RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Nuclear Fuel

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APPENDIX E
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EXECUTIVE SUMMARY

This report defines a key set of RD&D activities to support a safety case for disposal of heat-generating radioactive waste, such as used nuclear fuel (UNF) or high-level nuclear waste (HLW), in a generic bedded salt repository, given the current state of knowledge. The recommended RD&D activities are based on the outcomes of a DOE workshop held March 6-7, 2013: "Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt." This workshop had the goals of formulating an expert consensus on the relative importance of various technical issues and recommending RD&D activities to address them, including modeling studies, laboratory studies, and field testing. Recommendations about which RD&D activities to pursue are based on their expected relevance to the objectives and goals of a safety case for a generic bedded salt repository, as well as their ability to help resolve any remaining uncertainties associated with the technical issues they are designed to address.

In Fiscal Year 2012 (FY12), and continuing through FY13, DOE-NE funded an R&D effort to further advance the science of geologic disposal of heat-generating waste in a salt formation at a generic site. This effort is documented in the Salt R&D Study Plan dated March 23, 2012 and agreed upon by DOE-NE and DOE-EM (see Appendix C of this report). Based on the outcomes of the recent March 2013 Workshop, and the subsequent testing and modeling proposals that were submitted to address high and medium importance RD&D issues, the present report recommends initiating a few new activities, as described below, while continuing other ongoing Salt R&D Study Plan activities into FY14 and out-years.

In conducting the Workshop and developing this subsequent Study Plan, two key concepts were agreed upon: (1) future salt research is confirmatory for many technical issues and uncertainties because of the advanced state-of-the-art and technical knowledge base for salt repository science generated over the past half-century both in this country and internationally, and (2) potential releases for repositories located in bedded salt are expected to mainly arise from intrusive or disruptive scenarios, since the expected-evolution or nominal scenario should experience nearly complete containment and encapsulation of the emplaced waste due to creep of salt and the self-sealing nature and low permeability of halite host rock. Thus, much of the remaining research will be to confirm the ability of the host rock to achieve complete containment for heat-generating waste, such as commercial used nuclear fuel. There is an extensive knowledge base for non-heat-generating waste, such as the defense TRU waste emplaced at WIPP and, while there have been a number of well-designed *in situ* experiments for heat-generating waste, there remain some issues that could be explored with further RD&D activities, including laboratory and field testing, accompanied by high-fidelity assessment modeling.

To facilitate discussions about potential remaining technical issues for disposal of heat-generating waste in salt, a set of "strawman" RD&D issues was introduced at the Workshop, along with an initial set of importance ratings for these issues based on their relationship to the three most important postclosure safety functions of a repository: isolation/stability, containment, and limited or delayed releases. These safety functions represent the key attributes of a multiple-barrier repository system that will help achieve the objective of postclosure safety. The set of strawman issues was formulated from the existing knowledge base for salt, especially the expected evolution of physical-chemical processes during the nominal scenario, and also on a previous prioritization effort for generic RD&D issues for four potential repository concepts (clay/shale, granite, salt, and deep borehole), described in the UFD Roadmap (DOE 2012a).

An objectives hierarchy or "value tree," which is a standard part of decision analysis, was created to evaluate RD&D activities with respect to their relevance to the safety case. Postclosure safety and five other safety-related objectives that map to the primary elements of a successful safety case, were considered to be the top-level objectives for evaluating the importance of RD&D activities and the associated issues they are meant to address. Of these six objectives (site selection, site characterization, repository design, preclosure safety, postclosure safety, and confidence-building), postclosure safety was the only one used at this stage to establish a semi-quantitative importance rating for the technical issues (based on their relationship to the three safety functions). However, the other objectives were evaluated with respect to how well they could be supported by an *in situ* field-scale heater test.

Initial importance ratings for the strawman RD&D issues were reviewed by the workshop participants in two breakout sessions; one breakout group considered issues from a preclosure design/operations perspective and the other breakout focused on postclosure aspects of the disposal system. Of the thirty identified "feature/process" issues, about ten of them fell into the category of "high" importance for a nominal evolution scenario with high-heat load waste. The workshop participants also determined that for a human intrusion scenario another set of four issues, related to the waste form and associated chemical interactions, should be rated as "high" importance. It was agreed that although these human intrusion issues might not warrant first priority for the current generic research program (which is more focused on nominal performance), they need to be funded in the coming years at some level. Workshop breakout groups also reviewed ratings for the twenty other strawman RD&D issues (comprised of modeling issues, *in situ* testing issues, and confidence-building issues). Most of these were given high importance ratings, meaning that there is still some generic RD&D that could be completed.

