of rock salt and crushed salt backfill in a salt repository. The Asse experiences provided important lessons and guidance for future testing which can be used in corroborating the lower temperature range of the SDI.

1979 Also in Germany, the Gorleben salt dome has been investigated since 1979. In 1998, the German government expressed doubts with respect to the suitability of the Gorleben host rock. All exploration activities were halted by the end of 2000, and a moratorium was imposed. The moratorium ends in 2010, so German repository scientists are poised to restart salt repository investigations. Like the salt testing in the U.S., German research provides a wealth of information on salt disposal investigations, which has been and will be considered in collaboration efforts, as described in the SDI proposal.

1979-82 Brine migration tests were performed by RE/SPEC for the Office of Nuclear Waste Isolation (ONWI) in the Avery Island salt mine in Louisiana. The migration of brine inclusions surrounding a heater borehole were studied on a macroscopic level by investigating gross influences of thermal and stress conditions in situ. Field tests were augmented in the laboratory by microscopic observations of fluid inclusion migration within an imposed thermal gradient. The maximum temperature reached in the field test was only 51°C. Moisture collection was minimal during heating, amounting to grams of water per day. When the heaters were shut off, cooling caused changes in tangential stress, which led to microcracking, opening of grain boundaries, and moisture release. Much of the moisture released was a result of cooling from turning off the heaters, which drastically reversed the thermal gradient; this would not occur in a HLW repository.

1983-85 A bilateral U.S.-German cooperative Brine Migration Test in the Asse salt mine investigated the simultaneous effects of heat and radiation on salt. This field experiment used ^{60}Co sources with a total radioactivity of about 36,000 Ci. Test configuration included four identical heater arrays. The maximum temperature in the borehole was 200°C. Results of this test will be used to guide instrumentation selection and assessment of brine and vapor phase moisture movement in the proposed SDI field investigations. Contemporaneous German research is keenly interested in moisture movement, and they continue to analyze the specific brine and vapor migration experiments. These data and observations will be considered in test configuration, instrumentation, and methodology.

1984-1990 Three separate simulated heater tests were performed at WIPP: 1) 18W/m^2 DHLW mockup; 2) DHLW over-test; and 3) the Heated Axisymmetric Pillar test. The 18W/m^2 DHLW mockup and DHLW over-test were designed to identify how the host rock and the storage room respond to the excavation itself and then to the heat generated from waste placed in vertical holes in the drift floor. These field tests imparted a relatively modest thermal load in a vertical borehole arrangement and did not use crushed-salt backfill or explore reconsolidation of salt. These tests were primarily focused on the mechanical response of the salt under modest heat load. Although the results can be used, for example, to validate the next-generation high-performance codes over a portion of the multiphysics functionalities, the SDI disposal concept would need to explore the interactions created by higher heat loads, a horizontal placement and crushed-salt backfill. The Heated Axisymmetric Pillar test involved an isolated, cylindrically-shaped salt pillar and provides an excellent opportunity to calibrate scale effects from the laboratory to the field, as well as a convenient configuration for computer model validation over a small part of the thermomechanical range of interest. These experiments provide a foundation for the low temperature range of SDI investigations, as described in the general proposal.

APPENDIX C - KEY CONTRIBUTORS TO THE SDI PROPOSAL

U.S. Department of Energy – Carlsbad Field Office

Roger A. Nelson – Chief Scientist, Waste Isolation Pilot Plant
Roger Nelson has almost 40 years of experience managing and conducting environmental programs for public and private sector projects. As Chief Scientist for WIPP over the past ten years, he serves as the project principal technical/scientific advisor. His focus is on identification and development of innovative and cost-effective waste handling, treatment, characterization, packaging, transportation, and disposal technologies. He promotes use of the unique underground environment at WIPP for use as a laboratory for basic science experiments requiring extremely low dose rate background radiation. He also champions WIPP in national and international waste management venues.

Sandia National Laboratories

Dr. Frank D. Hansen
Dr. Hansen has over 30 years of experience in repository sciences and has contributed significant original research in rock mechanics, seal systems, materials, design, and analysis. He is a distinguished member of the technical staff at Sandia National Laboratories, a registered professional engineer, and an ASCE Fellow.

Los Alamos National Laboratory

Dr. Ned Z. Elkins
Dr. Elkins has 35 years of experience in mining salt, potash, coal and metals, mine/refinery design and management, and nuclear waste geologic disposal programs in Nevada and Carlsbad, New Mexico. He managed the underground facility design of testing infrastructure and was responsible for implementation of the overall geotechnical field testing program for Yucca Mountain from 1989 to 1998, and he subsequently managed SNL's WIPP Program Group in Carlsbad from 1998 to 2000. Since 2000, Dr. Elkins has established and manages the Los Alamos Carlsbad Operations and Program Office in support of WIPP and the National Transuranic Waste Program.

Timothy A. Hayes
Tim Hayes has over 25 years of experience in actinide science with LANL. His career at LANL has given him experience performing and managing technical operations in a nuclear facility such as: actinide recovery and purification, advanced technology development for nuclear materials disposition and handling, manufacture of actinide-containing components, waste management, nuclear material shipping and transportation, nuclear facility safety basis, and nuclear material control and accountability. He has held management positions as Division Leader of Stockpile Manufacturing, Group Leader of Nuclear Material Security and Accountability, Deputy Group Leader of Radioactive Waste Management, and Team Leader of Actinide Processing and Challenging Waste Disposition.

Dr. Bruce A. Robinson
Dr. Bruce Robinson has served as the Program Manager of LANL's Yucca Mountain Project and as the Deputy Division Leader of the Earth and Environmental Sciences Division. In repository science, he was the lead author of the Yucca Mountain License Application section on Radionuclide Transport in the Unsaturated Zone. His personal research interests include: nuclear waste disposal; groundwater characterization and modeling; flow and transport in porous media; and optimization and inverse modeling. He is the author of 50 peer-reviewed journal publications.

Clifford D. Stroud
Cliff Stroud has 25 years of experience in nuclear waste geologic disposal programs and management. This has included work abroad, throughout the United States, with the Congress in Washington, D.C., and with each Energy Secretary. He has played a key management role with LANL in decayed storage or permanent isolation of radioactive waste in salt resulting in more than a decade of successful disposal operations at the WIPP.

Douglas J. Weaver
Doug Weaver is a mechanical engineer at LANL with nearly 20 years of experience conducting and managing large scale testing programs. He served as the project engineer for a series of thermal tests at Yucca Mountain that included a large block heated test, an underground single heater test, and the largest underground thermal test in the world, the YMP Drift Scale Test. Doug later managed the Yucca Mountain Project Test Coordination Office responsible for all surface-based and underground testing on the Project, including large geotechnical drilling programs and performance confirmation monitoring.

Washington TRU Solutions

Dr. Stanley J. Patchet
Dr. Patchet is a Professional Engineer and Manager of Mine Engineering for Washington TRU Solutions at the WIPP.

RESPEC

RESPEC Consulting & Services are world experts in the areas of salt mechanics, rock salt testing, and field services. RESPEC's materials testing laboratory is the largest and one of the best equipped laboratories in the world for studying rock salt. Among many notable tests, RESPEC performed the geotechnical engineering characterization for the Deep Underground Science and Engineering Laboratory (DUSEL) in the former Homestake Mine located in Lead, South Dakota. Laboratory tests described in this proposal will likely be conducted in RESPEC laboratories and as such, RESPEC staff provided input and review of the laboratory thermal and mechanical studies section of this proposal.

Enclosure 3

The Nuclear Safety Impact Analysis on the Salt Disposal Investigations (SDI)

The salt disposal investigations (SDI) include a science-based scope of work incorporating both field and laboratory tests. The use of the WIPP underground for the field test portion of the SDI directly tests a safe disposal arrangement in the salt formation that balances heat loading with high level waste temperatures. It is anticipated that underground test bed will be heated to temperatures well above those for which current salt experimental data exist. The test program will provide knowledge of the behavior of thermally and radioactively high level nuclear waste in salt and support the hypothesis that the thermal pulse imparted by high level waste on salt leads to rapid encapsulation. The test bed will utilize the north area of the mine initially used for evaluating the interaction of simulated waste and thermal sources on bedded salt under controlled conditions. (Clayton and Gable, *3-D Thermal Analyses of High-Level Waste Emplaced in a Generic Salt Repository, February 2009)*

The Salt Disposal Investigations Impact on the Probability of Occurrence of an Accident

The proposed SDI to determine how salt reacts to temperatures over 100 to 200 degrees Celsius will not increase the probability of occurrence of an accident as previously analyzed in the WIPP safety analysis. The test bed will be located in the north experimental area of the WIPP underground, a few hundred feet south of the N-1100 drift and away from waste handling activities, equipment important to safety and waste disposal activities.

The WIPP DSA is required to consider a minimum set of hazard event scenarios which includes, fires explosions, loss of confinement, direct radiation exposure, criticality, and externally initiated and natural phenomena. The SDI does not involve material at risk, waste handling, or the use of equipment important to safety that would be impacted by the hazard event scenarios previously analyzed in the WIPP Documented Safety Analysis (DSA). Therefore, accidents previously analyzed or the occurrence of a new accident that could result in a release of radioactive material is not applicable to the SDI.

Could the proposed activity or potential inadequate safety analysis (PISA) increase the consequences of an accident previously evaluated in the existing safety analysis?

When establishing a new scientific investigation in the WIPP underground consideration must be given to potential consequences from accidents involving radiological exposure or a release of radioactive material to facility workers, collocated workers, and the public. Potential radioactive material releases or exposure are not applicable in this situation because the SDI field tests will be a mock-up with electrical heaters in place of radioactive materials. The spacing between heaters is intended to bound thermal conditions for radioactive disposal operations. The field tests will be located in the north experimental area of the underground where no radioactive waste is present.

Could the proposed activity or PISA increase the probability of occurrence of a malfunction of equipment important to safety previously evaluated in the existing safety analysis?

The proposed SDI will not increase the probability of a malfunction of equipment important to safety because the proposed location of the test bed is located far north of the waste disposal operations where other scientific experiments are being conducted. The SDI will have no impact on systems structures, and components (SSCs) along with safety-related SSC described in the WIPP safety analysis. The area is already configured with electrical power and cabling and interaction with equipment is also prevented by a two drift access drift. Cross-cuts will provide access/egress to the new test pillar as well as sufficient controlled ventilation to maintain reasonable conditions for personnel near the test bed.

Could the proposed activity create the possibility of an accident of a different type than any previously evaluated in the existing safety analysis?

The WIPP safety basis evaluated potential accident initiators that could result in the loss of confinement of a waste container caused from fires, drops, explosions, collisions, and natural phenomena. Since the closest panel to the experimental area is Panel 1, which is located south of S1600 at E300 approximately 700 meters from the proposed site of the SDI, there is no possibility of interacting with the waste, waste disposal activities, or waste handling equipment. According to a summary of calculations presented in *AP-156, Thermal Analysis Report, Rev. 0, SDI Heater Testing Long-Term thermal Effects Calculation,* dated May 27, 2011, two years use of five 8500 Watt heaters in the SDI thermal testing will have insignificant effects on the thermal state at the location of the waste disposal panels. The proposed testing of high thermal loading effects in bedded salt is not an accident initiator and because of the remote location of the experiment, does not create the possibility of an accident of a different type than any previously evaluated in the existing safety analysis.

Could the proposed activity create the possibility of a malfunction of equipment important to safety of a different type than any previously evaluated in the existing safety analysis?

The SDI will have no interaction with waste handling equipment or safety-related equipment important to safety. Therefore the possibility of a failure or malfunction of equipment important to safety of a different type than previously evaluated in the existing safety analysis is not applicable.

Could the proposed activity reduce a margin of safety?

Functional requirements and design of safety class and safety significant SSCs are identified in the WIPP safety analysis and are protected by controls established in the WIPP Technical Safety Requirements (TSRs). The SDI has no impact on the WIPP DSA, TSRs and their bases, or the design or functional performance and reliability of equipment important to safety as described in the WIPP safety basis. Therefore, there is no reduction in a margin of safety.

Conclusion

The SDI research program will have no impact on the waste disposal operations in the WIPP underground. However, if approved, WIPP DSA would require updating to include description of the new test and scope. Work on the project including mining could proceed once the unreviewed safety question determination is completed. The WIPP DSA can be updated subsequent to starting the work.

Enclosure 4

555622

Analysis Report
AP-156 Revision 0

SDI Heater Testing Long-Term Thermal Effects Calculation

(AP-156: Analysis Plan for the Impact Determination of

SDI Heater Testing on Long-Term WIPP Performance)

Task Number 1.4.2.3
Report Date: May 27, 2011

Author: Date: 5/27/11

Kris Kuhlman
Repository Performance Department (6212)

Technical Review: Date: 5/27/11

James Pasch
Performance Assessment Department (6211)

QA Review: Date: 5/27/11

Steve Davis
Carlsbad Programs Group (6210)

Management Review Date: 5/31/11

Moo Lee
Performance Assessment Department (6211)

Contents

1.0 Introduction and Objectives

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste. Containment of TRU waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The DOE demonstrates compliance with the containment requirements according to the Certification Criteria in Title 40 CFR Part 194 by means of performance assessment (PA) calculations performed by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequence of potential radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years after facility closure. The models are maintained and updated with new information as part of a recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999.

With the recertification of the WIPP in November of 2010 (U.S. EPA 2010), a new PA baseline was established by the PABC-2009. Following this most recent recertification decision, the DOE plans to submit a planned change notice (PCN) to the EPA that justifies additional excavation in the WIPP experimental area. This excavation will be done in order to support salt disposal investigations (SDI) that include field-scale heater tests at WIPP.

The proposed expansion of the WIPP experimental area in order to facilitate SDI work requires an assessment of the impact of planned heater tests on the thermal state of the repository at the time of closure must be evaluated and quantified. The DOE has requested that SNL undertake calculations and analyses to determine the impacts of planned heater tests will be via an assessment of the evolution of heat dissipation from the beginning of SDI experimental work to the time of facility closure. Analysis plan AP-156 outlines the approach SNL will use to determine the impacts of the planned additional excavation and heater tests in the WIPP experimental area on long-term repository performance.

2.0 Thermal Impacts Summary

An analytic heat conduction solution is used to conservatively estimate the rise in temperature at the WIPP waste disposal panels due to the proposed SDI heater tests. The calculation uses a well-known two-dimensional analytic solution and the method of superposition. These solutions and methods are found in heat conduction textbooks: for example Ozisik (1993), and Carslaw and Jaeger (2003). The solution is analytic (there is no computational grid, time steps, or solver) and uses the simple mathematical concept of superposition to find the resulting expected rise in temperature. The advantages of an analytic solution include the lack of ancillary parameters related to numerical solution (e.g., grid spacing, time steps, and convergence criteria). In this case an analytic solution will capture the conservative bounding nature of the proposed calculation without the complications introduced by a potentially more realistic gridded numerical model.

Superposition is used to take a simple two-dimensional solution and build up a solution that considers both the timing and geometry of the proposed SDI heater tests. Superposition is possible due to the linearity of heat conduction in a solid (with constant thermal properties). The analytic solution will ignore the effects that the excavations or any small-scale heterogeneity would have on the solution. The drifts may be circulated with relatively cool air, and would therefore serve as a sink for heat during the operational life of WIPP. This potential cooling effect will not be taken into account in the proposed superposition of analytic solutions.

The calculation begins with a solution for a line source with cylindrical symmetry. We use superposition in time of a co-located source and sink to simulate a finite source (in this case 2 years). The effect of anhydrite Marker Beds 138 and 139 (above and below the repository, respectively) are what make the solution two-dimensional, treating them as if they are perfectly insulating boundaries. In a purely homogeneous and isotropic medium with spherical symmetry, heat flow would be three-dimensional (*x*, *y* and *z*). Accounting for the marker beds will be quite conservative, forcing the heat to flow in a two-dimensional manner (*x* and *y* only).

Superposition in time will produce a field of predicted temperature rise due to one heater. The effects of all five of the proposed heaters will be estimated by superimposing the required number of these line solutions at the proposed heater locations, (x and y); this final superposition will determine the expected total rise in temperature due to all proposed heaters at any location in space or time after the heaters are turned on.

This report documents the calculation, material properties, and temporal and geometrical arrangement used. Section 5 lists the Python script used to compute and plot the solution, allowing the calculations to be checked and verified. Any deviations from details in the analysis plan were related to corrections and comments received in the review process; the approach used in this report is conceptually simpler while effectively the same as that in AP-156.

2.1 Thermal Effects Screening Calculation

A bounding-type calculation has been performed to evaluate the effects proposed SDI heaters would have on the long-term compliance performance assessment of the WIPP. The discussion of the results, assumptions, and limitations for the analytic solution are given below. The listing of the calculation and plotting script are presented in the following sections.

The heat conduction solution used is for a specified flux at a line source, assuming angular symmetry for each heater. The solution for temperature rise, T, is well known and is presented in Carslaw and Jaeger (2003), section 10.4 (p. 261) as

$$T(r,t) = \frac{q}{4\pi\alpha} \int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} du = -\frac{q}{4\pi\alpha} Ei\left(-\frac{r^2}{4\alpha t}\right)$$

where Ei() is the exponential integral, $q = \varphi\rho C$ is the strength of the line source per unit length in the *z*-direction, φ is the heater power [8500 W], ρ is the density of salt [2190 kg/m^3], C is heat capacity of salt [931 J/(kg·K)], $\alpha = \frac{k}{\rho C_p}$ is thermal diffusivity of salt [2.648E-6 m^2/s], and k is thermal conductivity of salt [5.4 W/(m·K)]. Material properties are taken from Table 1 of Stone et al. (2010). The two-dimensional line source strength, q, is related to the physical heater power, φ, with the assumption that the heaters are distributed across the entire thickness of the two-dimensional layer (16.67 m between Marker Beds 138 and 139; Beauheim & Roberts, 2002); this assumption is not unreasonable at a distance of more than 100 m from the proposed SDI heater experiment.

As an energy-balance check, the solution given in the next section are compared against

$$Qt_H = \rho V C \Delta T$$

where Q is the heater strength [8500 W = 8500 J/s], t_H is the length of time the heaters are on [2 yr = 6.312E+7 s], V is the volume of salt the energy is being distributed across [π(700 m)^2·16.67 m = 2.566E+7 m^3], and ΔT is the resulting average temperature rise across the volume V [K]. Using this relationship, the expected temperature rise due to five 8500 W heaters for two years over a cylindrical block 700 m × 16.67 m is 5.13E-2 K.

2.2 Heat conduction solution: results

The analytic solution allows the calculation of the predicted rise in temperature at any time after the heaters are turned on (the temperature rise is zero before they turn on). Figure 1 shows the predicted temperature rise due to the five 8,500 Watt heaters being on for two years at six different distances from the center of the constellation of five SDI experiment heaters. The distance to Panel 1 from the center of the SDI heater drift is approximately 700 meters (corresponding to the lowest curve in Figure 1).

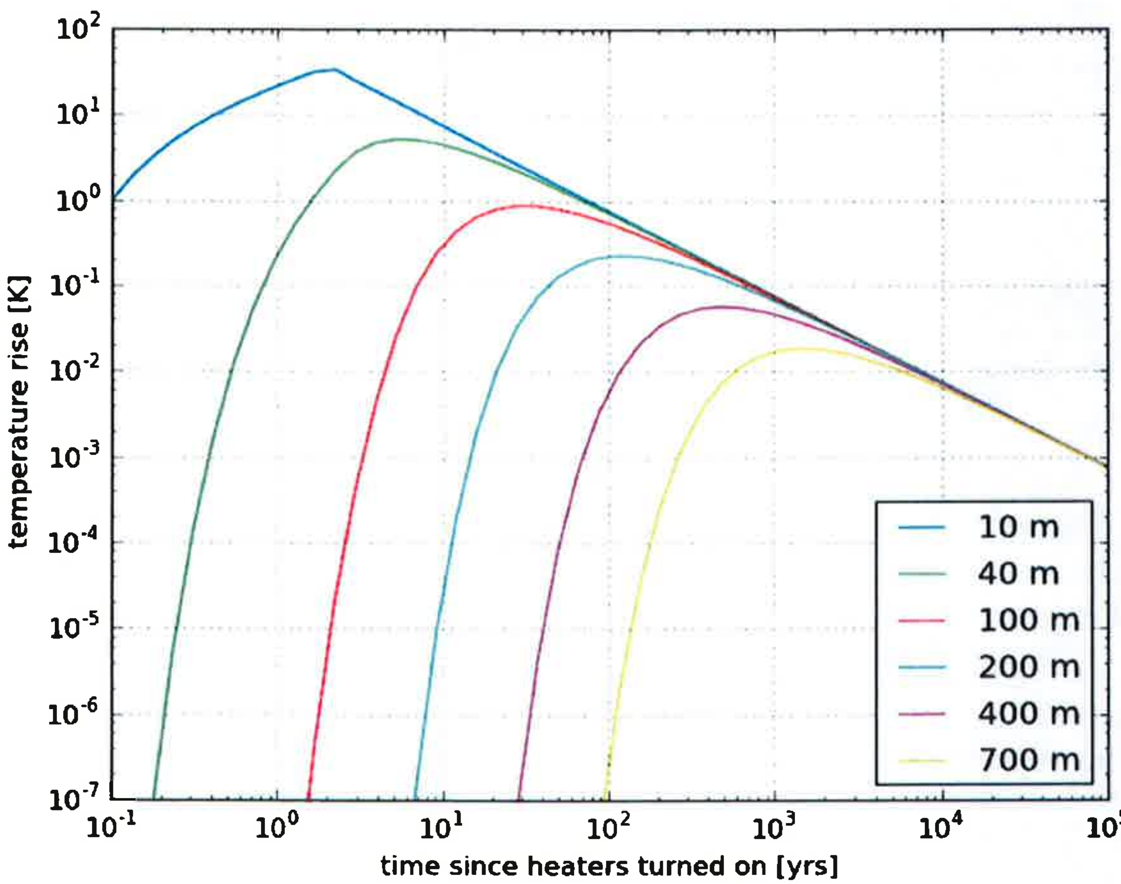

Figure 1. Predicted temperature rise through time (due to two years of heater tests) at six radial distances from proposed SDI experiment.

Figure 1 shows that the predicted peak temperature rise arrives at later times when observed from greater distance from the heaters. This is a simple well-known result from diffusion. At the distance

Panel 1 is from the SDI experiment, the peak temperature is very small (≈ 0.02 K) and arrives very late (>1,000 yrs). This prediction is a bounding conservative calculation (see following discussion of assumptions and limitations of this approach).

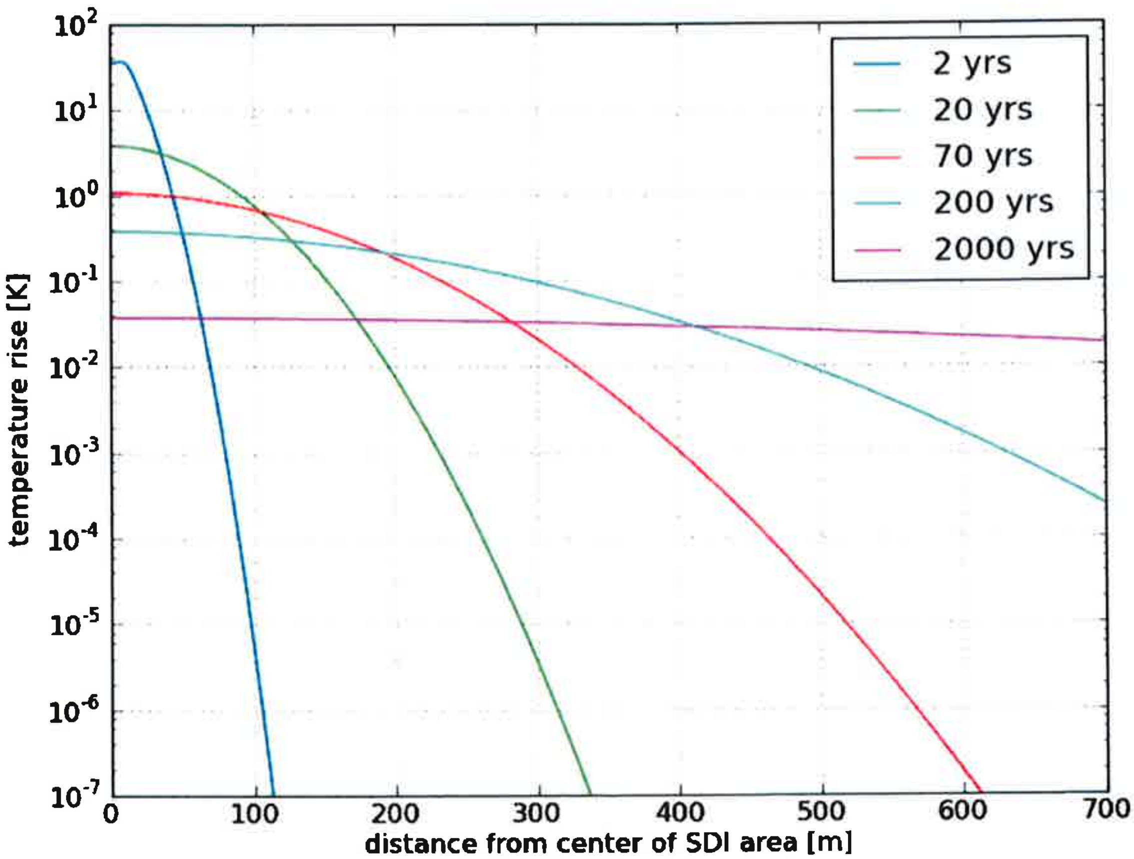

Figure 2. Predicted temperature rise profile (due to two years of heater tests) at five times after heaters are turned on (2013) from proposed SDI experiment.

Figure 2 shows the predicted spatial profile of the temperature rise At late time, the distribution of temperature rise becomes very uniform; the solution is close to the energy balance calculation in Section 2.1 (a uniform 0.05 K rise). After approximately 70 years the residual rise at almost all locations are at or below 1K. The assumptions and limitations of the analytic solution used to compute these results are given in the next section.

Figure 3 shows the predicted spatial distribution of the temperature rise 22 years after the beginning of heater tests (2035), which is the starting time for WIPP performance assessment calculations.

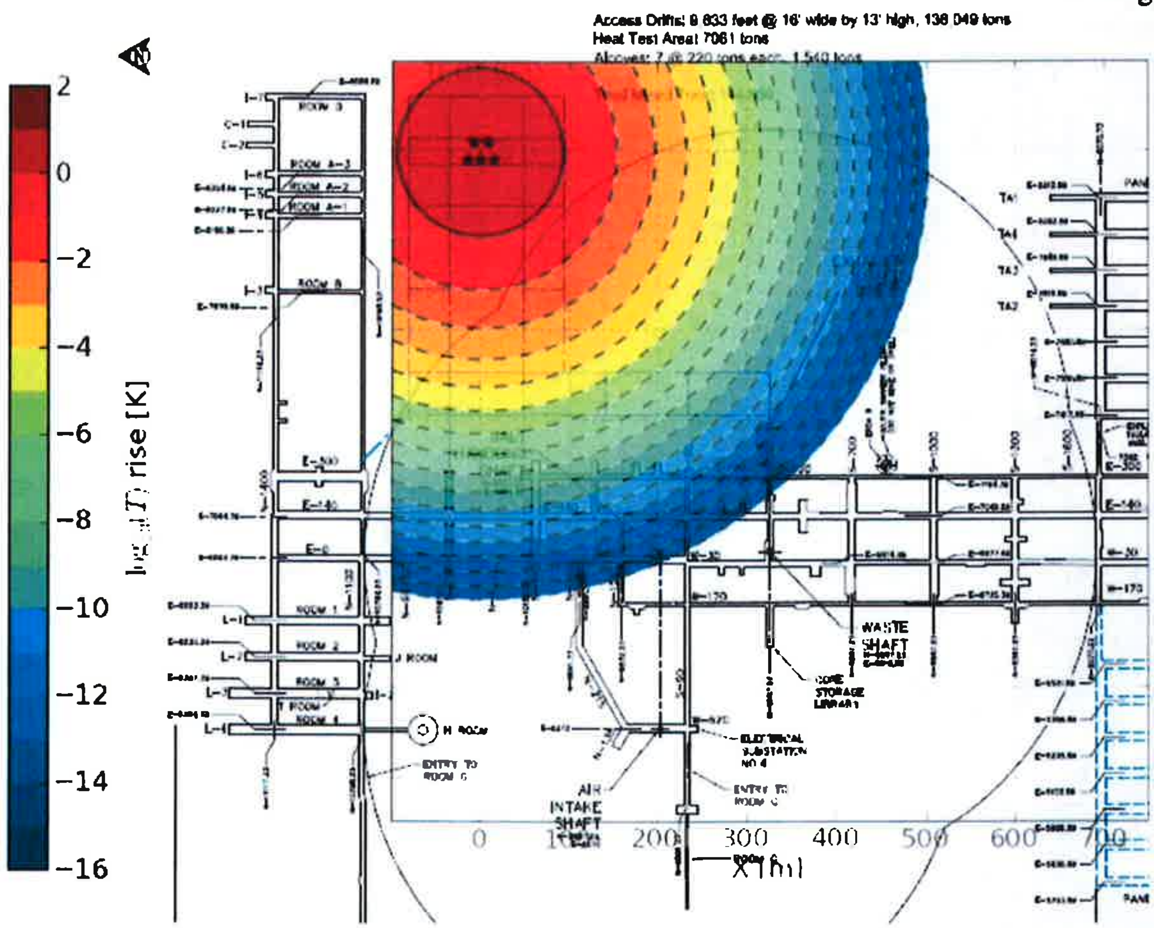

Figure 3. Predicted temperature rise distribution (due to two years of heater tests) at 2035, 22 years after heaters are turned on (2013) from proposed SDI experiment.

2.3 Analytic heat conduction solution: assumptions and limitations

The linear conduction of heat in a homogeneous isotropic solid is governed by the diffusion equation, and is covered in any textbook on heat transfer, diffusion, or conduction (e.g., Incropera & de Witt (1985), Carslaw & Jaeger (2003), Özişik (1993), or Crank (1985)). The salt in the underground facility at the WIPP deviates from the ideal circumstances in four main ways. These deviations are secondary effects or would lead to a less conservative result, and therefore the analytic solution is valid for a conservative screening calculation. The solution assumes homogeneous and linear properties, aside from the geometry handled through superposition. The most significant assumption is that heat conduction is the only mechanism to dissipate thermal energy introduced by heaters. Each of the deviations from the ideal conditions is discussed below, indicating how they were addressed, or explaining the ramifications of not addressing them.

1) The excavations within the salt do not contribute to the conduction of heat. Air-filled excavations have much lower thermal conductivity than intact salt and would essentially act as insulating boundaries for conduction (although radiation and convection would likely be significant heat transfer processes). By volume, the excavations are minor compared to the amount of salt available for conduction. Near the heaters, including the location and shapes of the excavations would be important

for predicting the temperature of the salt. At 700 m the effects of the excavations are of much less importance. Ignoring the thermal conductivity effects of the excavations does not necessarily lead to a more conservative estimate. Taking into account the heat transfer properties of excavations would preclude the use of a straightforward analytic solution.

2) The mine ventilation system will remove some thermal energy. During testing some drifts will be closed off to allow thermal energy to build up in the salt. The proposed design relies on the ability of the mine ventilation system to cool the drifts to a temperature low enough for human entry. The energy removed during convection of relatively cool air through the drifts is assumed to still be trapped in the salt, and must be dissipated by conduction.

When the test area is ventilated, thermal energy will be removed by convection and the salt will be cooled. This is the intention of ventilating the SDI experimental area. When the salt is cooled, the local thermal gradient will actually reverse, and heat will now flow towards the original heat source area, which is now a heat sink. This reversal is not accounted for in the analytic solution, and it is therefore considered a quite conservative estimate.

3) Thermal conductivity for WIPP salt is not constant. The straightforward analytic solution of the heat conduction problem is only possible when thermal conductivity is a constant. The variability of thermal conductivity over the range of expected temperature is less than an order of magnitude; specifically, thermal conductivity of halite at WIPP is given as (Stone et al., 2010)

$$k(T) = 5.4\left(\frac{300}{T}\right)^{1.14},$$

where k is thermal conductivity [W/(m*K)] and T is temperature [K]. It is considered to be a conservative approximation to use the highest value of thermal conductivity expected over that range, specifically $k(T=300\text{ K}) = 5.4$ W/(m*K). The volume of salt immediately surrounding the heater will have lower thermal conductivity than the far field, because of much higher temperatures; this will slow the flow of energy away from the heaters by conduction.

4) WIPP salt is not homogeneous and isotropic. The Salado formation consists of laterally extensive nearly horizontal layers of mostly halite, some anhydrite, minor clay, and minor other evaporites. The Salado formation has a much greater horizontal extent (tens to hundreds of kilometers) than vertical extent (few hundred meters). Any thermal pulse would encounter boundaries in the vertical direction much sooner, than in the horizontal directions. Halite has higher thermal conductivity than other materials found in the Salado (e.g., see point 5 on page 4 of DOE 2011b). A conservative prediction assumes these anhydrite marker beds just above and below the repository are perfectly insulating. In reality, the marker beds are only less conductive than halite, and there is a large thickness of halite both above and below these thin marker beds.

The analytic solution accounts for these maker beds by simulating the domain as being two dimensional. The vertical extent (approximately 16 meters) is much less than the horizontal extent (hundreds to thousands of meters) and therefore the two-dimensional approximation is conservative and accurate enough for the desired purpose. The analytic solution does not account for any other heterogeneity or anisotropy of thermal properties, aside from the insulating boundaries at the marker beds.

Although neglecting the excavation's effects on heat conduction is not handled in a conservative manner (point #1 above), it is believed that not taking credit for the heat lost to mine ventilation (#2) and conduction above and below the marker beds (#4) leads to a very conservative estimate of temperature rise at Panel 1. The overall result is conservative in its assumptions and shows that the

SDI heater experiments should create no discernable deviation from the current baseline condition at the WIPP.

3.0 Summary

The effects of two years of five 8500 Watt heaters in the SDI thermal tests will be insignificant at the location of the waste disposal panels(Panel 1 being the closest) for any time. The calculation in this report is very conservative and bounding; the results illustrate that even under such conservative estimates there is expected to be no change in repository conditions at the time the WIPP repository is planned for closure, based on the preliminary design presented in the letter and proposal from DOE (2011a; 2011b).

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5.0 Python Script Listing

The Python script used to compute the solution and plot the figures in this report is listed below for completeness.

```
# this script is part of the SNL SDI proposal scoping work
# by Kristopher L. Kuhlman, Repository Performance Dept. (6212)

import numpy as np              # array functionality
from scipy.special import exp1  # exponential integral
import matplotlib.pyplot as plt # plotting functionality

def G(a1,f1,t1,r1):
    """2D solution for line source

    a1 = thermal diffusivity [W/(m*K)]
    t1 = 1D time vector    [s]
    r1 = radial distance (any shape >= 1D) [m]
    """

    oldshape = list(r1.shape)
    nt = t1.shape[0]
    r1.shape = (1,-1)  # reform into 1D vector with singleton second dim
    t1.shape = (-1,1)  # make t conformable with r

    Z1 = f1/(4.0*np.pi*a1)*exp1(r1**2/(4.0*a1*t1))

    # change inputs back to original shape
    r1.shape = oldshape
    t1.shape = (nt,)

    # reshape result so it has dimensions like r
    # with the t dimension added in front
    oldshape.insert(0,nt)

    Z1.shape = oldshape
    return Z1

def H(a2,f2,t2,tau2,r2):
    """use superposition in time to compute a
    source that is non-zero boundary flux from 0 <= t <= tau

    a2,k2,t2,r2 are same as in G()
    tau2 = time heaters are turned off [s]
    f2 = actual flux strength [W]

    NB: routine assumes times are listed in increasing order
    """

    # source on at t=0
    T0 = G(a2,f2,t2,r2)

    tt = t2-tau2 # shifted times

    # number of non-zero times at beginning of vector
    nnz = (tt[:] < 0).sum()

    # sink on at t=tau (only positive times are valid)
    T1 = G(a2,f2,tt[nnz:],r2)

    # combine source and sink
    T2 = np.empty_like(T0)
    T2[:nnz] = T0[:nnz]             # before heater turns off
    T2[nnz:] = T0[nnz:] - T1[:]     # after heater turns off
    return T2

def heaters(a3,f3,t3,tau3,xg,yg,htrs):
    """ use superposition to in horizontal (x,y) to sum up
    effects of multiple heaters installed at different x,y locations,
    assuming all heaters are at the same elevation.
```

```
    a4,k4,t4 are same as G()
    tau4,f4 are same as H()
    xg,yg are arrays of observation coordinates [m]
    source terms are located at complex coordinates passed
    in the list htrs (heaters) [m].
    """

    Wshape = list(xg.shape)
    Wshape.insert(0,t3.shape[0])
    W3 = np.zeros(Wshape,dtype=np.float64)

    Zg = xg + yg*1j

    for i,heat in enumerate(htrs):

        # compute relative horizontal (2D) distance from heater
        rg = np.abs(Zg - heat)
        W3 += H(a3,f3,t3,tau3,rg)

    return W3

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# setup material properties

k = 5.4         # thermal conductivity  [Watt/(meter*Kelvin)]
alfa = 2.648E-6  # thermal diffusivity   [meter^2/second]
density = 2190.0  # density of salt [kg/m^3]
Cp = 931.0  # heat capacity of salt [Joule/(kilogram*Kelvin)]
strength = 8500.0   # power of each heater [Watt]
f0 = strength/(Cp*density*16.67)  # line source strength

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# setup calculation grid and input parameters

secperyr = 365.2422*24.0*60.0*60.0  # seconds in a year

# time after t=0 heaters get turned off [2 years in seconds]
tau =   2.0 *secperyr  # end of heaters
maxt = 20.0 *secperyr  # "final" map calculation date (2035, assuming begins in 2015)

# Computational grid is with respect to SDI
# proposal figure (north is to left), so computational
# x+ is South (x- is North), y+ is East (y- is West)

# compute out to 750m since it is about 680 m
# from proposed heater locations (as per SDI proposal) to panel 1
nt,nx,ny  = (22,100,100)
minx,miny = (-100.0, -750.0)
maxx,maxy = (750.0,  100.0)

tg = np.linspace(1.0E-6,maxt,nt)  # time [seconds]

# compute on a grid, with center of heater array at origin.
xg,yg = np.meshgrid(np.linspace(miny,maxy,ny),np.linspace(minx,maxx,nx))

# 3D mesh for plotting
X,Y = np.mgrid[minx:maxx:nx*1j, miny:maxy:ny*1j]

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# perform calculation

# distances related to proposed geometry of heaters
# estimated from figures in SDI proposal.
hdew = 15.5      # east-west distance between heaters
hdns = 20.0/2.0 # half north-south distance between heaters

htrs = [hdns - hdew/2.0*1j,
        hdns + hdew/2.0*1j,
        -hdns -hdew*1j,
        -hdns + 0j,
        -hdns + hdew*1j]
```

```
if __name__ == "__main__":

    # compute solution on a 3D grid from MB139 to MB138
    # T has dimensions : (nt,nx,ny,nz)
    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    # log plotting doesn't like zeros (underflow of calculation above)
    # but seems to be ok with NaNs
    T[T==0] = np.NaN

    ncnt = 19 # number of contours
    cntmin = -16.0  # min/max contour range
    cntmax = 2.0

    # @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
    # plot figures of results

    print 'X,Y,t,T',xg.shape,yg.shape,tg.shape,T.shape
    print 'min, max',np.nanmin(T),np.nanmax(T)

    # plot logT contours of heat at 2035
    fig = plt.figure(1)
    ax = fig.add_subplot(111)
    pp = ax.contourf(X[:,:],Y[:,:],np.log10(T[-1,:,:]),
                levels=np.linspace(cntmin,cntmax,ncnt))
    pc = ax.contour(X[:,:],Y[:,:],np.log10(T[-1,:,:]),
                levels=np.linspace(cntmin,cntmax,ncnt),colors='black',linewidth=0.5)
    cb = fig.colorbar(pp)
    cb.set_label('$\\log_{10}(T)$ rise [K]')
    ax.set_xlabel('X [m]')
    ax.set_ylabel('Y [m]')
    for h in htrs:
        ax.plot(h.imag,h.real,'k*')
    plt.axis('image')
    plt.grid()
    ax.set_title('temp rise contours at top of waste panel level')
    plt.savefig('end-logtemp-contours-at-panel-level.png',transparent=True)
    plt.close(1)

    # compute solution for radial profile at different times
    xg = np.linspace(0,700,500)
    yg = np.zeros_like(xg)
    mint = 0.1
    maxt = 100000.0
    tg = np.array([2,20,70,200,2000])*secperyr

    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    fig = plt.figure(1)
    ax = fig.add_subplot(111)
    for i,tval in enumerate(tg):
        ax.semilogy(xg,T[i,:],label='%.0f yrs' % (tval/secperyr,))
    ax.set_ylim([1.0E-7,100])
    ax.set_xlabel('distance from center of SDI area [m]')
    ax.set_ylabel('temperature rise [K]')
    plt.grid()
    ax.set_title('temp profile at different times')
    plt.legend(loc='upper right')
    plt.savefig('temp-profile.png')
    plt.close(1)


    # compute solution at log-spacing of time
    xg = np.array([10.0,40.0,100.0,200.0,400.0,700.0])
    yg = np.zeros_like(xg)
    mint = 0.1
    maxt = 100000.0
    tg = np.logspace(np.log10(mint*secperyr),np.log10(maxt*secperyr))

    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    # plot temperature through time 50, 100, 200, 400, and 700 m east of heaters
```

```
fig = plt.figure(1)
ax = fig.add_subplot(111)
for i,xval in enumerate(xg):
    print i,xval
    ax.loglog(tg/secperyr,T[:,i],label='%.0f m' % xval)
ax.set_xlabel('time since heaters turned on [yrs]')
ax.set_ylabel('temperature rise [K]')
ax.set_ylim([1.0E-7,100.0])
ax.set_xlim([mint,maxt])
plt.grid()
plt.legend(loc='lower right')
plt.savefig('temperature-through-time.png')
plt.close(1)
```

Kuhlman, Kristopher L

From:	Pasch, James Jay
Sent:	Wednesday, May 25, 2011 2:12 PM
To:	Kuhlman, Kristopher L
Cc:	Lee, Moo
Subject:	signature authority

I, James Pasch, give signature authority to Kris Kuhlman for the following document.

Analysis Report
AP-156 Revision 0
SDI Heater Testing Long-Term Thermal Effects Calculation

(AP-156: Analysis Plan for the Impact Determination of SDI Heater Testing on Long-Term WIPP Performance)

Enclosure 5

555824

SANDIA NATIONAL LABORATORIES
WASTE ISOLATION PILOT PLANT

Impact Assessment of SDI Excavation on Long-Term WIPP Performance

Revision 0

Author:	R. Chris Camphouse	[signature]	7/14/2011
	Print	Signature	Date
Author:	Dwayne C. Kicker	[signature]	7/14/2011
	Print	Signature	Date
Author:	Thomas B. Kirchner	[signature]	7/13/2011
	Print	Signature	Date
Author:	Jennifer J. Long	[signature]	7/14/11
	Print	Signature	Date
Author:	James J. Pasch	[signature]	7/13/2011
	Print	Signature	Date

Technical Review:	Janis R. Trone	[signature]	7/14/2011
	Print	Signature	Date
QA Review	Steve Davis	[signature]	7-13-11
	Print	Signature	Date
Management Review:	Moo Lee	[signature]	7/13/2011
	Print	Signature	Date

WIPP:1.4.1.2:PA:QA-L:555562

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EXECUTIVE SUMMARY

With the recertification of the WIPP in November of 2010 (U.S. EPA 2010), a new PA baseline was established by the 2009 Performance Assessment Baseline Calculation (PABC-2009). Following this most recent recertification decision, the DOE plans to submit a planned change notice to the EPA that justifies additional excavation in the WIPP experimental area. This excavation will be done in order to support salt disposal investigations (SDI) that include field-scale heater tests at WIPP. This report summarizes the impact of the additional SDI excavation on long-term repository performance with particular emphasis on spallings and direct brine releases, two of the dominant release mechanisms.

Total normalized releases calculated in the SDI impact assessment remain below their regulatory limits. As a result, the additional excavation in the WIPP experimental area to support SDI would not result in WIPP non-compliance with the containment requirements of 40 CFR Part 191. Cuttings and cavings releases and direct brine releases are the two primary release components contributing to total releases in the SDI calculations. Cuttings and cavings releases are unchanged from those calculated in the PABC-2009. Additional excavation for SDI results in small impacts to pressures and brine saturations in repository waste-containing regions, but these changes collectively result in a negligible difference between direct brine releases seen in the SDI impact assessment and the PABC-2009. Small reductions are observed in SDI spallings releases as compared to the PABC-2009, but these differences are relatively minor and do not have a significant impact on the overall total normalized releases found in the SDI impact assessment. As a result, total normalized releases found in the SDI calculations and the PABC-2009 are indistinguishable.

An additional component of the overall SDI analysis performed is a determination of the impact that planned heater tests have on the state of the repository at the time of closure. That analysis demonstrated that the impact of heater testing on the temperature of WIPP waste-containing areas is negligible. Results from the SDI thermal analysis are presented in a separate report (Kuhlman 2011).

1 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste. Containment of TRU waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The DOE demonstrates compliance with the containment requirements according to the Certification Criteria in Title 40 CFR Part 194 by means of performance assessment (PA) calculations performed by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequence of potential radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years after facility closure. The models are maintained and updated with new information as part of a recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999.

With the recertification of the WIPP in November of 2010 (U.S. EPA 2010), a new PA baseline was established by the 2009 Performance Assessment Baseline Calculation (PABC-2009). Following this most recent recertification decision, the DOE plans to submit a planned change notice (PCN) to the EPA that justifies additional excavation in the WIPP experimental area. This excavation will be done in order to support salt disposal investigations (SDI) that include field-scale heater tests at WIPP.

The proposed expansion of the WIPP experimental area in order to facilitate SDI work requires an assessment of associated impacts on long-term repository performance. The impacts of additional volume on pressure and brine saturation in and around the waste regions of the repository must be determined as these quantities potentially impact release mechanisms such as spallings and direct brine releases (DBRs). The DOE has requested that SNL undertake calculations and analyses to determine the impacts of additional repository volume on the long-term performance of the facility (U.S. DOE 2011a, 2011b). The impacts of additional excavated volume are determined by a comparison to results obtained in the PABC-2009. This report provides a summary of calculations and analyses used to determine the impact of additional excavated volume in the WIPP experimental area on regulatory compliance.

An additional component of the overall SDI analysis performed is a determination of the impact that planned heater tests have on the state of the repository at the time of closure. That analysis demonstrated that the impact of heater testing on the temperature of WIPP waste-containing areas is negligible. Results from the SDI thermal analysis are presented in a separate report (Kuhlman 2011).

The work undertaken in the SDI impact assessment is prescribed in AP-156, *Analysis Plan for the Impact Determination of SDI Heater Testing and Associated Excavation on Long-Term WIPP Performance* (Camphouse and Kuhlman 2011). In order to isolate the impacts of additional experimental volume on regulatory compliance, the SDI impact assessment was designed to deviate as little as possible from the PABC-2009 implementation. In particular, the SDI investigation utilizes the same waste inventory information, drilling rate and plugging pattern parameters, and radionuclide solubility parameters as were used in the PABC-2009. The SDI impact assessment is essentially a focused re-run of the PABC-2009 calculation using a slightly modified numerical grid in the Salado flow calculation that accounts for additional volume in the repository experimental area.

2 SDI EXCAVATION

A schematic depicting the additional SDI excavation to the repository experimental area is included in U.S. DOE (2011b), and is shown in Figure 2-1 for convenience. From that figure, the additional volume added to the experimental area can be calculated.

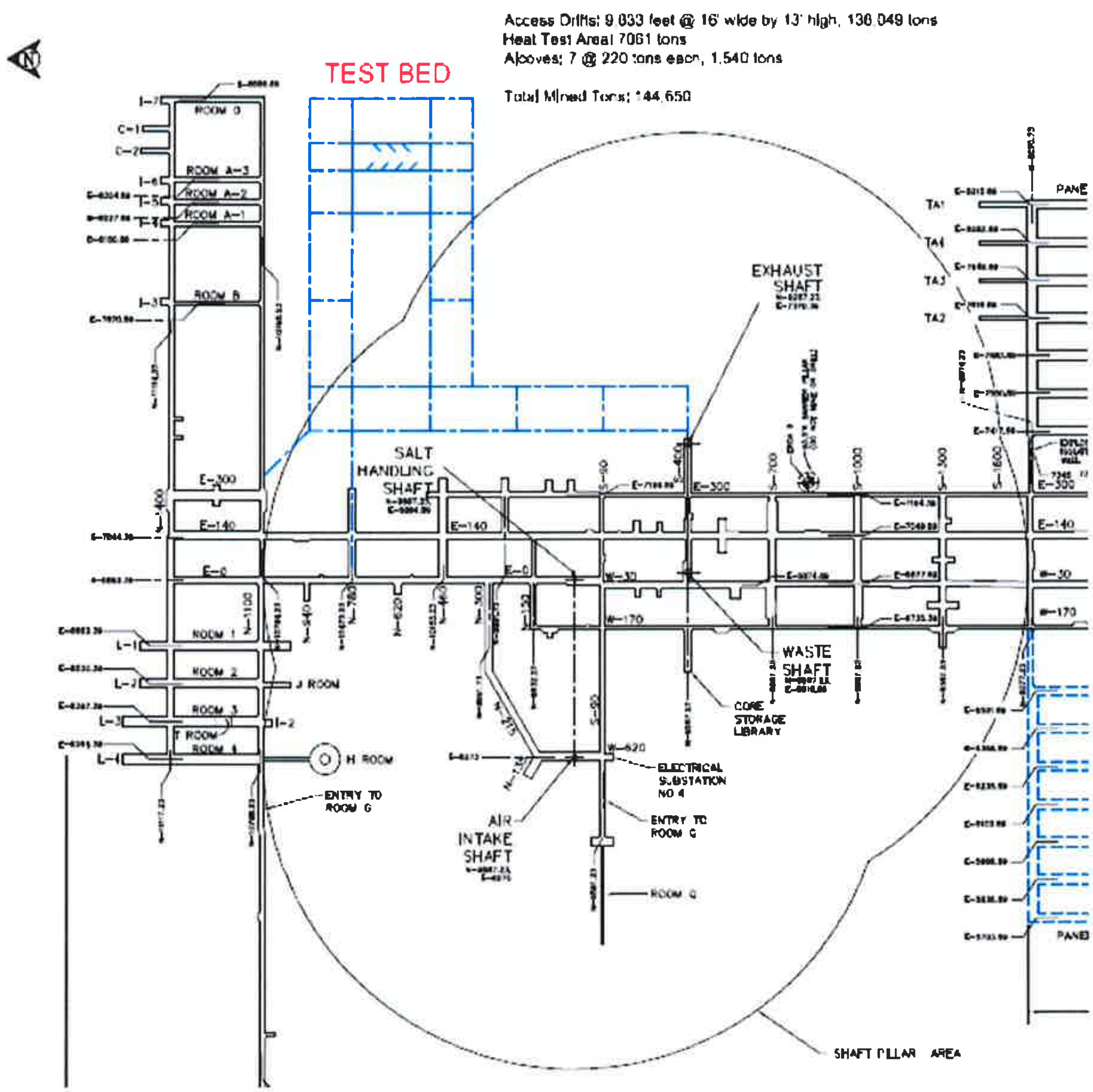


Figure 2-1: SDI Excavation Schematic

As seen in Figure 2-1, the volume of the SDI access drifts is (9,633 ft) x (16 ft) x (13 ft) = 2,003,664 ft^3. Moreover, from that figure, the tonnage of excavated salt corresponding to this volume is 136,049 tons. These quantities provide a conversion factor of tonnage to excavated volume of 1 excavated ton = 14.73 ft^3. The total mined tonnage associated with the SDI excavation is listed in Figure 2-1 as 144,650 tons because of some additional volume associated with the heater test area and alcoves. Using the conversion factor obtained above, the total volume corresponding to the additional SDI excavation is 2,130,694.5 ft^3, or 60,335 m^3 (after rounding). The SDI impact assessment includes this additional volume of 60,335 m^3 in the experimental sub-region of the numerical grid used for Salado flow modeling. Aside from this change to the Salado numerical grid, the parameters and sampled distribution values used in the SDI impact assessment are identical to those implemented in the PABC-2009.