The foregoing issue rating effort consumed the first day of the workshop. The second day of the workshop was devoted to evaluating *in situ* field-testing activities and whether a specific RD&D proposal called the Salt Defense Disposal Investigations (SDDI) test could potentially support the primary safety case objectives mentioned above, as well as addressed remaining uncertainties in the high- or medium-importance RD&D issues.

A post-workshop assignment, agreed to by the participants, was to suggest RD&D activities (lab, field, modeling) that would address remaining RD&D issues that had a high or medium rating. The proposed RD&D activities have been documented by filling out test questionnaires that provide detailed information about the conduct of each activity. After the workshop, twenty-four of these questionnaires were received. They have been used to inform the recommended activities for FY14 and beyond and, in a couple of cases, were adopted directly as new and high-priority RD&D activities. In other cases they were used to supplement and improve ongoing activities.

The recommended suite of RD&D activities going forward encompasses laboratory, modeling, and field testing. New activities are underlined and the numbering system conforms to the FY12 Salt R&D Study Plan that has been used previously to manage salt RD&D activities. The recommended FY14 activities are:

1. Existing Salt Data Compilation and Assessment

2. Test Planning for Re-Entry into the North Experimental Area of WIPP

3. Laboratory Studies
    3.1. Hot Granular Salt Consolidation, Constitutive Model and Micromechanics
    3.2. Laboratory Interbed Shear Testing
    3.3. Laboratory Thermomechanical Testing of Intact Salt
    3.4. Brine Migration Experimental Studies
    3.5. Thermal-Hydrologic-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay Interbeds on Permeability and Brine Migration in Salt at High Temperatures and Pressures
    3.6. Study of Thermodynamic Properties of Brines, Minerals and Corrosion Products in High Temperature Systems
    3.7. Radionuclide Solubility Measurements

4. Modeling Studies Related to Salt
    4.1. Safety Framework
    4.2. Total System Performance Assessment (TSPA) Model Development
    4.3. Generic Salt Repository Benchmarking – US/German Collaborative Effort
    4.4. Thermomechanical-Hydrological and Chemical (TMHC) Model Development
    4.5. Brine Migration Modeling in Rock Salt

5. International Collaboration

6. Salt Instrumentation Development and Test Methodologies

7. Thermal Field Testing

With regard to Activity 7, Thermal Field Testing, the conceptual SDDI proposal was considered as an example of full-scale *in situ* field tests, during the workshop discussions. The SDDI concept was developed to examine issues related to disposal of DOE-owned waste (primarily waste from defense-related activities), which is generally of lower heat output than either commercially generated UNF or HLW arising from reprocessing of commercial UNF. The SDDI is proposed for the newly mined area at the WIPP in the Salado bedded salt formation of the Permian Basin, but will provide generic information and concepts for bedded salt beyond the Salado (see Appendix I).

The workshop participants reached a consensus that large-scale *in situ* testing, such as the SDDI concept, has the potential to support a number of safety case objectives, if designed appropriately. A consensus was also reached that once the field test is designed and adequately instrumented to measure and monitor thermal and brine-related parameters, it has the potential to address several technical issues for lower heat-load waste. It should be emphasized that the specific SDDI proposal still requires detailed test modeling and planning before its technical merits and operational requirements can be finalized. Therefore, it is recommended that sufficient analysis and test planning be funded and conducted to finalize the specific objectives and details of the proposed SDDI test, prior to its implementation. It is also recommended that other individual lab or *in situ* tests (heated and non-heated) be conducted with simpler, more focused data objectives. An example of these more focused tests that received consideration during the workshop was an *in situ*, single-heater test (see Table H-2), which would allow measurement and monitoring of thermally driven processes in a shorter timeframe and thereby provide additional data to support the broader SDDI test design.

Several new testing and monitoring methods have been proposed that are intended to support an *in situ* thermal field test. Most of these have not yet been recommended for FY14 funding. However, it is recommended that these methods be evaluated for suitability as part of the detailed planning for the SDDI test and possibly incorporated into its final design.

Details about Activities 1 through 7 are given in Section 8 of this report, including progress on the activities for FY12 and FY13.