3 FEPS RE-ASSESSMENT

An assessment of the FEPs baseline was conducted to determine if the current FEPs basis remains valid in consideration of changes introduced by the proposed SDI experimental program, and was performed according to SP 9-4, *Performing FEPs Impact Assessment for Planned or Unplanned Changes*. The FEPs analysis concludes that no additional FEPs are needed to accurately represent the changes to the repository layout resulting from additional excavation in the WIPP experimental area. Additionally, no FEPs screening arguments and associated screening decisions require modification to account for these changes (Kirkes 2011).

4 METHODOLOGY

The performance assessment methodology accommodates both aleatory (i.e. stochastic) and epistemic (i.e. subjective) uncertainty in its constituent models. Aleatory uncertainty pertains to unknowable future events such as intrusion times and locations that may affect repository performance. It is accounted for by the generation of random sequences of future events. Epistemic uncertainty concerns parameter values that are assumed to be constants, but the exact parameter values are uncertain due to a lack of knowledge about the system. An example of a parameter with epistemic uncertainty is the permeability of a material. Epistemic uncertainty is accounted for by sampling of parameter values from assigned distributions. One set of sampled values required to run a WIPP PA calculation is termed a vector. In the SDI impact assessment, models were executed for three replicates of 100 vectors, each vector providing model realizations resulting from a particular set of parameter values. Parameter values sampled in the PABC-2009 were also used in the SDI impact assessment, and are documented in Kirchner (2009). A sample size of 10,000 possible sequences of future events is used in PA calculations to address aleatory uncertainty. The releases for each of 10,000 possible sequences of future events are tabulated for each of the 300 vectors, totaling 3,000,000 possible futures.

For a random variable, the complementary cumulative distribution function (CCDF) provides the probability of the variable being greater than a particular value. By regulation, performance assessment results are presented as a distribution of CCDFs of releases (U.S. EPA 1996). Each individual CCDF summarizes the likelihood of releases across all futures for one vector of parameter values. The uncertainty in parameter values results in a distribution of CCDFs.

Releases are quantified in terms of "EPA units". Each radionuclide has a release limit prescribed to it. This limit is defined as the maximum allowable release (in curies) of that radionuclide per a waste amount containing 1×10^6 curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years. Releases in EPA units result from a normalization by radionuclide and the total inventory. For each radionuclide, the ratio of its 10,000 year cumulative release (in curies) to its release limit is calculated. The sum of these ratios is calculated across the set of radionuclides and normalized by the transuranic inventory (in curies) of α-emitters with half-lives greater than 20 years, as specified by regulation. Mathematically, the formula used to calculate releases in terms of EPA units is of the form

$$R = \frac{1 \times 10^6\, curies}{C} \sum_i \frac{Q_i}{L_i}$$

where R is the normalized release in EPA units. Quantity Q_i is the 10,000 year cumulative release (in curies) of radionuclide i. Quantity L_i is the release limit for radionuclide i, and C is the total transuranic inventory (in curies) of α-emitters with half-lives greater than 20 years. Note that the definition of the release limit L_i results in a constant value of $1\text{x}10^6$ curies being factored out of the summation.

The SDI impact assessment was developed so that the structure of calculations performed therein was as similar as possible to that used in the PABC-2009. PABC-2009 calculated results impacted by additional excavated volume in the WIPP experimental area were updated, while the results from previous PAs were used for individual numerical codes not affected by these changes. The SDI impact assessment utilized the same waste inventory information, drilling rate and plugging pattern parameters, and radionuclide solubility parameters as were used in the PABC-2009.

Additional volume in the WIPP experimental area conceivably results in a pressure reduction in that region. Lower pressure in the experimental area in combination with the long WIPP regulatory time period of 10,000 years potentially results in an eventual reduction in pressure in WIPP waste-containing areas. Pressure changes in the waste panels translate directly to changes in spallings releases as reductions in pressure yield reductions in spallings volumes. Moreover, pressure reductions in waste areas potentially allow a larger influx of brine into these regions, corresponding to increases in brine saturation. Direct brine releases are a function of pressure and brine saturation at the time of intrusion. Two conditions must be met for a DBR to occur. First, the brine saturation in the intruded panel must exceed the residual brine saturation of the waste, a sampled parameter in PA. Second, the repository pressure near the drilling location must exceed the hydrostatic pressure of the drilling fluid, which is specified in PA to be 8 MPa. The combined impact of lower pressure and increased brine saturation on DBRs is nontrivial. A pressure reduction would be expected to result in a corresponding reduction in the number of vectors that satisfy the DBR pressure requirement. Increases in brine saturation would be expected to result in an increase in the number of vectors that satisfy the DBR brine saturation requirement. As a result, it is not apparent if the net impact of lower pressure and increased brine saturation results in more or fewer vectors overall that satisfy both DBR requirements. For these reasons, spallings and direct brine releases are the primary release mechanisms of interest in the SDI impact assessment. Additional volume in the experimental region has no impact on releases due to cuttings and cavings. Transport releases through the Culebra had virtually no impact on total normalized releases in the PABC-2009 (Clayton et al 2010). Additional volume in the repository experimental area will not change this result. Consequently, transport releases through the Culebra calculated in the PABC-2009 are also used in the SDI impact assessment.

5 RUN CONTROL

Run control documentation of codes executed in the SDI impact assessment is provided in APPENDIX A. This documentation contains:

1. A description of the hardware platform and operating system used to perform the calculations.
2. A listing of the codes and versions used to perform the calculations.
3. A listing of the scripts used to run each calculation.
4. A listing of the input and output files for each calculation.
5. A listing of the library and class where each file is stored.
6. File naming conventions.

As described previously, PABC-2009 results were used for individual numerical codes primarily unaffected by SDI excavation in the WIPP experimental area. Documentation of run control for results calculated in the PABC-2009 is provided in Long (2010).

6 RESULTS

Additional excavated volume in the WIPP experimental region has no impact on cuttings and cavings releases resulting from drilling intrusions in repository waste areas. Cuttings and cavings results obtained in the SDI impact assessment are identical to those found in the PABC-2009. In addition Culebra transport results calculated in the PABC-2009 were used in the SDI calculations. Discussions of cuttings and cavings releases, as well as Culebra transport releases, calculated in the PABC-2009 can be found in Clayton et al (2010) and the references therein. The primary focus of the SDI impact assessment is a determination of pressure and brine saturation changes in waste-containing repository regions, and the impacts these changes have on spallings releases and DBRs. Spallings releases and DBRs are two of the release components used to calculate total normalized releases. As a result, the impact of pressure and brine saturation changes on total normalized releases is of interest as well.

Summary results obtained from the SDI impact assessment are broken out in sections below, and are compared to PABC-2009 results. Salado flow modeling results are presented in Section 6.1. Spallings results are presented in Section 6.2. Direct brine releases are presented in Section 6.3. The impact of proposed SDI excavation on regulatory compliance is discussed in terms of total normalized releases in Section 6.4. Files used to generate plots and summary statistics in the results that follow are included on a CD submitted with this report. As the CCDF is the regulatory metric used to demonstrate compliance, CCDFs obtained in the SDI impact assessment and the PABC-2009 are compared for each component of release in the appropriate section.

6.1 Salado Flow Results

The BRAGFLO software calculates the flow of brine and gas in the vicinity of the WIPP repository over the 10,000-year regulatory compliance period. The computational grid used in the PABC-2009 BRAGFLO calculations is shown in Figure 6-1, where the WIPP experimental area is denoted by region "Exp". As seen in that figure, the volume of the experimental region implemented in the PABC-2009 discretization is

$$2(\,(30.61\text{m}) \times (361.65\text{m}) \times (1.32\text{m} + 1.32\text{m} + 1.32\text{m})\,) = 87{,}675\ \text{m}^3.$$

As developed in Section 2, the volume resulting from additional excavation in the experimental region for SDI is 60,335 m^3. As a result, the target volume of the experimental region implemented in the SDI BRAGFLO computational grid is 87,675 m^3 + 60,335 m^3 = 148,010 m^3. To achieve this value, the experimental region of the BRAGFLO grid implemented in the SDI impact assessment was modified from that used in the PABC-2009. Elements corresponding to the experimental area were lengthened in the z-direction for the SDI impact assessment. Two elements lengths of 30.61 meters in the z-direction were used in the PABC-2009. For the SDI calculations, these two lengths were increased to 51.67 meters and 51.68 meters. The resulting volume of the experimental region in the SDI BRAGFLO numerical grid is 148,011 m^3, one cubic meter greater than the target value. Changes in element sizes comprising the experimental region from the PABC-2009 to the SDI impact assessment are summarized in Figure 6-2. No other changes were made to the PABC-2009 BRAGFLO grid for the SDI impact assessment.

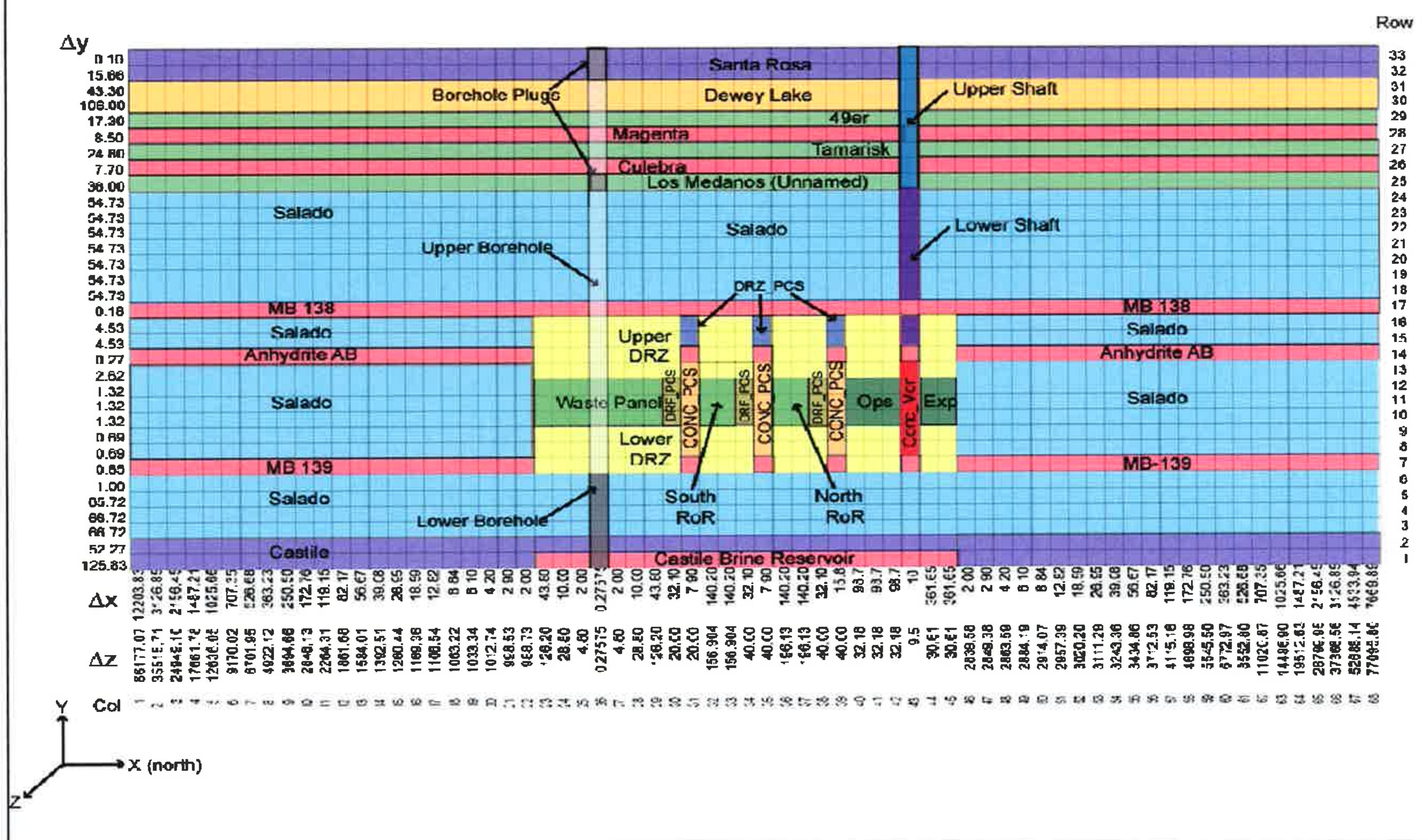


Figure 6-1: PABC-2009 BRAGFLO grid (Δx, Δy, and Δz dimensions in meters)

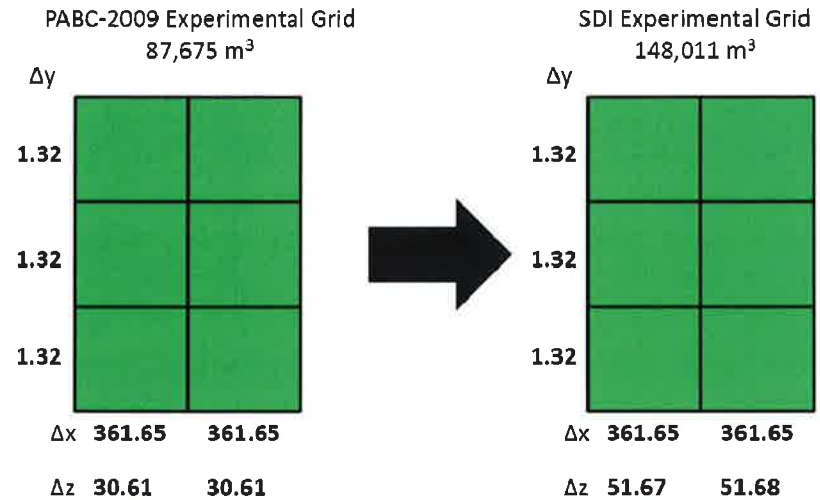


Figure 6-2: SDI BRAGFLO grid changes (Δx, Δy, and Δz dimensions in meters).

During BRAGFLO calculations, stochastic uncertainty is addressed by defining a set of six scenarios for which brine and gas flow is calculated for each of the vectors generated via parameter sampling. The total number of BRAGFLO simulations executed in the SDI impact assessment is 1,800 (300 vectors times 6 scenarios).

The six scenarios used in the SDI impact assessment are unchanged from those used for the PABC-2009. The scenarios include one undisturbed scenario (S1-BF), four scenarios that include a single inadvertent future drilling intrusion into the repository during the 10,000 year regulatory period (S2-BF to S5-BF), and one scenario investigating the effect of two intrusions into a single waste panel (S6-BF). Two types of intrusions, denoted as E1 and E2, are considered. An E1 intrusion assumes the borehole passes through a waste-filled panel and into a pressurized brine pocket that may exist under the repository in the Castile formation. An E2 intrusion assumes that the borehole passes through the repository but does not encounter a brine pocket. Scenarios S2-BF and S3-BF model the effect of an E1 intrusion occurring at 350 years and 1000 years, respectively, after the repository is closed. Scenarios S4-BF and S5-BF model the effect of an E2 intrusion at 350 and 1000 years. Scenario S6-BF models an E2 intrusion occurring at 1000 years, followed by an E1 intrusion into the same panel at 2000 years. Transport releases to the Culebra are captured in Scenario S6-BF. Transport releases from the Culebra obtained in the PABC-2009 are also used in the SDI impact assessment. However, results from BRAGFLO scenario S6-BF are briefly discussed in this report for the sake of completeness. In the Salado flow results that follow, summary statistics and plots were generated with Matlab, a commercial off-the-shelf software package. Matlab files used in the SDI impact assessment are included on a cd submitted with this summary report. BRAGFLO scenarios considered in the SDI impact assessment are summarized in Table 1.

Table 1: BRAGFLO Modeling Scenarios

Scenario	Description
S1-BF	Undisturbed Repository
S2-BF	E1 intrusion at 350 years
S3-BF	E1 intrusion at 1,000 years
S4-BF	E2 intrusion at 350 years
S5-BF	E2 intrusion at 1,000 years
S6-BF	E2 intrusion at 1,000 years; E1 intrusion at 2,000 years.

BRAGFLO results are presented for the SDI impact assessment and compared with those obtained in the PABC-2009. Results are discussed in terms of overall means. Overall means are obtained by forming the average of the 300 realizations calculated for a given quantity and scenario. Results are presented for undisturbed scenario S1-BF. Results associated with intrusions are presented for scenarios S2-BF and S4-BF, as these are representative of the intrusion types considered in scenarios S2-BF to S5-BF with the only differences being the timing of drilling intrusions. Results from BRAGFLO scenario S6-BF are also discussed.

The overall means of pressure in the experimental area, denoted by quantity EXP_PRES, are shown in Figure 6-3 for undisturbed scenario S1-BF, and Figure 6-4, Figure 6-5, Figure 6-6 for intrusion scenarios S2-BF, S4-BF, and S6-BF, respectively. As seen in those figures, the additional volume in the SDI calculations results in a reduction in the average pressure in the experimental area for all scenarios when compared to PABC-2009 results.

Reduced pressure in the experimental area combined with the long WIPP regulatory period of 10,000 years results in eventual lower average pressure in the waste panel as compared to PABC-2009 results. The reduction in average waste panel pressure, denoted by quantity WAS_PRES, for undisturbed scenario S1-BF is illustrated in Figure 6-7. Eventual pressure reductions in the waste panel are also seen for E1 intrusion scenarios (Figure 6-8), E2 intrusion scenarios (Figure 6-9), and the E2E1 intrusion scenario (Figure 6-10).

A probable consequence of lower average pressure in the waste panel is a corresponding increase in the average cumulative flow of brine into the panel, denoted by quantity BRNWASIC. As seen in Figure 6-11 through Figure 6-14, the reduction in average pressure in the waste panel does indeed yield slight increases in the total amount of brine entering the panel for both undisturbed and disturbed conditions. These slight increases of brine flow into the panel result in slight increases in the average panel brine saturation, denoted by quantity WAS_SATB. As seen for the undisturbed case shown in Figure 6-15 and the intrusion scenario results shown in Figure 6-16 through Figure 6-18, the average brine saturation in the waste panel is slightly increased for all scenarios considered in the SDI impact assessment as compared to the PABC-2009.

Summary statistics for the SDI BRAGFLO results discussed above are shown in Table 2. In that table, mean and maximum values for a given quantity are calculated over all 300 vectors. As the brine saturation in the waste panel only varies between 0 and 1, values in Table 2 for that quantity are listed to three decimal places to make differences between analyses more apparent.

Table 2: BRAGFLO SDI Summary Statistics

Quantity (units)	Scenario	Mean Value		Maximum Value	
		PABC-2009	SDI	PABC-2009	SDI
EXP_PRES (MPa)	S1-BF	4.46	4.04	15.65	15.15
	S2-BF	4.41	4.04	14.77	14.62
	S4-BF	3.70	3.36	14.70	14.56
	S6-BF	4.18	3.81	14.76	14.63
WAS_PRES (MPa)	S1-BF	6.52	6.34	16.19	16.18
	S2-BF	7.39	7.31	15.63	15.62
	S4-BF	4.64	4.56	14.92	14.68
	S6-BF	5.96	5.88	15.04	14.90
BRNWASIC ($x\ 10^3\ m^3$)	S1-BF	1.78	1.80	12.46	13.24
	S2-BF	14.03	14.10	182.15	186.63
	S4-BF	2.73	2.74	23.81	24.96
	S6-BF	7.71	7.84	180.24	184.55
WAS_SATB (dimensionless)	S1-BF	0.160	0.164	0.985	0.985
	S2-BF	0.677	0.681	0.999	0.999
	S4-BF	0.283	0.285	0.995	0.995
	S6-BF	0.418	0.424	0.999	0.999

Using the BRAGFLO results presented above, the impact of SDI excavation on individual components of release can now be initially discussed. Spallings release volumes are a function of pressure. A reduction in waste panel pressure results in a corresponding reduction in spallings release volumes. Therefore, one would expect that the additional SDI excavation results in a slight decrease in spallings releases as compared to the PABC-2009 as both analyses use the same waste inventory. Impacts on spallings releases are quantified in Section 6.2.

The impact of SDI excavation on DBRs is less straightforward. Sufficient pressure and brine saturation in the panel at the time of intrusion are prerequisites for a DBR to occur. In particular, brine saturation in the panel must exceed the residual brine saturation of the waste, a sampled parameter in PA. In addition, the repository pressure near the drilling location must exceed the hydrostatic pressure of the drilling fluid, which is observed at the repository elevation and specified in PA to be 8 MPa. As seen in the SDI BRAGFLO results above, the average waste panel pressure was lowered in all scenarios as compared to the PABC-2009. Thus, one would expect a corresponding reduction in the number of vectors that satisfy the pressure criteria for a DBR. On the other hand, the average brine saturation in the waste panel increased for all scenarios in the SDI calculation. From this, one would expect to see an increase in the number of vectors that satisfy the DBR brine saturation requirement. As a result, the BRAGFLO results shown above are not sufficient to determine the impacts of SDI excavation on DBRs with certainty. Additional analysis is required to quantify these impacts and is provided in Section 6.3.

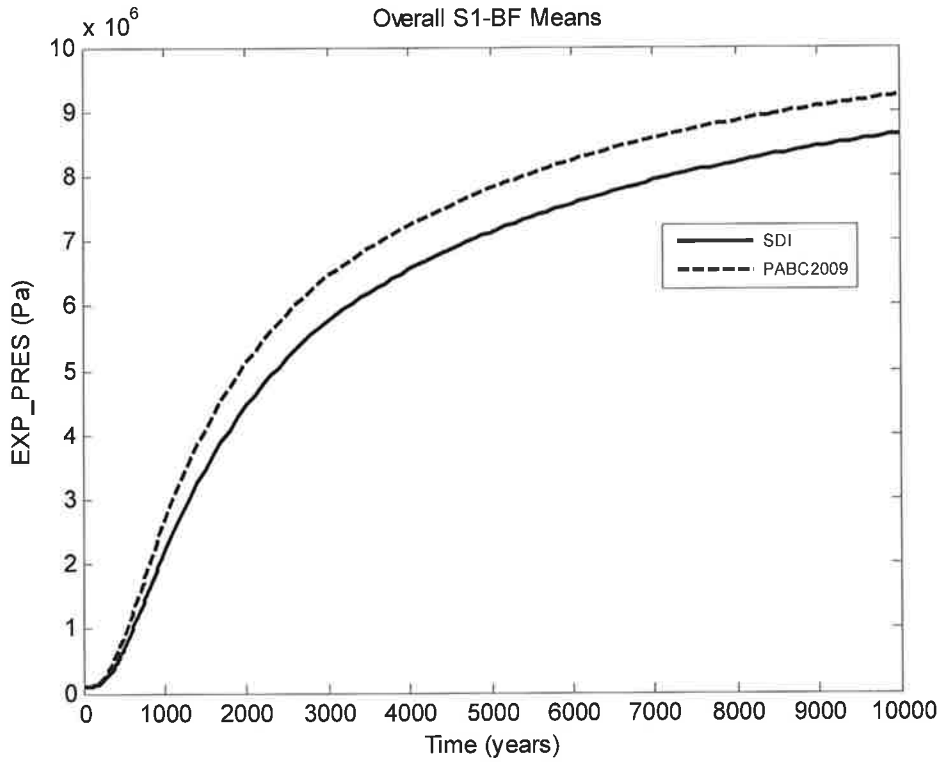


Figure 6-3: Overall Means of Volume Averaged Pressure for the Experimental Region, Scenario S1-BF.

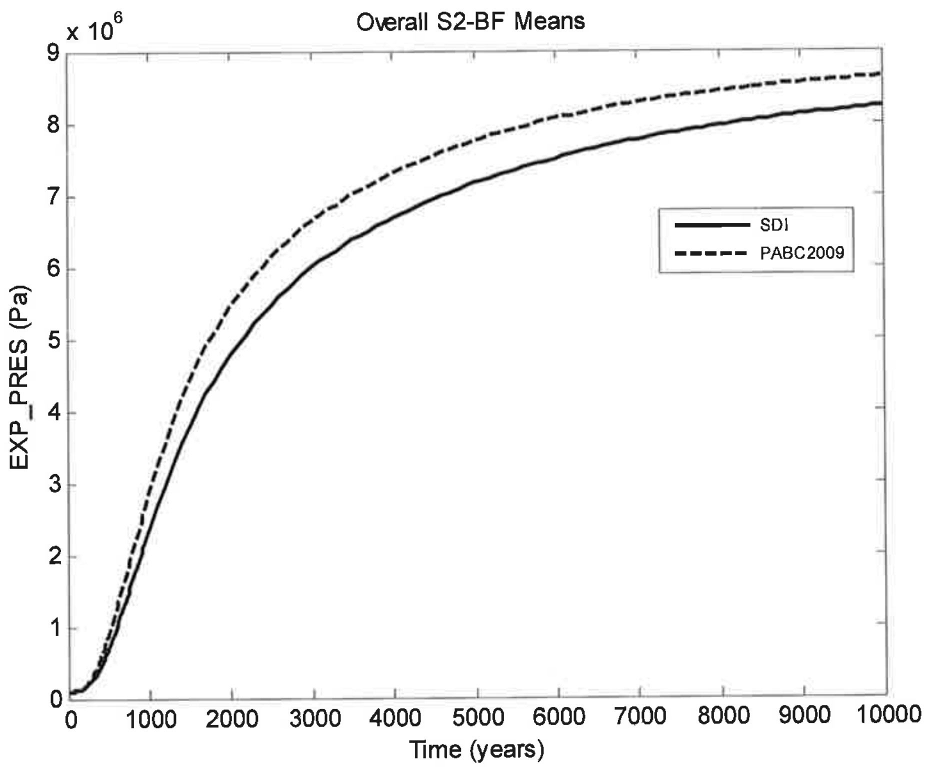


Figure 6-4: Overall Means of Volume Averaged Pressure for the Experimental Region, Scenario S2-BF.

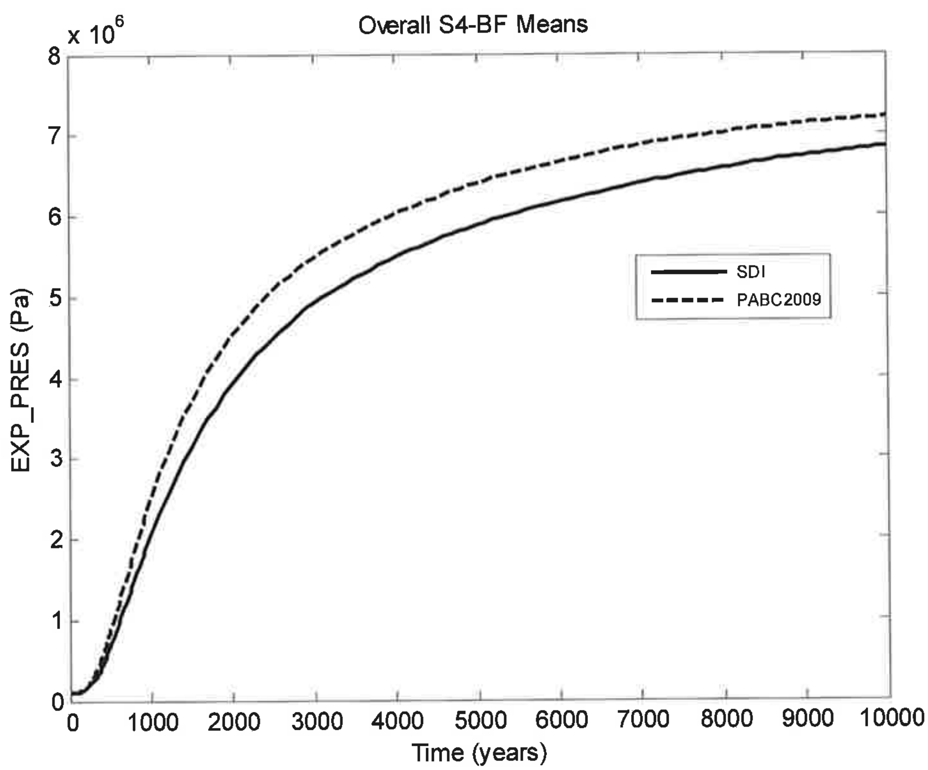


Figure 6-5: Overall Means of Volume Averaged Pressure for the Experimental Region, Scenario S4-BF.

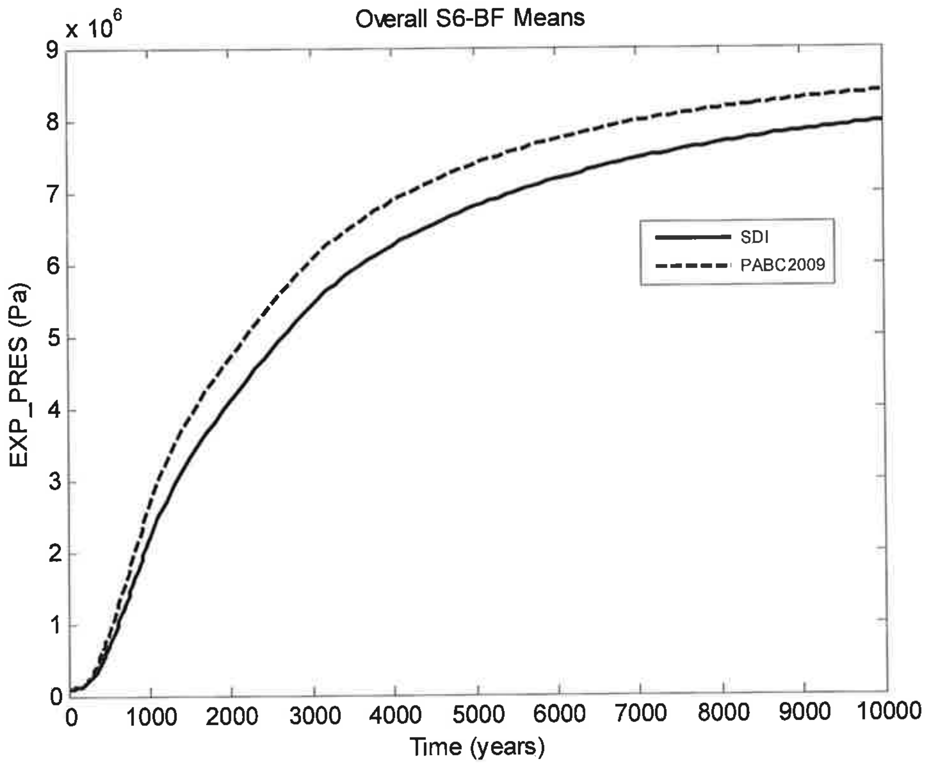


Figure 6-6: Overall Means of Volume Averaged Pressure for the Experimental Region, Scenario S6-BF.

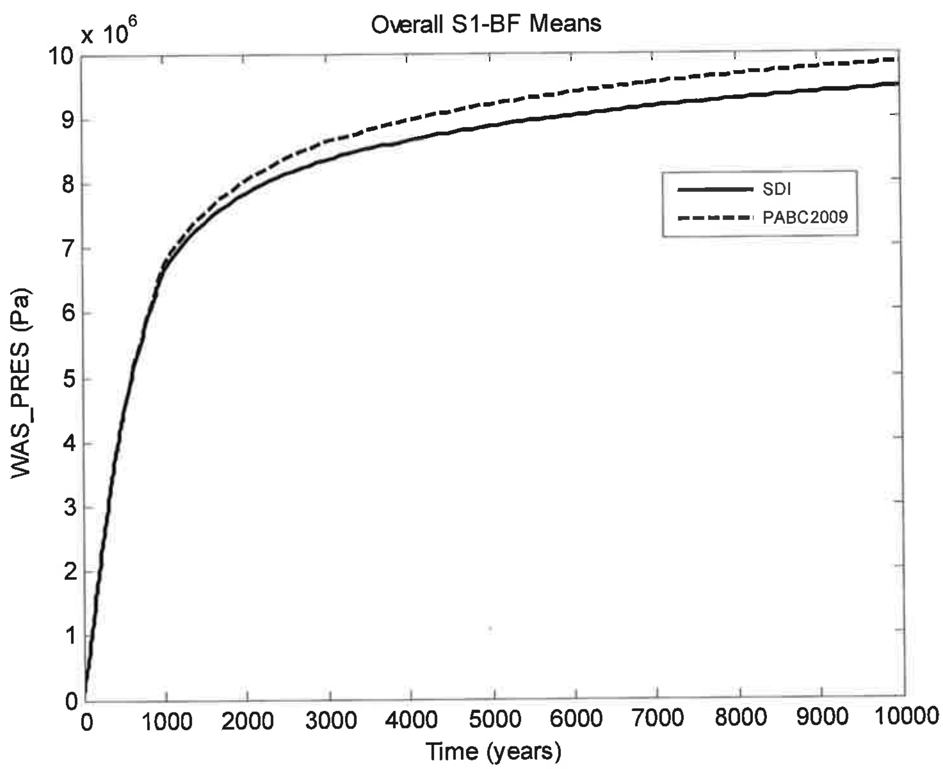


Figure 6-7: Overall Means of Volume Averaged Pressure for the Waste Panel, Scenario S1-BF.

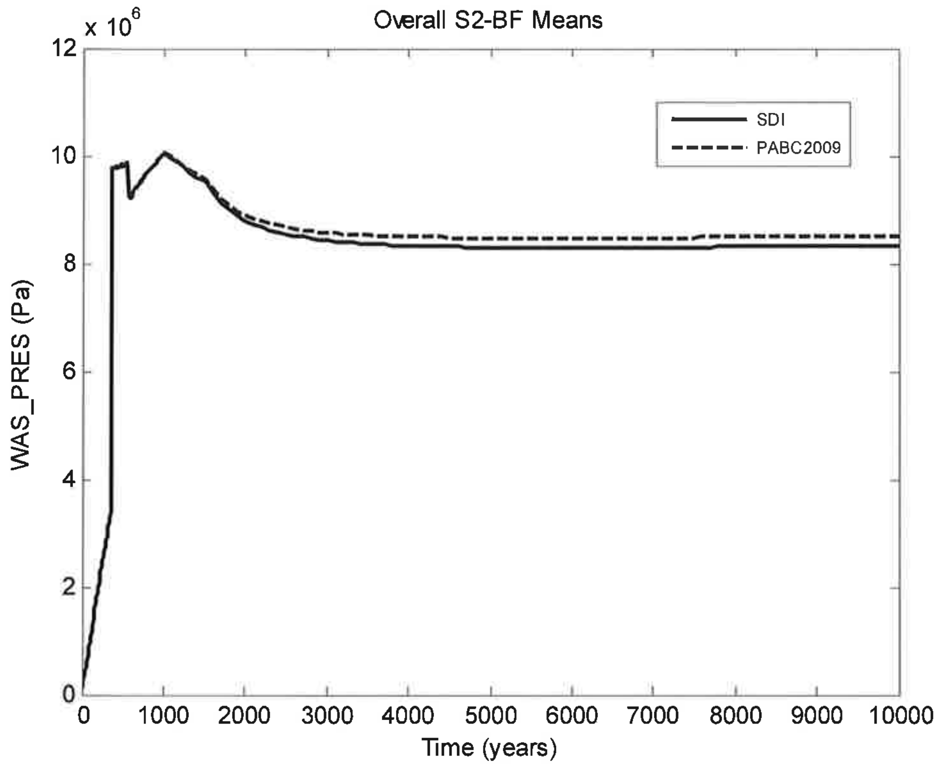


Figure 6-8: Overall Means of Volume Averaged Pressure for the Waste Panel, Scenario S2-BF.

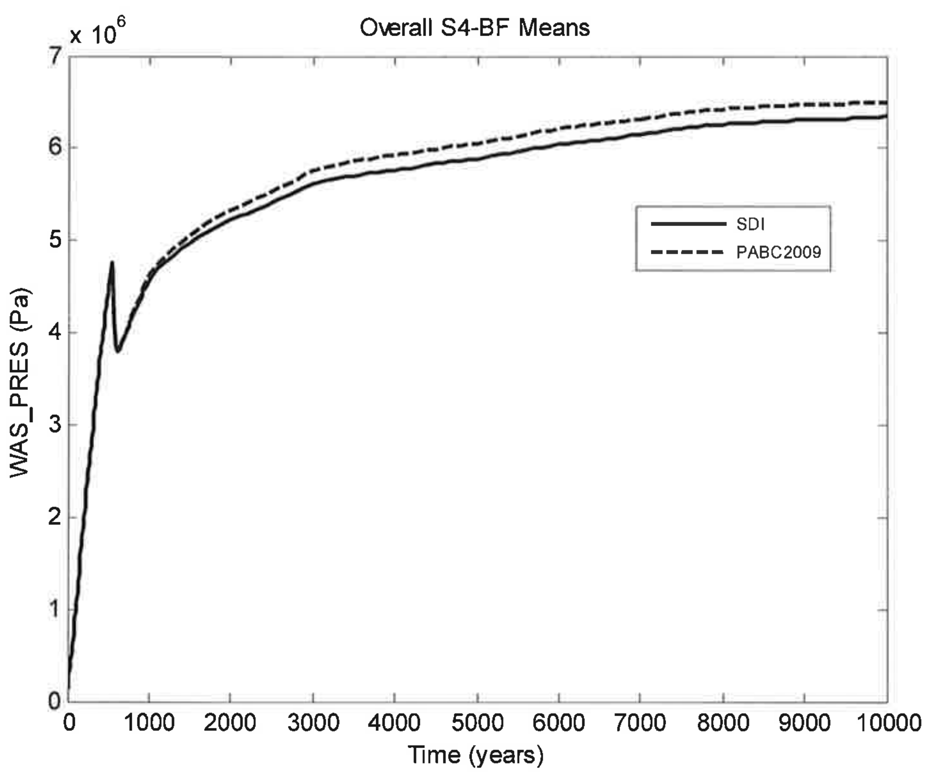


Figure 6-9: Overall Means of Volume Averaged Pressure for the Waste Panel, Scenario S4-BF.

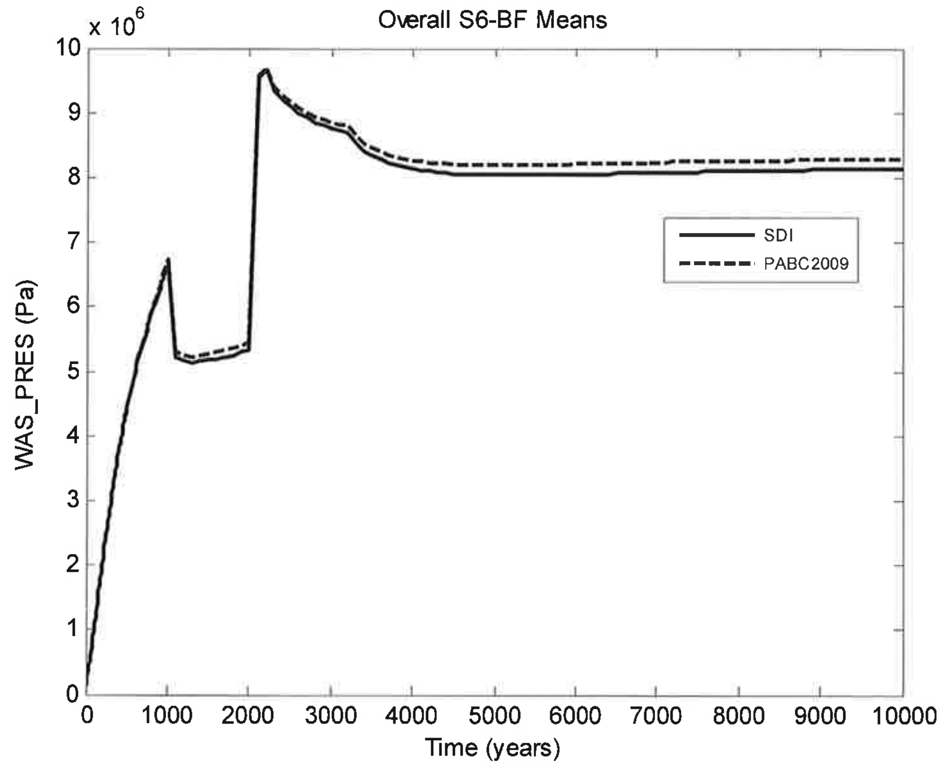


Figure 6-10: Overall Means of Volume Averaged Pressure for the Waste Panel, Scenario S6-BF.

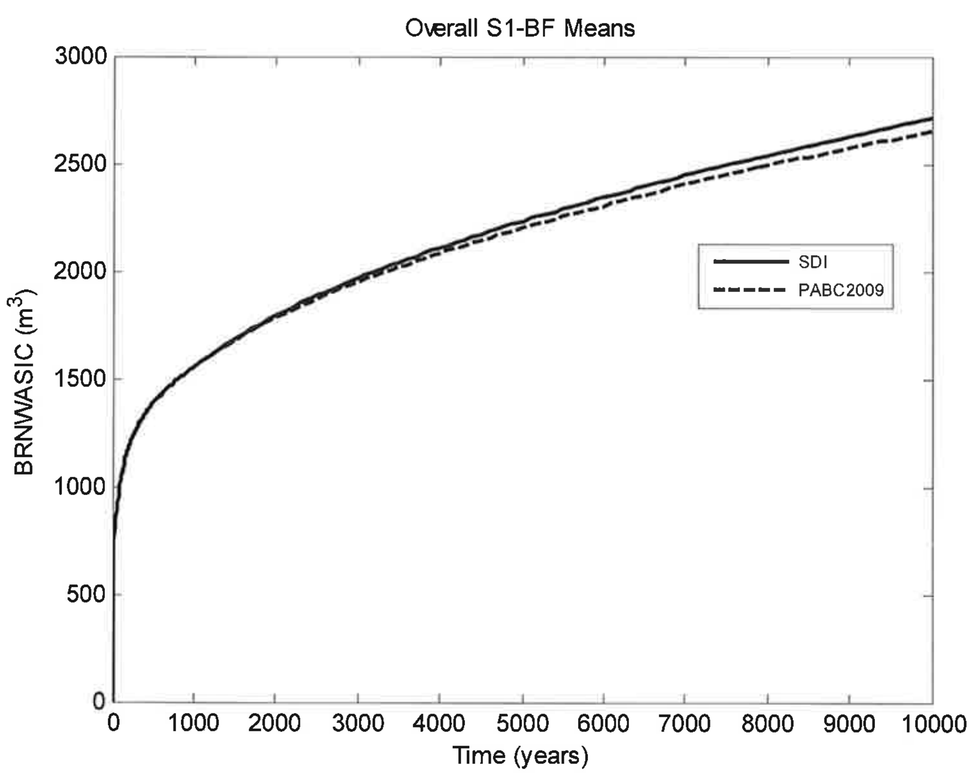


Figure 6-11: Overall Means of Total Brine Flow Into the Waste Panel, Scenario S1-BF

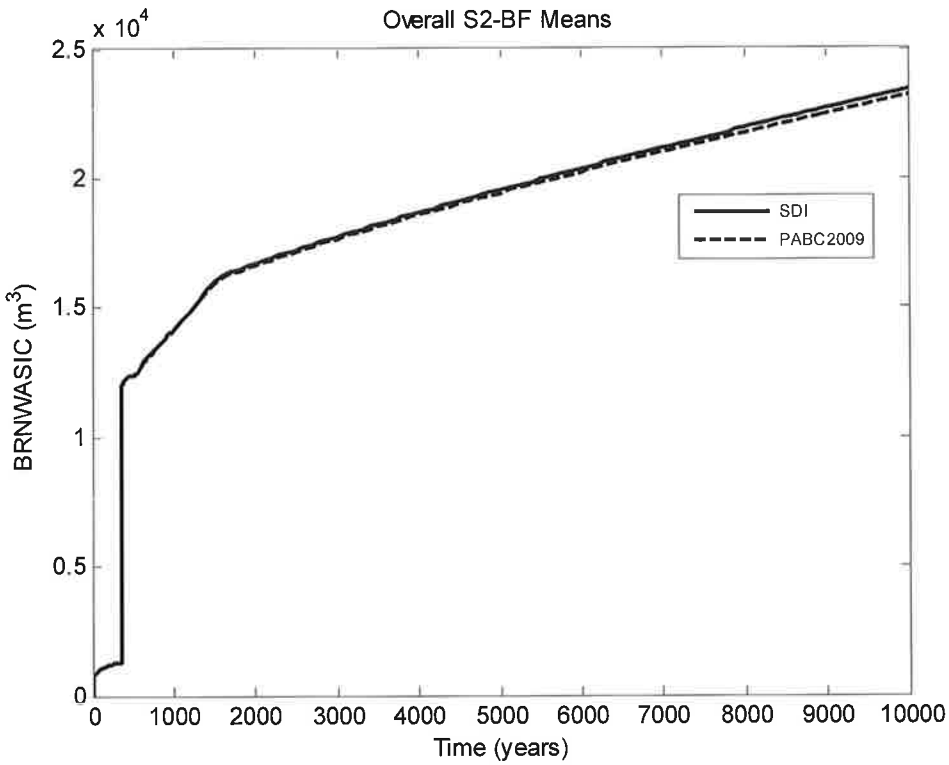


Figure 6-12: Overall Means of Total Brine Flow Into the Waste Panel, Scenario S2-BF

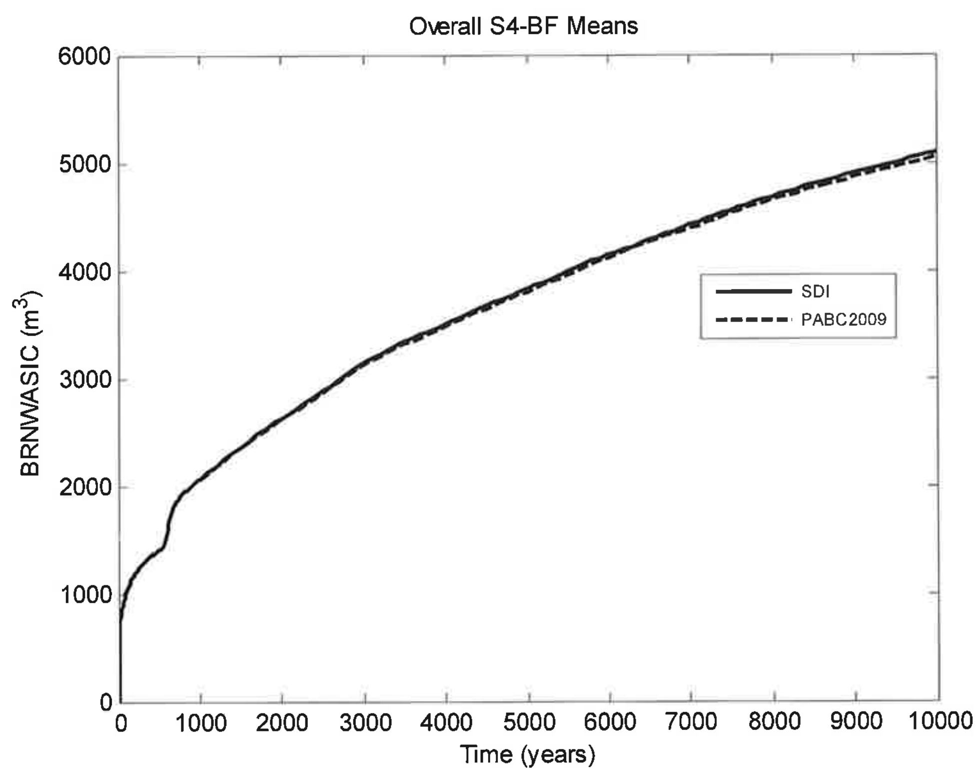


Figure 6-13: Overall Means of Total Brine Flow Into the Waste Panel, Scenario S4-BF

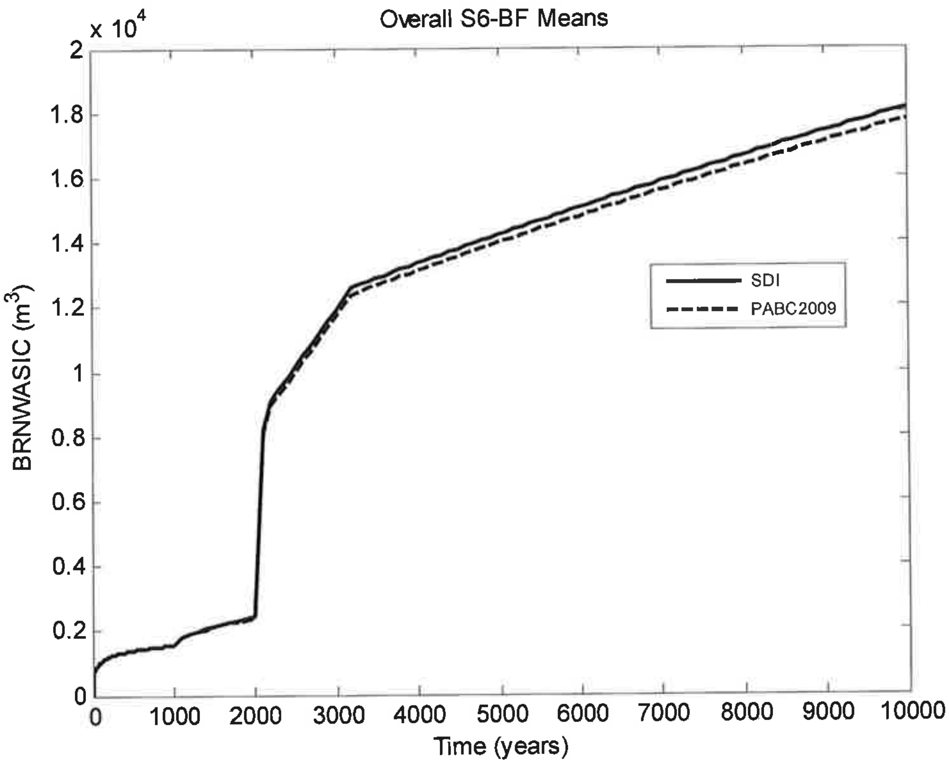


Figure 6-14: Overall Means of Total Brine Flow Into the Waste Panel, Scenario S6-BF

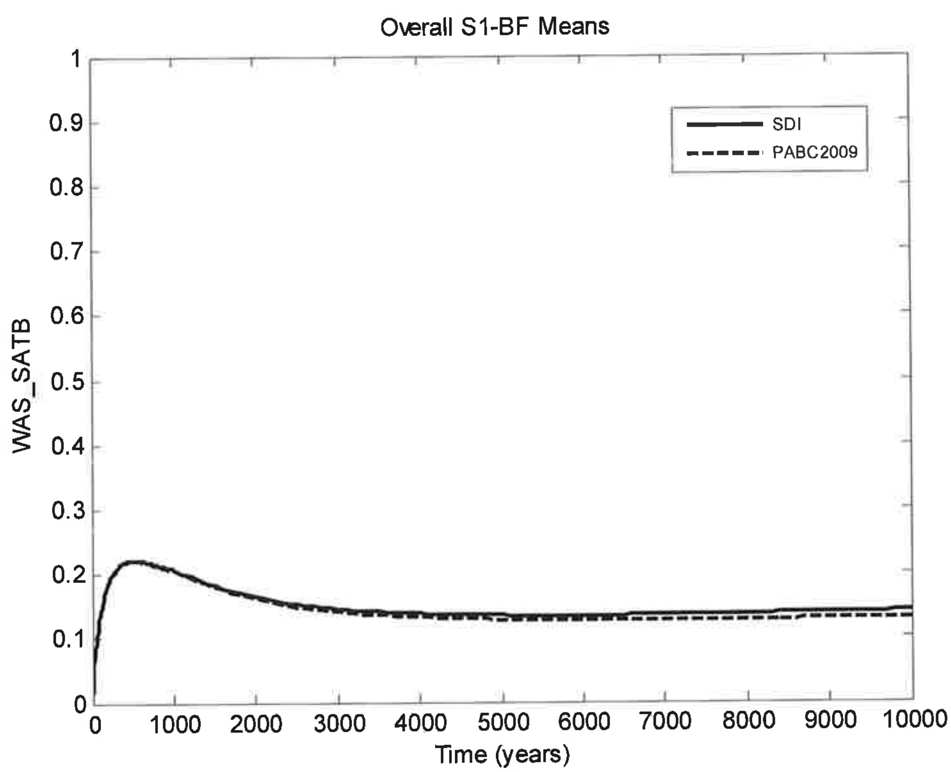


Figure 6-15: Overall Means of Brine Saturation in the Waste Panel, Scenario S1-BF

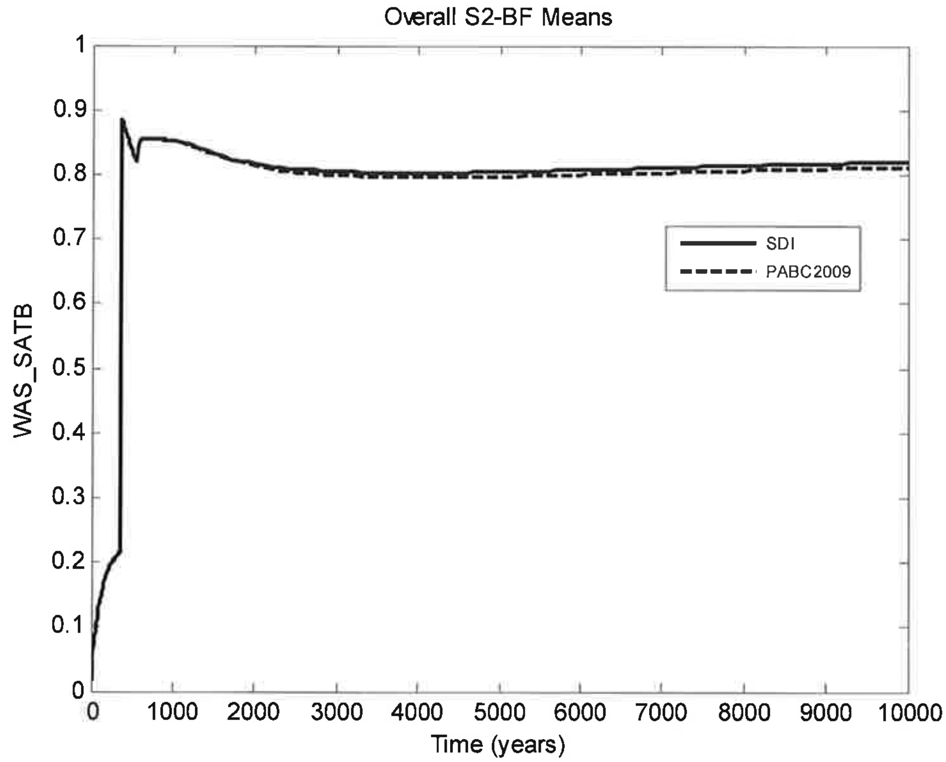


Figure 6-16: Overall Means of Brine Saturation in the Waste Panel, Scenario S2-BF

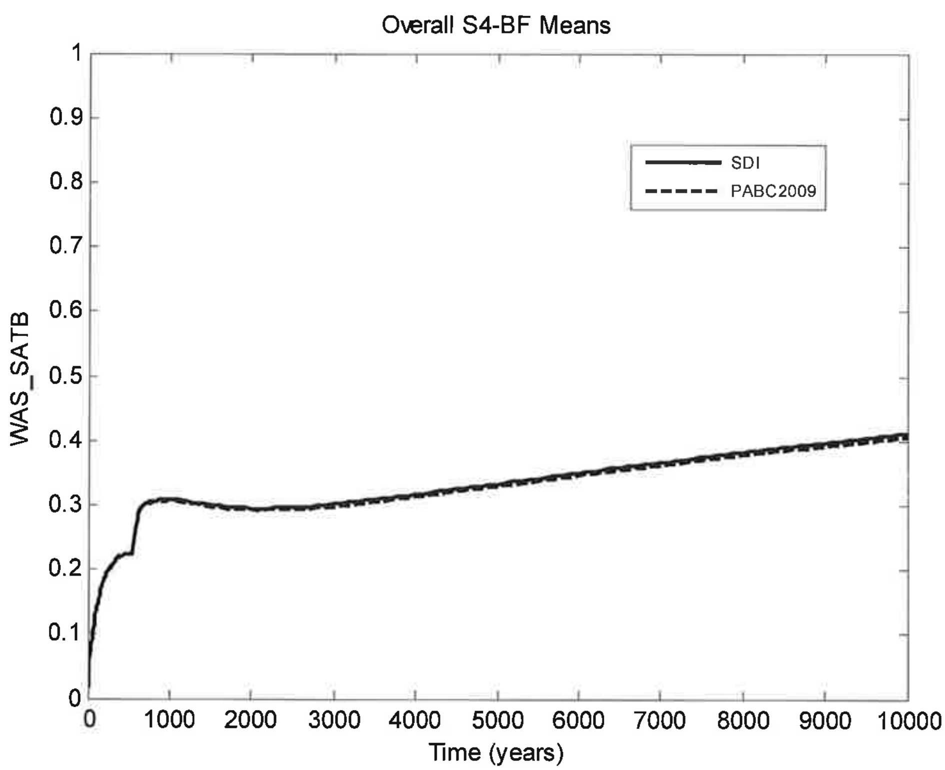


Figure 6-17: Overall Means of Brine Saturation in the Waste Panel, Scenario S4-BF

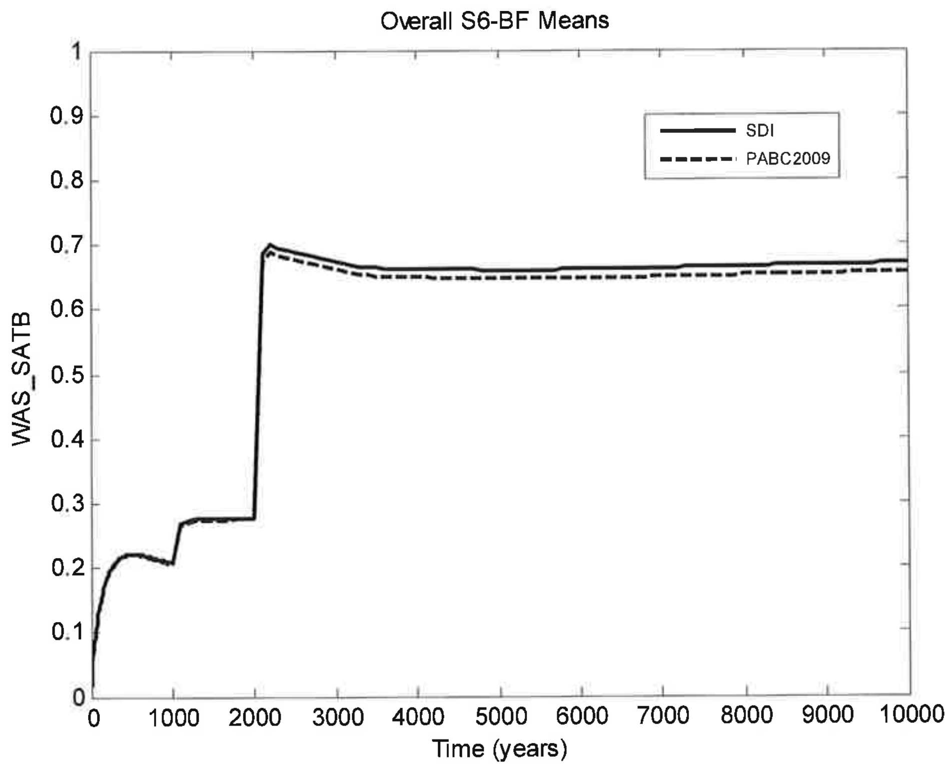


Figure 6-18: Overall Means of Brine Saturation in the Waste Panel, Scenario S6-BF

6.2 Spallings

Calculation of the volume of solid waste material released to the surface from a single drilling intrusion into the repository due to spallings is a two-part procedure. First, the code DRSPALL calculates the spallings volumes from a single drilling intrusion at four values of repository pressure (10, 12, 14, and 14.8 MPa). The second step in calculating spallings volumes from a single intrusion consists of using the code CUTTINGS_S to interpolate between DRSPALL volumes. The spallings volume for a given vector is determined in CUTTINGS_S by linearly interpolating between volumes calculated by DRSPALL based on the pressure calculated in each realization by BRAGFLO. DRSPALL volumes used in the PABC-2009 were also used in the SDI impact assessment.

PA code CUTTINGS_S is also used as a transfer program between the BRAGFLO Salado flow calculation and the BRAGFLO DBR calculation. Results obtained by BRAGFLO for each realization in scenarios S1-BF to S5-BF are used to initialize the flow field properties necessary for the calculation of DBRs. This requires that results obtained on the BRAGFLO grid be mapped appropriately to the DBR grid. Code CUTTINGS_S is used to transfer the appropriate scenario results obtained with BRAGFLO to the DBR calculation. These transferred flow results are used as initial conditions in the calculation of DBRs. As a result, intrusion scenarios and times used in the calculation of spallings volumes correspond to those used in the calculation of DBRs. Five intrusion scenarios are considered in the DBR calculations, and are listed in Table 3.

Table 3: PA Intrusion Scenarios Used in Calculating Direct Solids Releases

Scenario	Conditioning (or 1st) Intrusion Time (year) and Type	Intrusion Times – Subsequent (year)
S1-DBR	None	100, 350, 1000, 3000, 5000, 10000
S2-DBR	350, E1	550, 750, 2000, 4000, 10000
S3-DBR	1000, E1	1200, 1400, 3000, 5000, 10000
S4-DBR	350, E2	550, 750, 2000, 4000, 10000
S5-DBR	1000, E2	1200, 1400, 3000, 5000, 10000

While CUTTINGS_S uses these standard DBR scenarios as a basis for its calculations, it does so to provide flow field results (generated with BRAGFLO) as initial conditions to the DBR calculation at each subsequent intrusion time. CUTTINGS_S does not model the intrusion scenario itself. Scenario S1-DBR corresponds to an initial intrusion into the repository, with repository flow conditions at the time of intrusion transferred from BRAGFLO scenario S1-BF results. Scenarios S2-DBR through S5-DBR are used to model an intrusion into a repository that has already been penetrated. The times at which intrusions are assumed to occur for each scenario are outlined in the last column of Table 3; six intrusion times are modeled for scenario S1-DBR, while five times are modeled for each of scenarios S2-DBR through S5-DBR.

Utilizing the spallings volumes calculated by DRSPALL and the SDI repository pressures calculated by BRAGFLO, the impact of SDI excavation on spallings volumes can be determined. Summary statistics of spallings volumes for the intrusion scenarios considered by CUTTINGS_S are shown in Table 4 for both the SDI impact assessment and the PABC-2009. PABC-2009 results reported in that table are taken from Ismail (2010). As seen in that table, values obtained in the SDI impact assessment are generally equal or lower overall when compared to those obtained in the PABC-2009. For scenario S1-DBR, a consistent reduction in the number of nonzero spallings volumes is seen across replicates R1 – R3 in the SDI impact assessment. Moreover, the average and maximum spallings volumes seen in that scenario are lower in all three replicates for the SDI calculation. Similar reductions are evident in scenarios S2-BF to S5-BF. Overall, the general trend is an equal or lower maximum volume, an equal or lower average volume, and a lower percentage of vectors resulting in nonzero spallings volumes in the SDI calculation than were seen in the PABC-2009.

Spallings volumes are a function of repository pressure. Previous analyses have determined that no tensile failure of repository material occurs at initial repository pressures less than 10 MPa, and that no spallings are observed at pressures less than 13 MPa (Lord et al 2003). Thus, waste failure and subsequent transport for spallings is assumed to be non-existent for repository pressures less than 10 MPa. As seen in the BRAGFLO results in Section 6.1, additional excavation in the WIPP experimental area for SDI translates to an eventual pressure reduction in waste-containing regions. As there is a minimum threshold pressure of 10 MPa required for a spallings release, a decrease in repository pressure also decreases the percentage of vectors with nonzero spallings volumes.

Table 4: Summary of Spallings Releases by Scenario

		Scenarios					Total
		S1-DBR	S2-DBR	S3-DBR	S4-DBR	S5-DBR	
SDI PA							
R1	Maximum [m^3]	1.67	8.29	7.98	1.67	1.67	8.29
R1	Average nonzero volume [m^3]	0.35	0.54	0.55	0.29	0.37	0.43
R1	Number of nonzero volumes	127	105	99	58	74	463
R1	Percent of nonzero volumes	7.1%	7.0%	6.6%	3.9%	4.9%	5.9%
R2	Maximum [m^3]	2.17	2.74	1.73	2.26	1.93	2.74
R2	Average nonzero volume [m^3]	0.28	0.35	0.34	0.42	0.40	0.34
R2	Number of nonzero volumes	145	100	108	54	80	487
R2	Percent of nonzero volumes	8.1%	6.7%	7.2%	3.6%	5.3%	6.2%
R3	Maximum [m^3]	3.66	6.20	2.48	0.85	1.08	6.20
R3	Average nonzero volume [m^3]	0.41	0.38	0.23	0.24	0.23	0.32
R3	Number of nonzero volumes	140	92	98	36	63	429
R3	Percent of nonzero volumes	7.8%	6.1%	6.5%	2.4%	4.2%	5.5%
PABC-2009							
R1	Maximum [m^3]	2.24	8.29	7.97	1.67	1.67	8.29
R1	Average nonzero volume [m^3]	0.37	0.54	0.50	0.30	0.37	0.43
R1	Number of nonzero volumes	142	117	111	59	77	506
R1	Percent of nonzero volumes	7.9%	7.8%	7.4%	3.9%	5.1%	6.5%
R2	Maximum [m^3]	2.36	2.76	1.86	2.26	1.93	2.76
R2	Average nonzero volume [m^3]	0.32	0.39	0.37	0.50	0.47	0.39
R2	Number of nonzero volumes	168	122	122	57	84	553
R2	Percent of nonzero volumes	9.3%	8.1%	8.1%	3.8%	5.6%	7.1%
R3	Maximum [m^3]	4.91	6.23	2.62	1.47	1.49	6.23
R3	Average nonzero volume [m^3]	0.53	0.39	0.28	0.30	0.28	0.38
R3	Number of nonzero volumes	156	113	118	45	72	504
R3	Percent of nonzero volumes	8.7%	7.5%	7.9%	3.0%	4.8%	6.5%

The impacts of the changes in spallings volumes on the overall mean CCDF for normalized spallings releases obtained in the SDI impact assessment can be seen in Figure 6-19. As seen in that figure, the CCDF of spallings releases obtained in the SDI impact assessment is consistently lower than that found in the PABC-2009. The overall reduction in spallings volumes and in the number of vectors that result in a nonzero spallings volume translate to a reduction in spallings releases as both analyses use the same waste inventory.

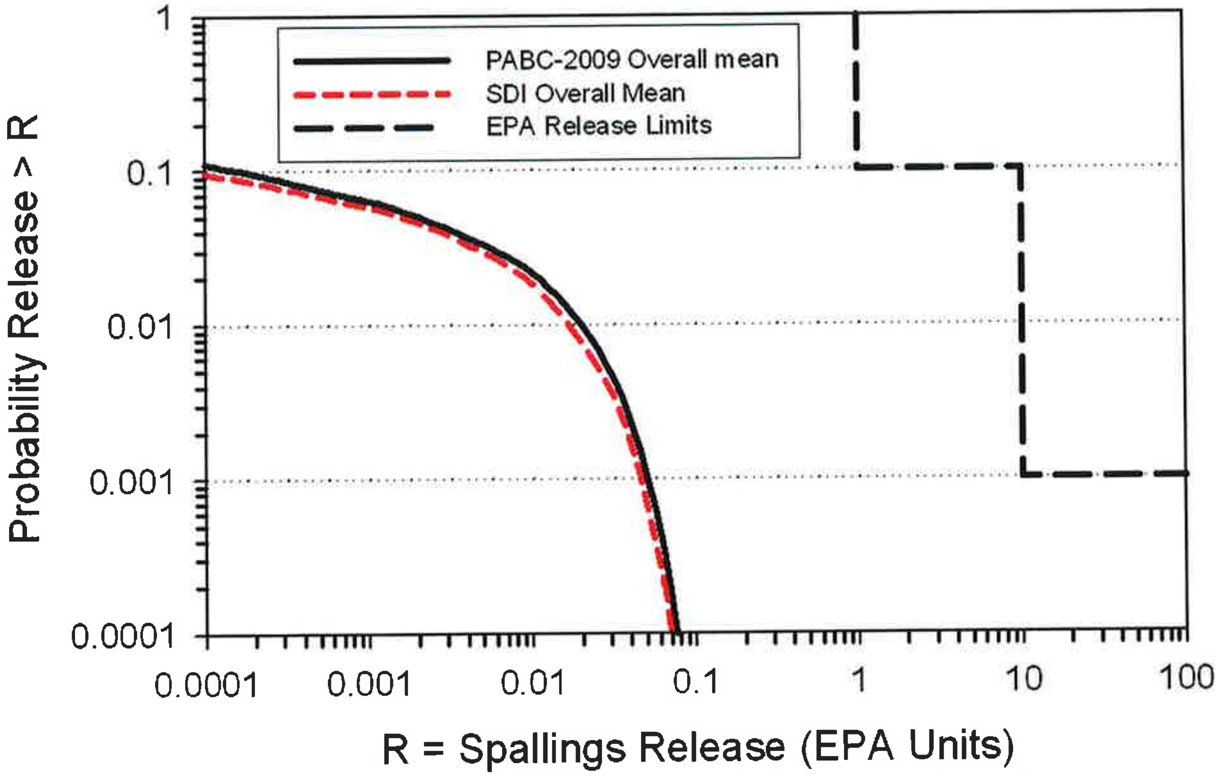
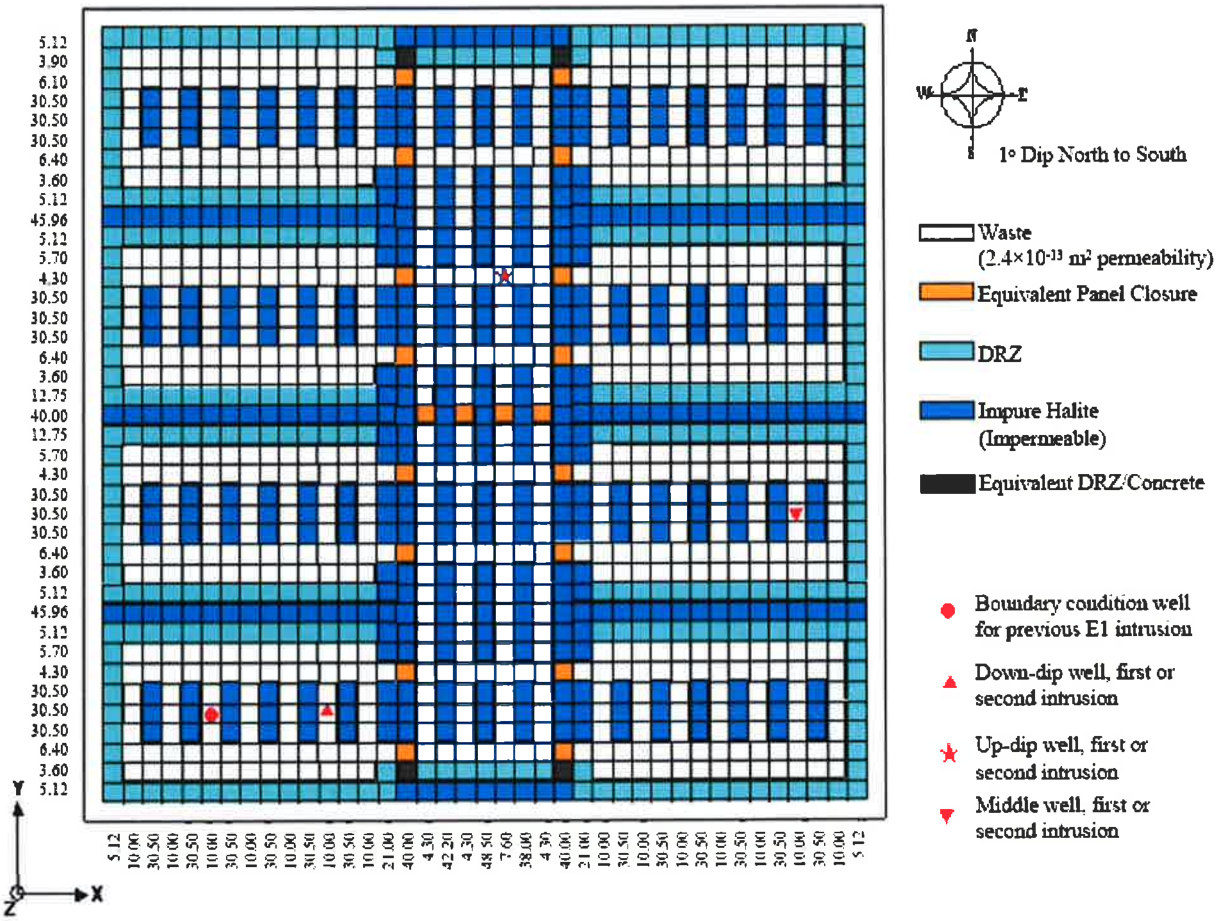


Figure 6-19: SDI and PABC-2009 Overall Mean CCDFs for Normalized Spallings Releases

6.3 Direct Brine Releases

PA code BRAGFLO is used in two ways in WIPP PA calculations. First, it is used to calculate the flow of brine and gas in and around the repository for undisturbed and disturbed conditions. SDI results from this application of BRAGFLO are shown in Section 6.1. Second, it is used for the calculation of direct brine releases. These two uses of BRAGFLO require different computational grids. The grid used to calculate brine and gas flow in and around the repository is different than that used to calculate DBRs. However, results obtained from the brine and gas flow calculation are used to initialize conditions in the DBR calculation. The representation of the waste area by three regions in the SDI and PABC-2009 BRAGFLO grids (see Figure 6-1) yields initial conditions to waste regions comprising the waste panel (panel 5), the South Rest of Repository or SROR (panels 3,4,6, and 9), and the North Rest of Repository or NROR (panels 1,2,7,8, and 10) in the DBR calculation, with drilling intrusions considered in each of these regions. The types of intrusions considered in the DBR calculation and the times at which they occur are listed in Table 3. The DBR computational grid and drilling locations used for the SDI impact assessment are identical to those used in the PABC-2009, and are shown in Figure 6-20.



Note: Model cells are not to scale. The actual dimensions of the grid blocks are indicated along the edge of the diagram.

Figure 6-20: SDI and PABC-2009 DBR material map (logical grid).

With the DBR computational grid and intrusion locations in hand, DBR results from the SDI impact assessment and the PABC-2009 can now be compared. Summary statistics of the calculated DBR volumes for replicates 1-3 and scenarios S1-DBR to S5-DBR are provided in Table 5. As was also the case in the PABC-2009, release volumes less than 1×10^{-7} m^3 are considered to be inconsequential and are not included in the tally of vectors that result in DBR release volumes in the SDI calculations. In Table 5, maximums shown are the maximum DBR volumes calculated over all replicates, times, vectors and drilling locations. As seen by the statistics for the maximum DBR volumes in Table 5, the additional excavation to the WIPP experimental area for SDI results in a decrease in the maximum DBR volume as compared to the PABC-2009. The maximum DBR volume realized in the PABC-2009 was 48.2 m^3 while that seen in the SDI impact assessment is 42.3 m^3. Additionally, the average DBR volume remained equal or decreased in the SDI impact assessment for all scenarios considered. When calculated over all intrusion scenarios and all nonzero releases, the average volumes are the same at 0.9 m^3 in the PABC-2009 and in the SDI impact assessment. As seen in the BRAGFLO results of Section 6.1, a reduction in the average pressure with a corresponding increase in average brine saturation was seen in waste-containing regions for all scenarios considered in the Salado flow calculation. These changes effectively cancel each other out in the DBR calculation, resulting in equal average DBR volumes in the SDI and PABC-2009 results. These changes have a slight impact on the number of vectors resulting in nonzero DBR volumes, however. In the PABC-2009, a total of 2,999 vectors resulted in a nonzero DBR volume realization. The number of vectors resulting in nonzero DBR volumes in the SDI impact assessment is 2,880, a reduction by 119 vectors when compared to the PABC-2009 results.

Table 5: PABC-2009 and SDI PA DBR Volume Statistics

Scenario	Maximum Volume (m^3)		Average Volume (m^3)		Number of Vectors	
	PABC-2009	SDI PA	PABC-2009	SDI PA	PABC-2009	SDI PA
S1-DBR	27.6	18.5	0.1	0.1	369	356
S2-DBR	48.2	42.3	2.8	2.7	1179	1139
S3-DBR	40.6	42.1	1.5	1.5	926	901
S4-DBR	20.4	18.9	0.1	0.0	211	198
S5-DBR	21.1	21.3	0.1	0.1	314	286
S1-DBR to S5-DBR	48.2	42.3	0.9	0.9	2999	2880

DBR releases are less likely to occur during upper drilling intrusions when compared with the lower drilling location. Of all the intrusions that had a non-zero DBR volume for the SDI impact assessment, 67.3% occurred during a lower drilling intrusion. Furthermore, of all the intrusions that had a non-zero DBR volume and occurred during a lower drilling intrusion, 83.4% are found in scenarios S2-DBR and S3-DBR. Therefore, the majority of the non-zero DBR volumes occur when there is a previous E1 intrusion within the same panel. Not only are DBRs less likely to occur during upper drilling intrusions, but also the DBR volumes from such intrusions tend to be much smaller than DBR volumes compared to those of lower drilling intrusions. For all three replicates of the SDI impact assessment, the maximum DBR volume for the upper drilling location is 13.4 m^3 compared to 42.3 m^3 for the lower drilling location. These observations support the conclusion that lower drilling intrusions are the primary source for significant DBRs. This trend is similarly seen in the PABC-2009 DBR results.

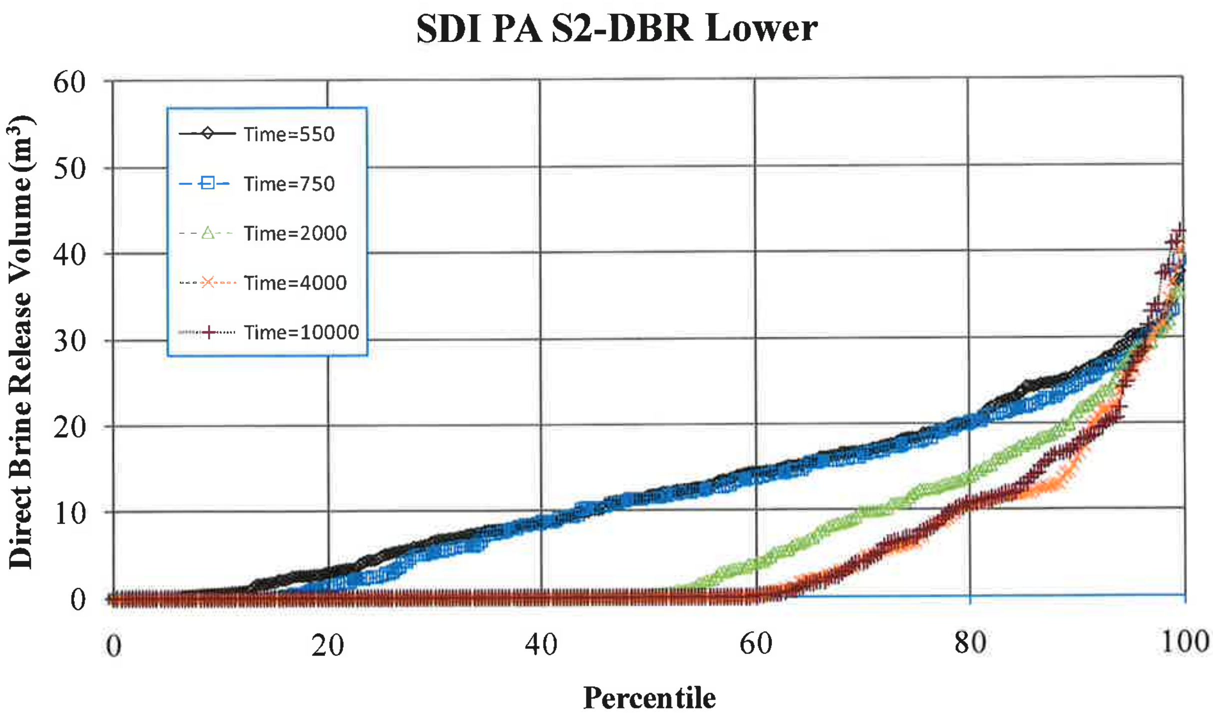


Figure 6-21: All replicates for SDI scenario S2-DBR lower intrusions.

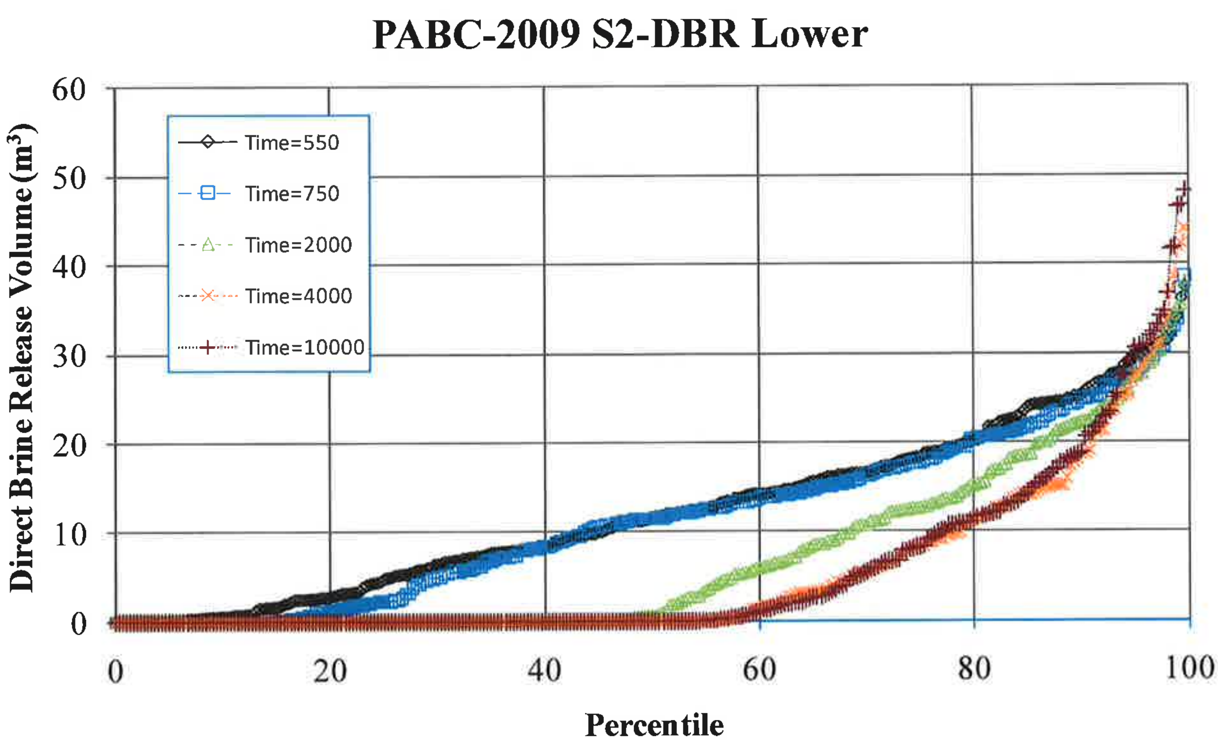


Figure 6-22, All replicates for PABC 2009 scenario S2-DBR lower intrusions

The marked similarity in DBR volumes and trends between the PABC 2009 and the SDI impact assessment is apparent by comparing S2-DBR volume percentiles. Figure 6-21 and Figure 6-22 present these results for the SDI impact assessment and the PABC-2009 across all three replicates at the five times listed in Table 3. Those figures show the percentage of vectors on the X-axis where DBR volumes are less than the value on the Y-axis. As is evident, all significant aspects of these curves are almost identical, with the exception of the maximum DBR volume attained. SDI impact assessment maximum volumes are slightly lower than for the PABC 2009 results.

Figure 6-23 presents DBR volumes versus intruded panel pressure for all replicate 1, scenario S2-DBR lower intrusions. For a nonzero DBR volume to be realized, the repository pressure near the drilling location must exceed the hydrostatic pressure of the drilling fluid, which is specified in PA to be 8 MPa. As a result, there are no releases at panel pressures less than 8 MPa in Figure 6-23. The data in that figure are segregated into mobile brine saturation fractions, for which higher numbers indicate more mobile brine available to flow up an intrusion borehole. It is noted in this figure that low mobile brine values lead to low DBR releases, as expected.

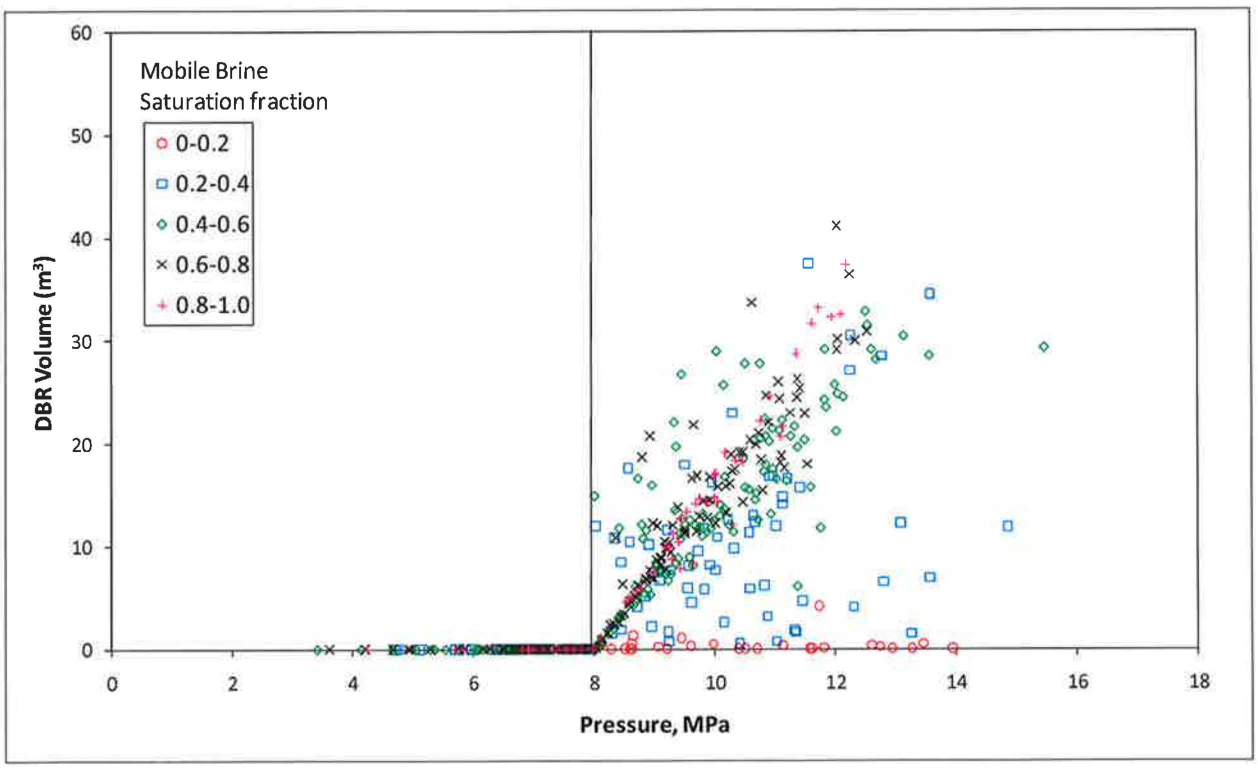


Figure 6-23: SDI DBR Volume vs. Pressure, Scenario S2-DBR, Replicate 1, Lower Intrusion

To further facilitate comparisons of DBRs calculated in the SDI impact assessment to those obtained in the PABC-2009, the overall mean CCDFs obtained in these two analyses are plotted simultaneously in Figure 6-24. As seen in that figure, the CCDF curves obtained for direct brine releases in the PABC-2009 and the SDI impact assessment are virtually identical. Additional excavation in the WIPP experimental area for SDI has slight impacts on pressures and brine saturations in waste-containing regions. These slight changes impact the number of vectors that result in nonzero DBR volumes, with slight reductions seen in the SDI impact assessment. Taken collectively, however, these slight changes result in negligible differences between the DBR CCDF curve obtained in the SDI impact assessment and that found in the PABC-2009.

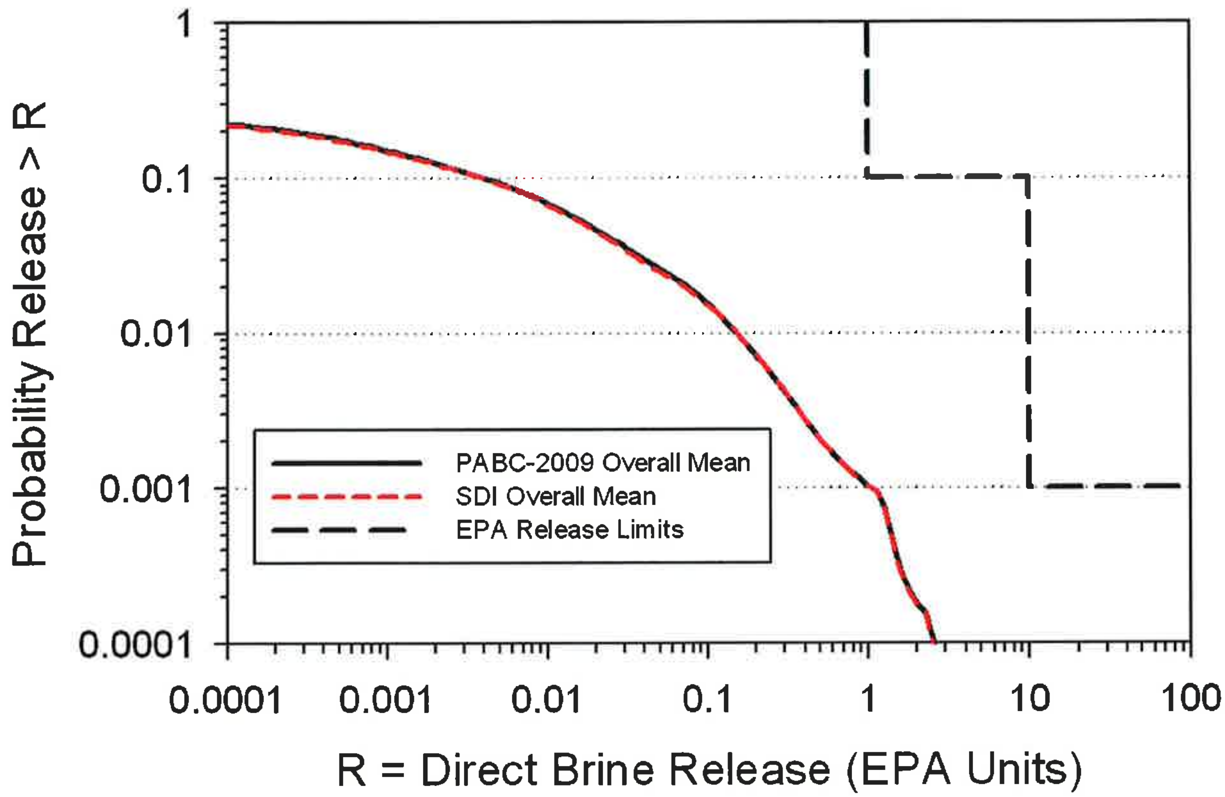


Figure 6-24: SDI and PABC-2009 Overall Mean CCDFs for Normalized Direct Brine Releases

6.4 Total Normalized Releases

Total normalized releases for the SDI impact assessment are presented in this section and subsequently compared to results obtained in the PABC-2009. Total releases are calculated by forming the summation of releases across each potential release pathway, namely cuttings and cavings releases, spallings releases, direct brine releases, and transport releases. As prescribed in AP-156 (Camphouse & Kuhlman 2011), transport results obtained in the PABC-2009 are also used in the SDI calculations. SDI CCDFs for total releases are presented in Figure 6-25, Figure 6-26, and Figure 6-27 for replicates 1, 2, and 3, respectively. These curves are virtually unchanged from those found in the PABC-2009. Mean and quantile CCDF distributions for the three replicates are shown together in Figure 6-28. Figure 6-29 contains the 95 percent confidence limits about the overall mean of total releases. As seen in Figure 6-29, the overall mean for normalized total releases and its lower/upper 95% confidence limits are well below acceptable release limits. As a result, the additional SDI excavation in the WIPP experimental area does not result in WIPP non-compliance with the containment requirements of 40 CFR Part 191.

The SDI impact assessment and PABC-2009 overall mean CCDFs for total releases are virtually identical (Figure 6-30). Cuttings and cavings releases and direct brine releases are the two primary release components contributing to total releases found in the SDI calculations (Figure 6-31). Additional excavation in the WIPP experimental area for SDI has no impact on cuttings and cavings releases. Consequently, SDI cuttings and cavings results are unchanged from those found in the PABC-2009. As discussed in Section 6.3, the excavation envisioned for SDI has a negligible impact on direct brine releases.

A comparison of the statistics on the overall mean for total normalized releases obtained in the SDI calculations and the PABC-2009 can be seen in Table 6. In that table, PABC-2009 values are taken from Camphouse (2010). At probabilities of 0.1 and 0.001, values obtained for mean total releases are nearly identical in both analyses and are indistinguishable statistically.

Table 6: SDI PA and PABC-2009 Statistics on the Overall Mean for Total Normalized Releases in EPA Units at Probabilities of 0.1 and 0.001

Probability	Analysis	Mean Total Release	90^{th} Percentile	Lower 95% CL	Upper 95% CL	Release Limit
0.1	SDI PA	0.093	0.15	0.090	0.095	1
	PABC-2009	0.094	0.16	0.091	0.096	1
0.001	SDI PA	1.1	1.0	0.38	1.8	10
	PABC-2009	1.1	1.0	0.37	1.8	10

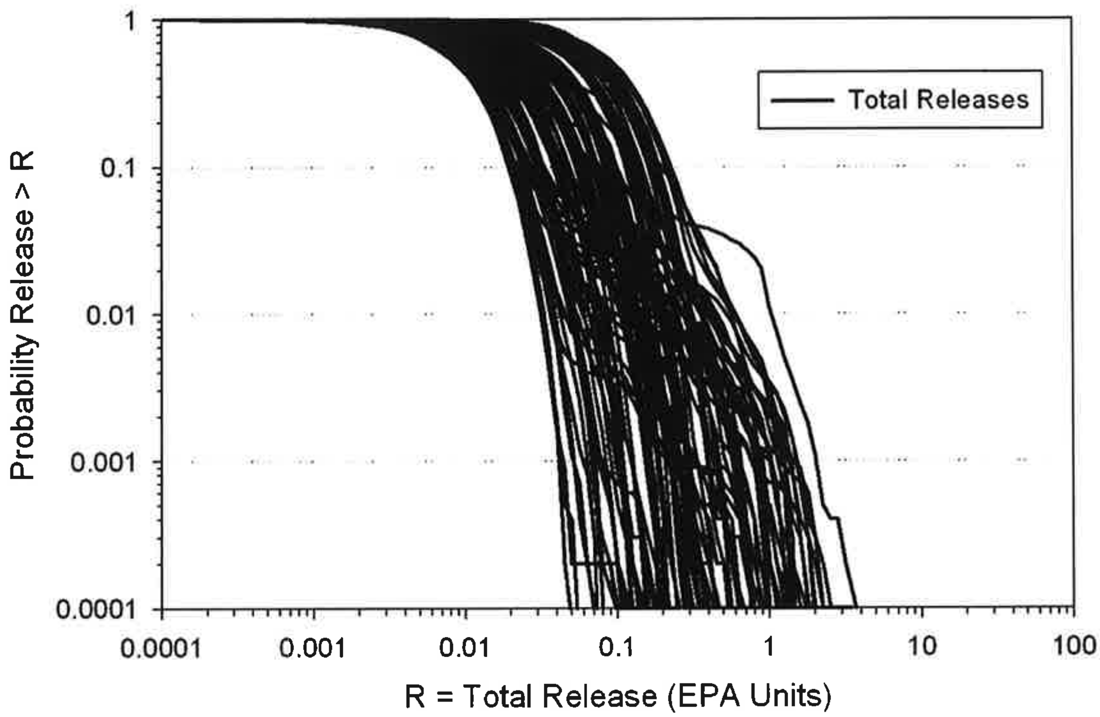


Figure 6-25: SDI Replicate 1 Total Normalized Releases

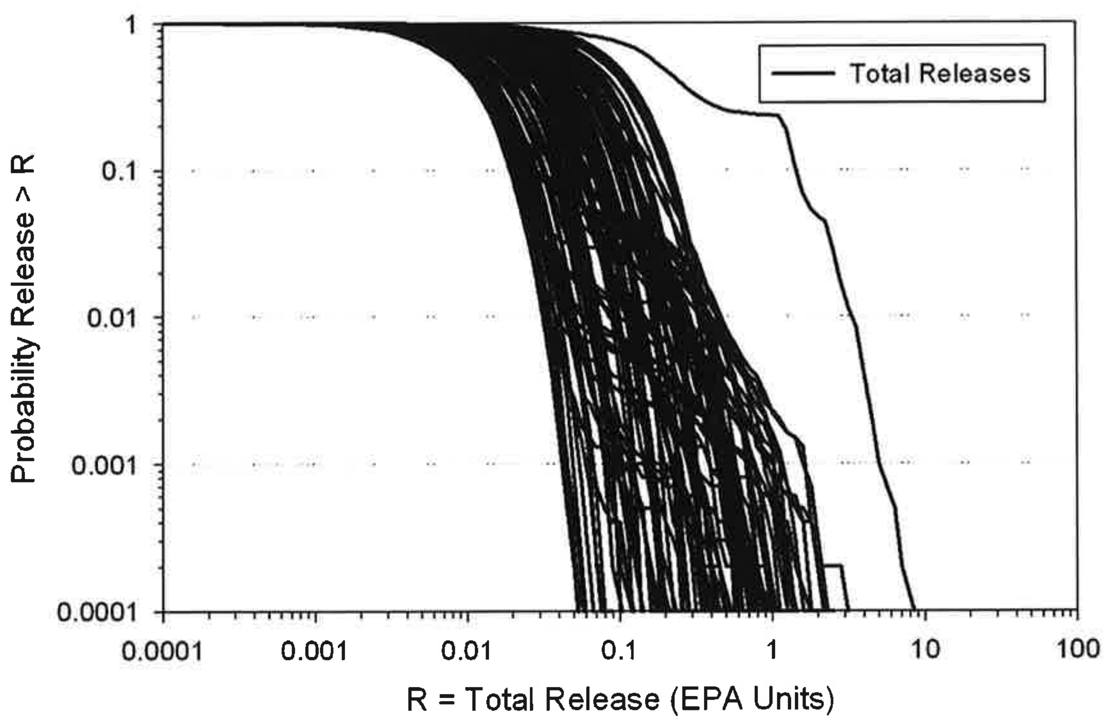


Figure 6-26: SDI Replicate 2 Total Normalized Releases

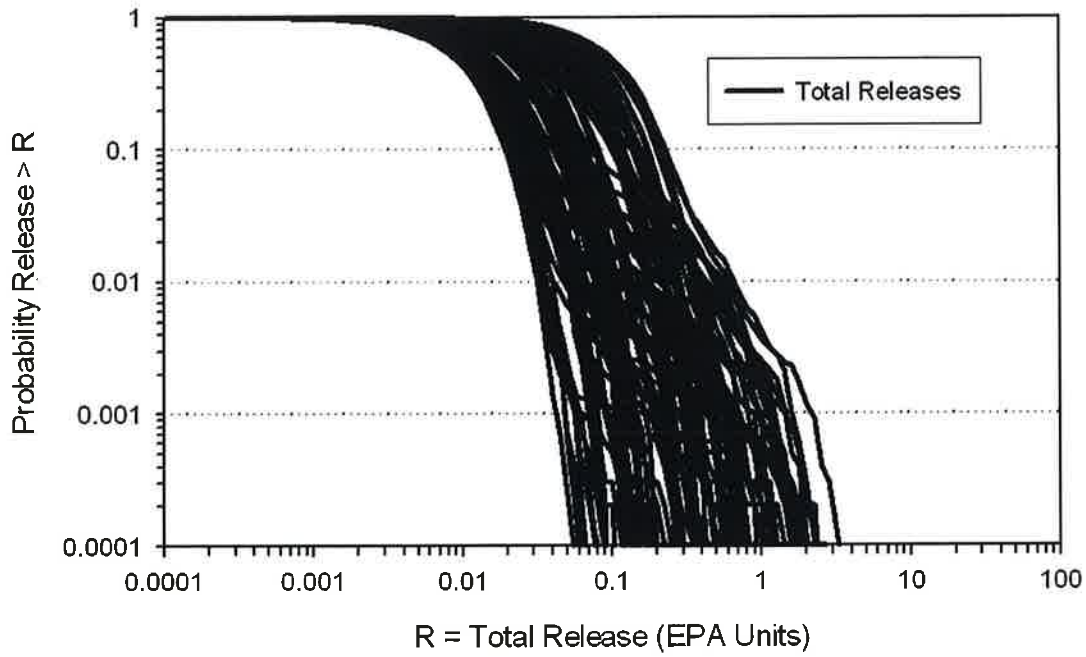


Figure 6-27: SDI Replicate 3 Total Normalized Releases

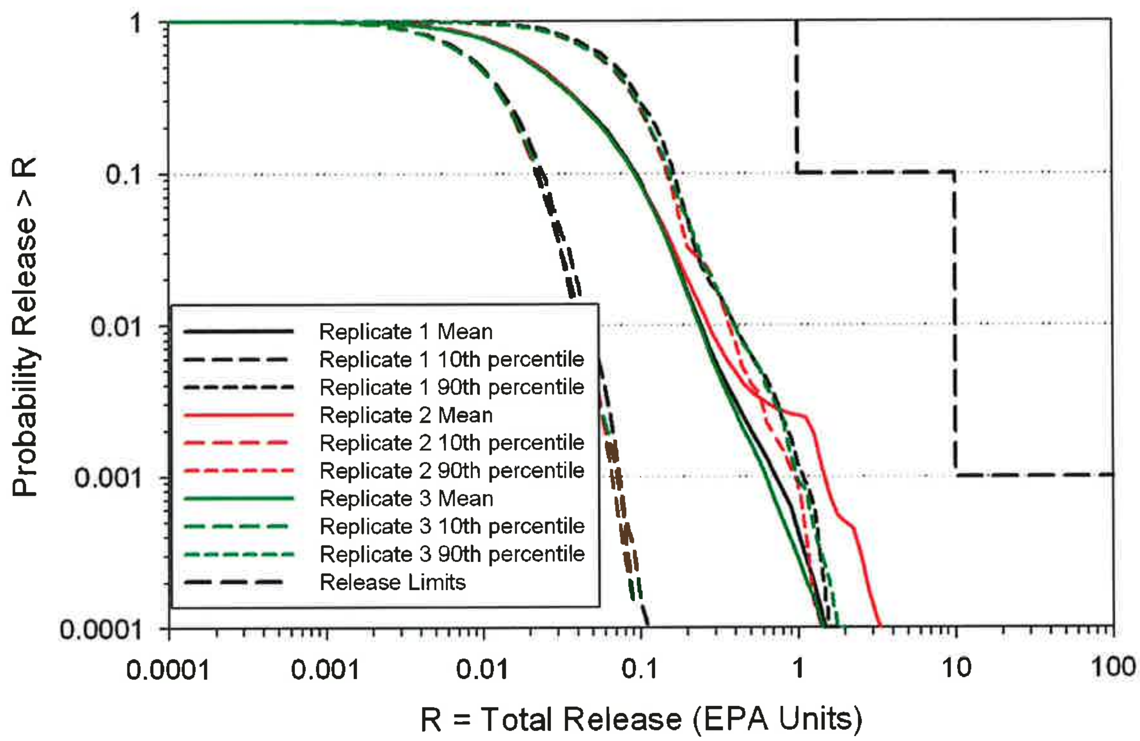


Figure 6-28: SDI Mean and Quantile CCDFs for Total Normalized Releases, Replicates 1-3

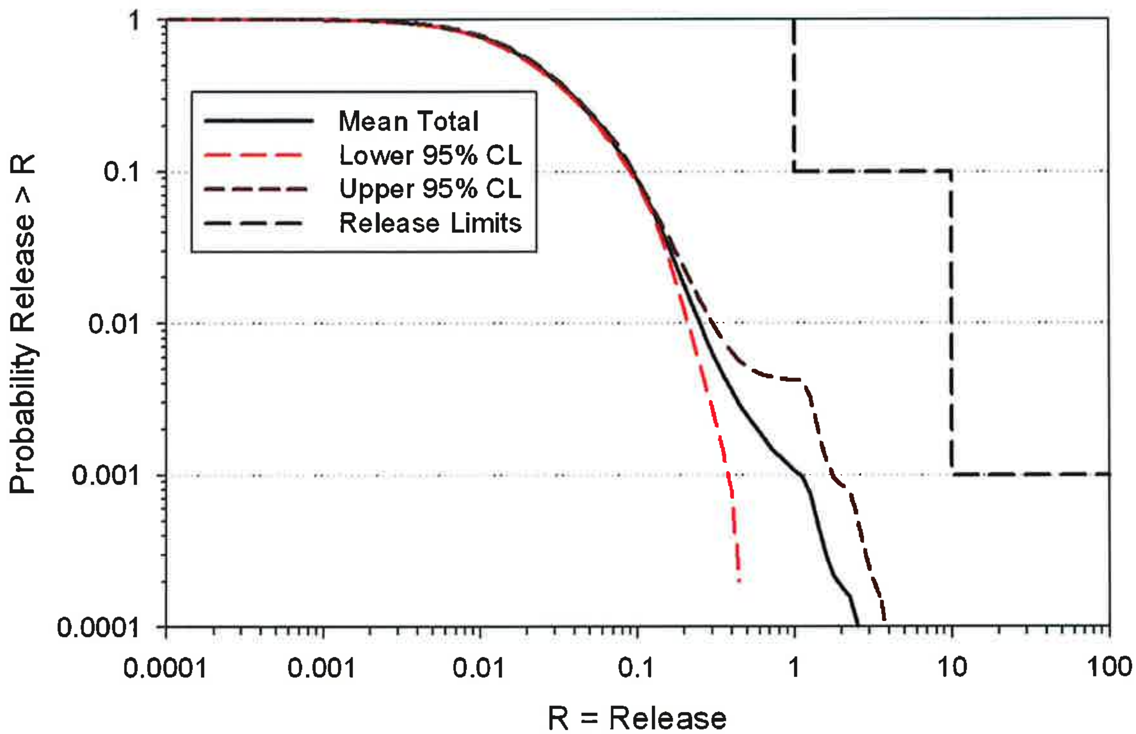


Figure 6-29: SDI Confidence Limits on Overall Mean for Total Normalized Releases

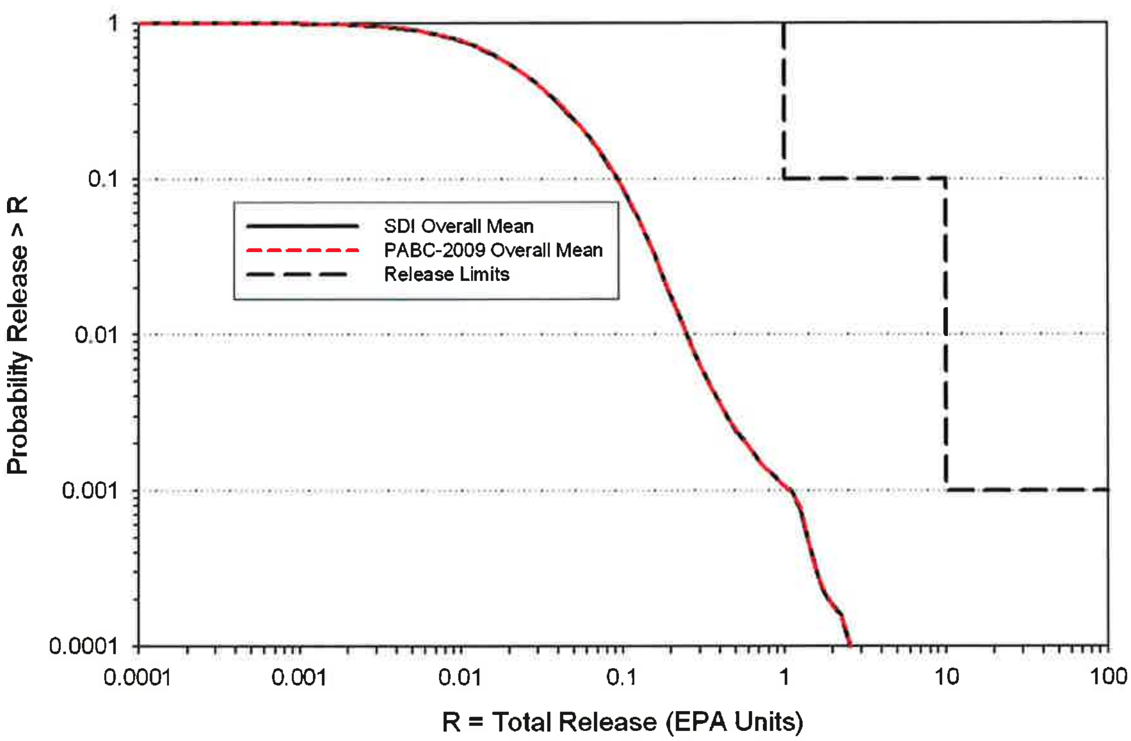


Figure 6-30: SDI and PABC-2009 Overall Mean CCDFs for Total Normalized Releases

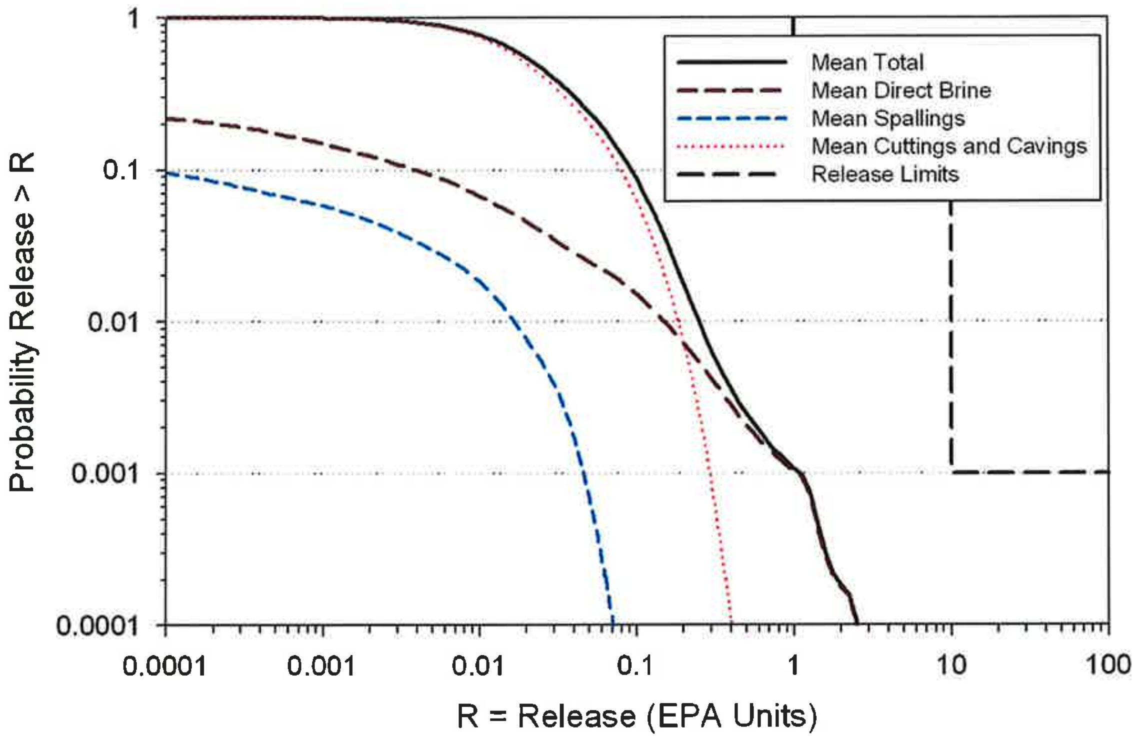


Figure 6-31: SDI Primary Components Contributing to Total Releases

7 SUMMARY

Total normalized releases calculated in the SDI impact assessment remain below their regulatory limits. As a result, the additional excavation in the WIPP experimental area to support SDI would not result in WIPP non-compliance with the containment requirements of 40 CFR Part 191. Cuttings and cavings releases and direct brine releases are the two primary release components contributing to total releases in the SDI calculations. Cuttings and cavings releases are unchanged from those calculated in the PABC-2009. Additional excavation for SDI results in small changes to pressures and brine saturations in repository waste-containing regions, but these collectively result in a negligible difference between direct brine releases seen in the SDI impact assessment and the PABC-2009. Small reductions are observed in SDI spallings releases as compared to the PABC-2009, but these differences are relatively minor and do not have a significant impact on the overall total normalized releases found in the SDI impact assessment. Total normalized releases found in the SDI calculations and the PABC-2009 are indistinguishable.

8 REFERENCES

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APPENDIX A SDI Code Execution

As mentioned in Section 1 and outlined in AP-156 (Camphouse and Kuhlman 2011), the SDI impact assessment is essentially a focused re-run of the PABC-2009 calculation using a slightly modified numerical grid in the Salado flow calculation. Execution and run control for the PABC-2009 are documented in Long (2010). The hardware and operating system used in the SDI impact assessment are identical to those used in the PABC-2009, and are shown in Table 7.

Table 7: WIPP PA Alpha Cluster Nodes Used in SDI Calculations

Node	Hardware Type	# of CPUs	CPU	Operating System
TBB	HP AlphaServer ES47	4	Alpha EV7	Open VMS 8.2
TRS	HP AlphaServer ES47	4	Alpha EV7	Open VMS 8.2
GNR	HP AlphaServer ES47	4	Alpha EV7	Open VMS 8.2
MC5	HP AlphaServer ES47	4	Alpha EV7	Open VMS 8.2
CCR	HP AlphaServer ES45 Model 2	4	Alpha EV68	Open VMS 8.2
TDN	HP AlphaServer ES45 Model 2	4	Alpha EV68	Open VMS 8.2
BTO	HP AlphaServer ES45 Model 2	4	Alpha EV68	Open VMS 8.2
CSN	HP AlphaServer ES45 Model 2	4	Alpha EV68	Open VMS 8.2

Determining the impact of additional SDI excavation on spallings and DBRs as compared to the PABC-2009 is the primary focus of the SDI impact assessment. Quantifying these impacts requires an execution of the Salado flow, spallings, DBR, and CCDFGF PA code chains. The necessary suite of codes that were executed in the SDI impact assessment is listed in Table 8, and has been qualified under Nuclear Waste Management Procedure NP 19-1: Software Requirements (Chavez 2006).

Table 8: WIPP PA VMS Software Used in the SDI Calculations

Code	Version	Executable	Build Date	CMS Library	CMS Class
ALGEBRACDB	2.35	ALGEBRACDB_PA96.EXE	31-01-96	LIBALG	PA96
BRAGFLO	6.0	BRAGFLO_QB0600.EXE	12-02-07	LIBBF	QB0600
PREBRAG	8.00	PREBRAG_QA0800.EXE	08-03-07	LIBBF	QA0800
POSTBRAG	4.00A	POSTBRAG_QA0400A.EXE	28-03-07	LIBBF	QA0400A
CCDFGF	5.02	CCDFGF_QB0502.EXE	13-12-04	LIBCCGF	QB0502
PRECCDFGF	1.01	PRECCDFGF_QA0101.EXE	07-07-05	LIBCCGF	QA0101
CUTTINGS_S	6.02	CUTTINGS_S_QA0602.EXE	09-06-05	LIBCUSP	QA0602
GENMESH	6.08	GM_PA96.EXE	31-01-96	LIBGM	PA96
ICSET	2.22	ICSET_PA96.EXE	01-02-96	LIBIC	PA96
POSTLHS	4.07A	POSTLHS_QA0407A.EXE	25-04-05	LIBLHS	QA0407A
MATSET	9.10	MATSET_QA0910.EXE	29-11-01	LIBMS	QA0910
RELATE	1.43	RELATE_PA96.EXE	06-03-96	LIBREL	PA96
SUMMARIZE	3.01	SUMMARIZE_QB0301.EXE	21-12-05	LIBSUM	QB0301

Discussion of run control is limited to the execution of codes done for the SDI impact assessment. Discussion of run control for PABC-2009 results used in the SDI calculation can be found in Long (2010).

A.1 Salado Flow Calculations (BRAGFLO)

Brine and gas flow in and around the repository and in overlying formations is calculated using the BRAGFLO suite of codes (PREBRAG, BRAGFLO, and POSTBRAG) in conjunction with several utility codes. The brine and gas flow calculations are divided into several steps. The steps, the codes run in each step, and the DCL script(s) used to perform the step are shown in Table 9.

Table 9: Salado Flow Run Control Scripts

Step	Codes in Step	Script(s)	CMS Library	CMS Class
1	GENMESH MATSET	EVAL_GENERIC_STEP1.COM	LIBSDI_EVAL	SDI-0
2	POSTLHS	EVAL_GENERIC_STEP2.COM	LIBSDI_EVAL	SDI-0
3	ICSET ALGEBRACDB	EVAL_BF_STEP3.COM	LIBSDI_EVAL	SDI-0
4	PREBRAG	EVAL_BF_STEP4.COM	LIBSDI_EVAL	SDI-0
5	BRAGFLO POSTBRAG ALGEBRACDB	EVAL_BF_STEP5_MASTER.COM EVAL_BF_STEP5_SLAVE.COM	LIBSDI_EVAL LIBSDI_EVAL	SDI-0 SDI-0

A.1.1 Salado Flow Step 1

Step 1 uses GENMESH and MATSET to generate the computational grid and assign material properties to element blocks. Step 1 is run once. The input and log files for the Step 1 script as well as the input and output files for GENMESH and MATSET are shown in Table 10.

Table 10: Salado Flow Step 1 Input and Output Files

	File Names	CMS Library	CMS Class
SCRIPT			
Input	EVAL_BF_SDI_STEP1.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_BF_SDI_STEP1.LOG	LIBSDI_BF	SDI-0
GENMESH			
Input	GM_BF_SDI.INP	LIBSDI_BF	SDI-0
Output	GM_BF_SDI.CDB	LIBSDI_BF	SDI-0
Output	GM_BF_SDI.DBG	NOT KEPT	NOT KEPT
MATSET			
Input	MS_BF_SDI.INP	LIBSDI_BF	SDI-0
Input	GM_BF_SDI.CDB	LIBSDI_BF	SDI-0
Output	MS_BF_SDI.CDB	LIBSDI_BF	SDI-0
Output	MS_BF_SDI.DBG	NOT KEPT	NOT KEPT

A.1.2 Salado Flow Step 2

Step 2 uses POSTLHS to assign the sampled parameter values used by BRAGFLO (generated by LHS) to the appropriate materials and element block properties. Step 2 is run once per replicate. POSTLHS loops over all 100 vectors in the replicate. The input and log files for the Step 2 script as well as the input and output files for POSTLHS are shown in Table 11.

Table 11: Salado Flow Step 2 Input and Output Files

	File Names[1,2]	CMS Library	CMS Class
SCRIPT			
Input	EVAL_BF_SDI_STEP2_R*r*.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_BF_SDI_STEP2_R*r*.LOG	LIBSDI_BF	SDI-0
POSTLHS			
Input	LHS3_DUMMY.INP	LIBPABC09_LHS	SDI-0
Input	LHS2_PABC09_R*r*_CON.TRN	LIBPABC09_LHS	SDI-0
Input	MS_BF_SDI.CDB	LIBSDI_BF	SDI-0
Output	LHS3_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	LHS3_BF_SDI_R*r*.DBG	LIBSDI_BF	SDI-0

1. $r \in \{1, 2, 3\}$
2. $vvv \in \{001, 002, ..., 100\}$ for each r

A.1.3 Salado Flow Step 3

Step 3 assigns initial conditions with ICSET and performs some pre-processing of input data with ALGEBRACDB. Since ALGEBRACDB is used in multiple BRAGFLO steps, this use is referred to as ALG1. Step 3 is run once for each replicate. The script loops over all 100 vectors in the replicate. The input and log files for the Step 3 script as well as the input and output files for ICSET and ALGEBRACDB are shown in Table 12.

Table 12: Salado Flow Step 3 Input and Output Files

	File Names[1,2]	CMS Library	CMS Class
SCRIPT			
Input	EVAL_BF_SDI_STEP3_R*r*.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_BF_SDI_STEP3_R*r*.LOG	LIBSDI_BF	SDI-0
ICSET			
Input	IC_BF_SDI.INP	LIBSDI_BF	SDI-0
Input	LHS3_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	IC_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	IC_BF_SDI_R*r*_V*vvv*.DBG	NOT KEPT	NOT KEPT
ALGEBRACDB			
Input	ALG1_BF_SDI.INP	LIBSDI_BF	SDI-0
Input	IC_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	ALG1_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	ALG1_BF_SDI_R*r*_V*vvv*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $vvv \in \{001, 002, ..., 100\}$ for each r

A.1.4 Salado Flow Step 4

Step 4 consists of running the pre-processing code PREBRAG. Step 4 is repeated for each replicate/scenario combination. The script loops over all 100 vectors in the replicate/scenario combination. The input and log files for the Step 4 script as well as the input and output files for PREBRAG are shown in Table 13.

Table 13: Salado Flow Step 4 Input and Output Files

	File Names[1,2,3]	CMS Library[1,2]	CMS Class
SCRIPT			
Script Input	EVAL_BF_SDI_STEP4_R*r*_S*s*.INP	LIBSDI_EVAL	SDI-0
Script Log	EVAL_BF_SDI_STEP4_R*r*_S*s*.LOG	LIBSDI_BFR*r*S*s*	SDI-0
PREBRAG			
Input	BF1_SDI_S*s*.INP	LIBSDI_BF	SDI-0
Input	ALG1_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	BF2_SDI_R*r*_S*s*_V*vvv*.INP	LIBSDI_BFR*r*S*s*	SDI-0
Output	BF1_SDI_R*r*_S*s*_V*vvv*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5, 6\}$ for each r
3. $vvv \in \{001, 002, ..., 100\}$ for each s

A.1.5 Salado Flow Step 5

Step 5 runs BRAGFLO, POSTBRAG, and ALGEBRACDB (ALG2). This step has been separated from Step 4 to allow the analysts to edit/modify the BRAGFLO input file in cases where the generic numerical control parameters are not sufficient to obtain a converged solution. In the paragraphs that follow, the procedure for the general case is described first and then the procedure followed to re-run certain replicate/scenario/vector combinations that were run with modified BRAGFLO input files due to lack of or unreasonably slow convergence.

A.1.5.1 General Case

Two DCL run control scripts are used in Step 5. The master script is invoked once for each replicate/scenario combination. The master script loops over all 100 vectors in the replicate/scenario combination. For each vector, the master script writes an input file for the slave script, and then calls the slave script with that input file to run BRAGFLO, POSTBRAG, and ALGEBRACDB. The input and log files for the Step 5 script as well as the input and output files for BRAGFLO, POSTBRAG, and ALGEBRACDB are shown in Table 14.

Table 14: Salado Flow Step 5 Input and Output Files (Generic Case)

	File Names[1,2,3,4]	CMS Library[1,2,5]	CMS Class
MASTER SCRIPT			
Input	EVAL_BF_SDI_STEP5_R*r*_S*s*.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_BF_SDI_STEP5_R*r*_S*s*.LOG	LIBSDI_BFR*r*S*s*	SDI-0
SLAVE SCRIPT			
Log[4]	EVAL_BF_SDI_STEP5_R*r*_S*s*_V*vvv*.LOG	LIBSDI_BFR*r*S*s*	SDI-0
BRAGFLO			
Input	BF2_SDI_R*r*_S*s*_V*vvv*.INP	LIBSDI_BFR*r*S*s*	SDI-0
Input	BF2_SDI_CLOSURE.DAT	LIBSDI_BF	SDI-0
Output	BF2_SDI_R*r*_S*s*_V*vvv*.OUT	NOT KEPT	NOT KEPT
Output	BF2_SDI_R*r*_S*s*_V*vvv*.SUM[5]	LIBSDI_BF	SDI-0
Output	BF2_SDI_R*r*_S*s*_V*vvv*.BIN	NOT KEPT	NOT KEPT
Output	BF2_SDI_R*r*_S*s*_V*vvv*.ROT	NOT KEPT	NOT KEPT
Output	BF2_SDI_R*r*_S*s*_V*vvv*.RIN	NOT KEPT	NOT KEPT
POSTBRAG			
Input	BF2_SDI_R*r*_S*s*_V*vvv*.BIN	NOT KEPT	NOT KEPT
Input	ALG1_BF_SDI_R*r*_V*vvv*.CDB	LIBSDI_BF	SDI-0
Output	BF3_SDI_R*r*_S*s*_V*vvv*.CDB	LIBSDI_BFR*r*S*s*	SDI-0
Output	BF3_SDI_R*r*_S*s*_V*vvv*.DBG	NOT KEPT	NOT KEPT
ALGEBRACDB			
Input	ALG2_BF_SDI.INP	LIBSDI_BF	SDI-0
Input	BF3_SDI_R*r*_S*s*_V*vvv*.CDB	LIBSDI_BFR*r*S*s*	SDI-0
Output	ALG2_BF_SDI_R*r*_S*s*_V*vvv*.CDB	LIBSDI_BFR*r*S*s*	SDI-0
Output	ALG2_BF_SDI_R*r*_S*s*_V*vvv*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5, 6\}$ for each r
3. $vvv \in \{001, 002, ..., 100\}$ for each s
4. The script inputs are echoed into the log file, so the input file is not kept
5. Due to an error in the master script input file, the *.SUM output files were placed in CMS library LIBSDI_BF instead of the library for the replicate/scenario combination. Note that output files for simulations reported in Table 15 (modified input runs) were archived in the correct libraries (LIBSDI_BFR*r*S*s*).

A.1.5.2 Modified BRAGFLO Input Case

In the few instances when BRAGFLO failed to converge using the generic numerical control parameters, a new BRAGFLO input file was submitted by the analysts and the case was re-run in a manner similar to that described above in Section A.1.5.1 In order to track these cases a special tag ("MOD") was inserted into the BRAGFLO input file name, as well as the master script input file and log file names.

The replicate/scenario/vectors requiring modified BRAGFLO input files are shown in Table 15. For all vectors listed in that table, simulation control parameter FTOL_SAT was increased from the default value of 1e-2 to a value of 1e-1. With that modification, vectors listed in Table 15 were successfully run to the final time of 10,000 years. The modified file names are shown in Table 16. All other files have the same names as for the generic case. Files in the libraries from the un-converged runs were replaced with files from the re-run.

Table 15: Salado Flow Step 5 Modified Input Runs

Replicate	Scenario	Vectors
R1	S1	29
R2	S1	99
	S4	95, 99
	S5	99
R3	S3	35

Table 16: Salado Flow Step 5 Modified Input Runs File Names

	File Names[1,2,3]	CMS Library[1,2]	CMS Class
MASTER SCRIPT			
Input	EVAL_BF_SDI_STEP5_R*r*_S*s*_V*vvv*_MOD.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_BF_SDI_STEP5_R*r*_S*s*_V*vvv*_MOD.LOG	LIBSDI_BFR*r*S*s*	SDI-0
BRAGFLO			
Input	BF2_SDI_R*r*_S*s*_V*vvv*_MOD.INP	LIBSDI_BFR*r*S*s*	SDI-0

1. $r \in \{1, 2, 3\}$ as shown in Table 15
2. $s \in \{1, 2, 3, 4, 5, 6\}$ as shown in Table 15
3. vectors as shown in Table 15

A.2 Single-Intrusion Solids Volume Calculations (CUTTINGS_S)

The total volume of radionuclide-contaminated solids that may reach the surface during a drilling intrusion event is calculated by the CUTTINGS_S code. The single intrusion solids volume calculations are divided into 3 steps. The codes run in each step, and the DCL script(s) used to perform the steps are shown in Table 17. Step 3 also includes a small utility used to submit the script to a batch queue.

Table 17: Solids Volume (CUTTINGS_S) Run Control Scripts

Step	Codes in Step	Scripts	Script CMS Library	Script CMS Class
1	GENMESH MATSET	EVAL_CUSP_STEP1.COM	LIBSDI_EVAL	SDI-0
2	POSTLHS	EVAL_CUSP_STEP2.COM	LIBSDI_EVAL	SDI-0
3	CUTTINGS_S	EVAL_CUSP_STEP3.COM SUB_CUSP_STEP3.COM	LIBSDI_EVAL	SDI-0

A.2.1 Solids Volume Step 1

Step 1 uses GENMESH and MATSET to generate the computational grid and assign material properties to element blocks. Step1 is run once. The input and log files for the script as well as the input and output files for GENMESH and MATSET are shown in Table 18.

Table 18: Solids Volume Step 1 Input and Output Files

	File Names	CMS Library	CMS Class
SCRIPT			
Input	EVAL_CUSP_SDI_STEP1.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_CUSP_SDI_STEP1.LOG	LIBSDI_CUSP	SDI-0
GENMESH			
Input	GM_CUSP_SDI.INP	LIBSDI_CUSP	SDI-0
Output	GM_CUSP_SDI.CDB	LIBSDI_CUSP	SDI-0
Output	GM_CUSP_SDI.DBG	NOT KEPT	NOT KEPT
MATSET			
Input	MS_CUSP_SDI.INP	LIBSDI_CUSP	SDI-0
Input	GM_CUSP_SDI.CDB	LIBSDI_CUSP	SDI-0
Output	MS_CUSP_SDI.CDB	LIBSDI_CUSP	SDI-0
Output	MS_CUSP_SDI.DBG	NOT KEPT	NOT KEPT

A.2.2 Solids Volume Step 2

Step 2 uses POSTLHS to assign the sampled parameter values used by CUTTINGS_S (generated by LHS) to the appropriate materials and element block properties. Step 2 is run once per replicate. POSTLHS loops over all 100 vectors in the replicate. The input and log files for the script as well as the input and output files for POSTLHS are shown in Table 19.

Table 19: Solids Volume Step 2 Input and Output Files

	File Names[1,2]	CMS Library	CMS Class
SCRIPT			
Script Input	EVAL_CUSP_SDI_STEP2_R*r*.INP	LIBSDI_EVAL	SDI-0
Script Log	EVAL_CUSP_SDI_STEP2_R*r*.LOG	LIBSDI_CUSP	SDI-0
POSTLHS			
Input	LHS3_DUMMY.INP	LIBPABC09_LHS	SDI-0
Input	LHS2_PABC09_R*r*_CON.TRN	LIBPABC09_LHS	SDI-0
Input	MS_CUSP_SDI.CDB	LIBSDI_CUSP	SDI-0
Output	LHS3_CUSP_SDI_R*r*_V*vvv*.CDB	LIBSDI_CUSP	SDI-0
Output	LHS3_CUSP_SDI_R*r*.DBG	LIBSDI_CUSP	SDI-0

1. $r \in \{1, 2, 3\}$
2. $vvv \in \{001, 002, ..., 100\}$ for each r

A.2.3 Solids Volume Step 3

Step 3 runs the CUTTINGS_S code, and is invoked for each replicate. The script generates the CUTTINGS_S master input control file. The CUTTINGS_S code itself loops over scenarios, intrusion times, intrusion locations, and vectors. The input and log files for the Step 3 script as well as the input and output files for CUTTINGS_S are shown in Table 20.

Table 20: Solids Volume Step 3 Input and Output Files

	File Names[1,2,3,4,5]	CMS Library[1,2]	CMS Class
SCRIPT			
Input	EVAL_CUSP_SDI_STEP3_R*r*.INP	LIBSDI_EVAL	SDI-0
Output	CUSP_SDI_MASTER_R*r*.INP	LIBSDI_CUSP	SDI-0
Log	EVAL_CUSP_SDI_STEP3_R*r*.LOG	LIBSDI_CUSP	SDI-0
CUTTINGS_S			
Input	CUSP_SDI_MASTER_R*r*.INP	LIBSDI_CUSP	SDI-0
Input	CUSP_SDI.INP	LIBSDI_CUSP	SDI-0
Input	LHS3_CUSP_SDI_R*r*_V*vvv*.CDB	LIBSDI_CUSP	SDI-0
Input	BF3_SDI_R*r*_S*s*_V*vvv*.CDB	LIBSDI_BFR*r*S*s*	SDI-0
Input	MSPALL_DRS_CRA1BC_R*r*.OUT	LIBCRA1BC_DRS	SDI-0
Output	CUSP_SDI_R*r*.TBL	LIBSDI_CUSP	SDI-0
Output	CUSP_SDI_R*r*_S*s*_T*tttt*_*c*_V*vvv*.CDB	LIBSDI_CUSPR*r*S*s*	SDI-0
Output	CUSP_SDI_R*r*.DBG	LIBSDI_CUSP	SDI-0

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5\}$ for each r
3. $tttt \in \begin{cases} \{100, 350, 1000, 3000, 5000, 10000\} & \text{for S1} \\ \{550, 750, 2000, 4000, 10000\} & \text{for S2, S4} \\ \{1200, 1400, 3000, 5000, 10000\} & \text{for S3, S5} \end{cases}$
4. $c \in \{L, U, M\}$ for each intrusion time
5. $vvv \in \{001, 002, ..., 100\}$ for each c

A.3 Single-Intrusion Direct Brine Release Calculations (BRAGFLO)

Single-intrusion direct brine release volumes are calculated using the BRAGFLO suite of codes (PREBRAG, BRAGFLO, POSTBRAG), in conjunction with several utility codes. The steps, the codes run in each step, and the DCL script(s) used to perform the step are shown in Table 21.

Table 21: Direct Brine Release Run Control Scripts

Step	Codes in Step	Script(s)	Script CMS Library	Script CMS Class
1	GENMESH MATSET	EVAL_DBR_STEP1.COM	LIBSDI_EVAL	SDI-0
2	ALGEBRACDB RELATE ICSET	EVAL_DBR_STEP2.COM SUB_DBR_STEP2.COM	LIBSDI_EVAL	SDI-0
3	PREBRAG BRAGFLO POSTBRAG ALGEBRACDB	EVAL_DBR_STEP3.COM SUB_DBR_STEP3.COM	LIBSDI_EVAL	SDI-0

A.3.1 Direct Brine Release Step 1

Step 1 uses GENMESH and MATSET to generate the computational grid and assign material properties to element blocks. Step 1 is run once. The input and log files for the script as well as the input and output files for GENMESH and MATSET are shown in Table 22.

Table 22: Direct Brine Release Step 1 Input and Output Files

	File Names	CMS Library	CMS Class
SCRIPT			
Input	EVAL_DBR_SDI_STEP1.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_DBR_SDI_STEP1.LOG	LIBSDI_DBR	SDI-0
GENMESH			
Input	GM_DBR_SDI.INP	LIBSDI_DBR	SDI-0
Output	GM_DBR_SDI.CDB	LIBSDI_DBR	SDI-0
Output	GM_DBR_SDI.DBG	NOT KEPT	NOT KEPT
MATSET			
Input	MS_DBR_SDI.INP	LIBSDI_DBR	SDI-0
Input	GM_DBR_SDI.CDB	LIBSDI_DBR	SDI-0
Output	MS_DBR_SDI.CDB	LIBSDI_DBR	SDI-0
Output	MS_DBR_SDI.DBG	NOT KEPT	NOT KEPT

A.3.2 Direct Brine Release Step 2

Step 2 performs pre-processing of input data with ALGEBRACDB (because ALGEBRACDB is used in multiple steps, this use is referred to as ALG1). The RELATE code is used to assign material properties to element blocks. RELATE is run twice (RELATE_1 and RELATE_2). Finally, ICSET is used to assign initial conditions. The Step 2 script is run for each replicate/scenario combination. The script loops over the appropriate intrusion times for the scenario. For each intrusion time, the script loops over all 100 vectors. The input and log files for the Step 2 script as well as the input and output files for ALGEBRACDB, RELATE, and ICSET are shown in Table 23.

Table 23: Direct Brine Release Step 2 Input and Output Files

	File Names[1,2,3,4]	**CMS Library[1,2]**	**CMS Class**
SCRIPT			
Input	EVAL_DBR_SDI_STEP2_R*r*_S*s*.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_DBR_SDI_STEP2_R*r*_S*s*.LOG	LIBSDI_DBRR*r*S*s*	SDI-0
ALGEBRACDB			
Input	ALG1_DBR_SDI.INP	LIBSDI_DBR	SDI-0
Input	CUSP_SDI_R*r*_S*s*_T*ttttt*_L_V*vvv*.CDB[5]	LIBSDI_CUSPR*r*S*s*	SDI-0
Output	ALG1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	ALG1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.DBG	NOT KEPT	NOT KEPT
RELATE_1			
Input	REL1_DBR_SDI.INP	LIBSDI_DBR	SDI-0
Input	MS_DBR_SDI.CDB	LIBSDI_DBR	SDI-0
Input	ALG1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	REL1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	REL1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.DBG	NOT KEPT	NOT KEPT
RELATE_2			
Input	REL2_DBR_SDI_S*s*.INP	LIBSDI_DBR	SDI-0
Input	REL1_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Input	BF3_SDI_R*r*_S*s*_V*vvv*.CDB	LIBSDI_BFR*r*S*s*	SDI-0
Output	REL2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	REL2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.DBG	NOT KEPT	NOT KEPT
ICSET			
Input	IC_DBR_SDI_S*s*.INP	LIBSDI_DBR	SDI-0
Input	REL2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	IC_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	IC_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.DBG	NOT KEPT	NOT KEPT
ALGEBRACDB			
Input	ALG2_DBR_SDI_S*s*.INP	LIBSDI_DBR	SDI-0
Input	IC_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	ALG2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	ALG2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5\}$ for each r
3. $ttttt \in \begin{cases} \{00100, 00350, 01000, 03000, 05000, 10000\} & \text{for S1} \\ \{00550, 00750, 02000, 04000, 10000\} & \text{for S2, S4} \\ \{01200, 01400, 03000, 05000, 10000\} & \text{for S3, S5} \end{cases}$
4. $vvv \in \{001, 002, ..., 100\}$ for each intrusion
5. The files CUSP_SDI_R*r*_S*s*_T*ttttt*_L_V*vvv*.CDB do not have leading zeros in front of the intrusion time *ttttt*.

A.3.3 Direct Brine Release Step 3

Step 3 runs PREBRAG, BRAGFLO, POSTBRAG, and ALGEBRACDB (ALG3). The Step 3 script is invoked for each replicate/scenario combination. The script loops over the appropriate intrusion times for the scenario. For each intrusion time, the script loops over all three intrusion locations. For each intrusion location, the script loops over all 100 vectors. The PREBRAG, BRAGFLO, POSTBRAG, ALGEBRACDB sequence is run for each replicate/scenario/intrusion time/intrusion location/vector combination. The input and log files for the Step 3 script as well as the input and output files for PREBRAG, BRAGFLO, POSTBRAG, ALGEBRACDB are shown in Table 24.

Table 24: Direct Brine Release Step 3 Input and Output Files

	File Names[1,2,3,4,5]	CMS Library[1,2]	CMS Class
SCRIPT			
Input	EVAL_DBR_SDI_STEP3_R*r*_S*s*.INP	LIBSDI_EVAL	SDI-0
Log	EVAL_DBR_SDI_STEP3_R*r*_S*s*.LOG	LIBSDI_DBRR*r*S*s*	SDI-0
PREBRAG			
Input	BF1_DBR_SDI_*c*.INP	LIBSDI_DBR	SDI-0
Input	ALG2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.INP	LIBSDI_DBRR*r*S*s*	SDI-0
Output	BF1_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.DBG	NOT KEPT	NOT KEPT
BRAGFLO			
Input	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.INP	LIBSDI_DBRR*r*S*s*	SDI-0
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.OUT	NOT KEPT	NOT KEPT
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.SUM	NOT KEPT	NOT KEPT
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.BIN	NOT KEPT	NOT KEPT
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.ROT	NOT KEPT	NOT KEPT
Output	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.RIN	NOT KEPT	NOT KEPT
POSTBRAG			
Input	ALG2_DBR_SDI_R*r*_S*s*_T*ttttt*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Input	BF2_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.BIN	NOT KEPT	NOT KEPT
Output	BF3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	BF3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.DBG	NOT KEPT	NOT KEPT
ALGEBRACDB			
Input	ALG3_DBR_SDI.INP	LIBSDI_DBR	SDI-0
Input	BF3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	ALG3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	ALG3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5\}$ for each r
3. $ttttt \in \begin{cases} \{00100, 00350, 01000, 03000, 05000, 10000\} & \text{for S1} \\ \{00550, 00750, 02000, 04000, 10000\} & \text{for S2, S4} \\ \{01200, 01400, 03000, 05000, 10000\} & \text{for S3, S5} \end{cases}$
4. $c \in \{L, M, U\}$ for each intrusion
5. $vvv \in \{001, 002, ..., 100\}$ for each c

A.4 CCDF Input Tabulations (SUMMARIZE)

The output CDB files from the various process model codes are combined into text tables by the SUMMARIZE code for subsequent use in calculating releases to the accessible environment. The run control scripts used to process the CDB data for the various process models are shown in Table 25. A single run control script is used to extract data from CDB files for all process model codes. The script performs the following steps:

- Fetch the required CDB files
- Write an input control file for SUMMARIZE by filling in items in an input control file template
- Run SUMMARIZE on the collection of CDB files

A small utility script is used to submit the main script to a batch queue.

Table 25: CCDF Input Tabulation Run Control Scripts

Code	Script	Script CMS Library	Script CMS Class
SUMMARIZE	EVAL_SUM.COM SUB_SUM.COM	LIBSDI_EVAL	SDI-0

A.4.1 CCDF Input Tabulation for Direct Brine Release

SUMMARIZE is used to extract and tabulate brine release volume data from the appropriate post-BRAGFLO_DBR ALGEBRACDB output CDB files (see Section A.3). The run control script is invoked for scenarios S1-DBR through S5-DBR for each replicate. The script loops over the appropriate intrusion times for each scenario. There is a single SUMMARIZE input control file template, which the script uses to generate a SUMMARIZE input control file for each replicate/scenario/intrusion time/intrusion location combination. The script input and log files along with the SUMMARIZE input and output files are shown in Table 26.

Table 26: CCDF Input Tabulation Input and Output Files (Direct Brine Release)

	File Names[1,2,3,4,5]	CMS Library[1,2]	CMS Class
SCRIPT			
Input	EVAL_SUM_DBR_SDI_R*r*_S*s*.INP	LIBSDI_EVAL	SDI-0
Input	SUM_DBR_SDI.TMPL	LIBSDI_SUM	SDI-0
Output	SUM_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*.INP	LIBSDI_SUM	SDI-0
Log	EVAL_SUM_DBR_SDI_R*r*_S*s*.LOG	LIBSDI_SUM	SDI-0
SUMMARIZE			
Input	SUM_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*.INP	LIBSDI_SUM	SDI-0
Input	ALG3_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*_V*vvv*.CDB	LIBSDI_DBRR*r*S*s*	SDI-0
Output	SUM_DBR_SDI_R*r*_S*s*_Tttttt_*c*.TBL	LIBSDI_SUM	SDI-0
Output	SUM_DBR_SDI_R*r*_S*s*_Tttttt_*c*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $s \in \{1, 2, 3, 4, 5\}$ for each r
3. $ttttt \in \begin{cases} \{00100, 00350, 01000, 03000, 05000, 10000\} \text{ for S1} \\ \{00550, 00750, 02000, 04000, 10000\} \text{ for S2 and S4} \\ \{01200, 01400, 03000, 05000, 10000\} \text{ for S3 and S5} \end{cases}$
4. $c \in \{L, M, U\}$ for each intrusion time
5. $vvv \in \{001, 002, ..., 100\}$ for each c

A.5 CCDF Construction (PRECCDFGF, CCDFGF)

The complimentary cumulative distribution functions (CCDFs) for radionuclide releases to the accessible environment are constructed using the PRECCDFGF/CCDFGF code suite. The calculations are separated into several steps according to the number of times a particular code is run and to allow for timely inspection of intermediate results. The steps, the codes run in each step, and the DCL script(s) used to perform the steps are shown in Table 27.

Table 27: CCDF Construction Run Control Scripts

Step	Codes in Step	Scripts	CMS Library	CMS Class
1	GENMESH MATSET	EVAL_CCGF_STEP1.COM	LIBSDI_EVAL	SDI-0
2	POSTLHS	EVAL_CCGF_STEP2.COM	LIBSDI_EVAL	SDI-0
3	PRECCDFGF CCDFGF	EVAL_CCGF_STEP3.COM SUB_CCGF_STEP3.COM	LIBSDI_EVAL	SDI-0

A.5.1 CCDF Construction Step 1

Step 1 uses GENMESH and MATSET to generate the computational grid and assign material properties to element blocks. Step 1 is run once. The input and log files for the script as well as the input and output files for GENMESH and MATSET and are shown in Table 28.

Table 28: CCDF Construction Step 1 Input and Output Files

	File Names	CMS Library	CMS Class
SCRIPT			
Script Input	EVAL_CCGF_SDI_STEP1.INP	LIBSDI_EVAL	SDI-0
Script Log	EVAL_CCGF_SDI_STEP1.LOG	LIBSDI_CCGF	SDI-0
GENMESH			
Input	GM_CCGF_SDI.INP	LIBSDI_CCGF	SDI-0
Output	GM_CCGF_SDI.CDB	LIBSDI_CCGF	SDI-0
Output	GM_CCGF_SDI.DBG	NOT KEPT	NOT KEPT
MATSET			
Input	MS_CCGF_SDI.INP	LIBSDI_CCGF	SDI-0
Input	GM_CCGF_SDI.CDB	LIBSDI_CCGF	SDI-0
Output	MS_CCGF_SDI.CDB	LIBSDI_CCGF	SDI-0
Output	MS_CCGF_SDI.DBG	NOT KEPT	NOT KEPT

A.5.2 CCDF Construction Step 2

Step 2 uses POSTLHS to assign the sampled parameter values used by CCDFGF (generated by LHS) to the appropriate materials and element block properties. Step 2 is run once per replicate. POSTLHS loops over all 100 vectors in the replicate. The input and log files for the script as well as the input and output files for POSTLHS are shown in Table 29.

Table 29: CCDF Construction Step 2 Input and Output Files

	File Names[1,2]	CMS Library	CMS Class
STEP 2			
Script Input	EVAL_CCGF_SDI_STEP2_R*r*.INP	LIBSDI_EVAL	SDI-0
Script Log	EVAL_CCGF_SDI_STEP2_R*r*.LOG	LIBSDI_CCGF	SDI-0
POSTLHS			
Input	LHS3_DUMMY.INP	LIBPABC09_LHS	SDI-0
Input	LHS2_PABC09_R*r*_CON.TRN	LIBPABC09_LHS	SDI-0
Input	MS_CCGF_SDI.CDB	LIBSDI_CCGF	SDI-0
Output	LHS3_CCGF_SDI_R*r*_V*vvv*.CDB	LIBSDI_CCGF	SDI-0
Output	LHS3_CCGF_SDI_R*r*.DBG	LIBSDI_CCGF	SDI-0

1. $r \in \{1, 2, 3\}$
2. $vvv \in \{001, 002, ..., 100\}$ for each r

A.5.3 CCDF Construction Step 3

Step 3 uses PRECCDFGF to organize and format output from all of the process model codes for use by CCDFGF (i.e. builds the release table file), then runs CCDFGF to compute the CCDFs. Step 3 is run once per replicate. The script loops over the appropriate scenarios and/or intrusions and/or waste types to fetch the large number of data files that are input to PRECCDFGF. The input and log files for the script as well as the input and output files for PRECCDFGF are shown in Table 30.

Table 30: CCDF Construction Step 3 Input and Output Files

	File Names[1-7]	CMS Library	CMS Class
SCRIPT			
Script Input	EVAL_CCGF_STEP3_SDI_R*r*.INP	LIBSDI_EVAL	SDI-0
Script Log	EVAL_CCGF_STEP3_SDI_R*r*.LOG	LIBSDI_CCGF	SDI-0
PRECCDFGF			
Input	INTRUSIONTIMES.IN	LIBPABC09_CCGF	SDI-0
Input	MS_CCGF_SDI.CDB	LIBSDI_CCGF	SDI-0
Input	LHS3_CCGF_SDI_R*r*_V*vvv*.CDB	LIBSDI_CCGF	SDI-0
Input	SUM_DBR_SDI_R*r*_S*s*_T*ttttt*_*c*.TBL	LIBSDI_SUM	SDI-0
Input	CUSP_SDI_R*r*.TBL	LIBSDI_CUSP	SDI-0
Input	SUM_NUT_PABC09_R*r*_S1.TBL	LIBPABC09_SUM	SDI-0
Input	SUM_NUT_PABC09_R*r*_S*s*_T*ttttt*.TBL	LIBPABC09_SUM	SDI-0
Input	SUM_PANEL_INT_PABC09_R*r*_S6_T*ttttt*.TBL	LIBPABC09_SUM	SDI-0
Input	SUM_ST2D_PABC09_R*r*_M*m*.TBL	LIBPABC09_SUM	SDI-0
Input	EPU_PABC09_*h*H.DAT	LIBPABC09_EPU	SDI-0
Input	SUM_PANEL_CON_PABC09_R*r*_S*s*.TBL	LIBPABC09_SUM	SDI-0
Input	SUM_PANEL_ST_PABC09_R*r*_S*s*.TBL	LIBPABC09_SUM	SDI-0
Output	CCGF_SDI_RELTAB_R*r*.DAT	LIBSDI_CCGF	SDI-0
CCDFGF			
Input	CCGF_SDI_CONTROL_R*r*.INP	LIBSDI_CCGF	SDI-0
Input	CCGF_SDI_RELTAB_R*r*.DAT	LIBSDI_CCGF	SDI-0
Output	CCGF_SDI_R*r*.OUT	LIBSDI_CCGF	SDI-0
Output	CCGF_SDI_R*r*.DBG	NOT KEPT	NOT KEPT

1. $r \in \{1, 2, 3\}$
2. $vvv \in \{001, 002, ..., 100\}$ for each r
3. $s \in \begin{cases} \{1, 2, 3, 4, 5\} \text{ for SUM\_DBR} \\ \{2, 3, 4, 5\} \text{ for SUM\_NUT} \\ \{1, 2\} \text{ for SUM\_PANEL\_CON and SUM\_PANEL\_ST} \end{cases}$
4. $ttttt \in \begin{cases} \{00100, 00350, 01000, 03000, 05000, 10000\} \text{ for S1 for each } r \text{ for SUM\_DBR} \\ \{00550, 07500, 02000, 04000, 10000\} \text{ for S2, S4 for each } r \text{ for SUM\_DBR} \\ \{01200, 01400, 03000, 05000, 10000\} \text{ for S3, S5 for each } r \text{ for SUM\_DBR} \\ \{00100, 00350\} \text{ for S2, S4 for each } r \text{ for SUM\_NUT} \\ \{01000, 03000, 05000, 07000, 09000\} \text{ for S3, S5 each } r \text{ for SUM\_NUT} \\ \{00100, 00350, 01000, 02000, 04000, 06000, 09000\} \text{ for each } r \text{ for SUM\_PANEL\_INT} \end{cases}$
5. $c \in \{L, M, U\}$ for each intrusion for SUM_DBR
6. $m \in \{F, P\}$
7. $h \in \{C, R\}$