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ACRONYMS

C	Chemical processes
CSNF	Commercial Spent Nuclear Fuel
DOE	Department of Energy
DOE-CBFO	Department of Energy Carlsbad Field Office
DOE-NE	Department of Energy Office of Nuclear Energy
DOE-EM	Department of Energy Office of Environmental Management
DRZ	Disturbed Rock Zone (same as the EDZ)
EBS	Engineered Barrier System
EDZ	Excavation Disturbed Zone
FEP	Feature, Event, Process
H	Hydrologic processes
HLW	High-Level Radioactive Waste
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
M	Mechanical processes
NBS	Natural Barrier System
PA	Performance Assessment
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RH	Relative Humidity
SDDI	Salt Defense Disposal Investigations
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
T	Thermal processes
TRU	Transuranic
TSPA	Total System Performance Assessment
UFD	Used Fuel Disposition (Campaign)
UNF	Used Nuclear Fuel
URL	Underground Research Laboratory

U.S.	United States
WIPP	Waste Isolation Pilot Plant
WP	Waste Package

1. INTRODUCTION

Because the future site of a permanent U.S. geologic repository for used nuclear fuel and nuclear waste will not be established for some time (DOE 2013), the Department of Energy's Used Fuel Disposition (UFD) Campaign within its Office of Nuclear Energy (DOE-NE) has pursued research, development, and demonstration (RD&D) activities to support four of the most likely disposal concepts (DOE 2012a). The first three are mined repositories in three different "generic" host-rock media: salt, shale/clay, and crystalline/granite. The fourth concept is emplacement of radioactive waste in deep vertical boreholes in crystalline basement rock (Brady et al. 2009). The work described in the present study focuses in greater detail on the generic bedded salt repository concept, and aims to define a set of key RD&D activities needed to support a generic safety case for disposal of heat-generating radioactive waste, such as high-level radioactive waste (HLW) and used nuclear fuel (UNF), in bedded salt, given the current state of knowledge. The RD&D activities recommended here are based on the outcomes of a DOE workshop held March 6-7, 2013: "Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt." This workshop had the goals of (1) formulating an expert consensus on the relative importance of various technical issues for disposal of heat-generating waste in bedded salt and (2) recommending RD&D activities to address these issues, including modeling studies, laboratory studies, and field testing.

Disposal of heat-generating radioactive waste in a suitable salt formation is attractive because the salt host rock is essentially impermeable, self-sealing, and thermally conductive. Thus, a mined repository in salt (referred to herein as a salt repository) could potentially achieve complete containment, with no radionuclide releases to the environment for the undisturbed scenario, i.e., for the expected evolution scenario that does not have any human intrusions into the repository, such as borehole drilling, and does not encounter any natural disruptive events, such as volcanism (Hansen and Leigh 2011). Furthermore, a significant experience base exists from earlier studies and ongoing efforts (Pierce and Rich 1962; DOE 1986; DOE 1996; Lomenick 1996; Kuhlman et al. 2012; GRS 2012; Hansen et al. 2013; Kuhlman 2013). Chief among these efforts is the operational radioactive waste salt repository for defense-generated transuranic (TRU) waste, the Waste Isolation Pilot Plant (WIPP)[1], sited in the Delaware Basin of Southeast New Mexico in the U.S. Lessons learned from siting and operating this facility can be used to support the development of a generic salt repository for heat-generating waste (Robinson et al. 2012). However, phenomena caused by decay heat from used nuclear fuel (UNF) and HLW could add some potentially beneficial and/or detrimental features, events, and processes (FEPs) that are not necessarily important for the ambient or isothermal TRU waste that is disposed at WIPP. Many of these FEPs, or "issues" as they will be called here, could benefit from additional research and development activities, as well as further *in situ* demonstration and testing, to build confidence for the salt repository concept for heat-generating radioactive waste. However, given the already substantial basis for successful disposal and demonstrated robust performance,

[1] The Waste Isolation Pilot Plant is a DOE waste disposal facility designed to safely isolate defense-related transuranic (TRU) waste from people and the environment. Waste temporarily stored at sites around the country is shipped to WIPP and permanently disposed in rooms mined out of a bedded salt formation 2,150 feet below the surface. WIPP, which began waste disposal operations in 1999, is located 26 miles outside of Carlsbad, NM.

including past *in situ* experiments to investigate disposal of heat-generating waste (Stickney and Sambeek, 1984; Tyler et al. 1988; Rothfuchs et al. 1988; Bechthold et al. 2004), the RD&D activities recommended as a result of March 2013 Workshop are primarily meant to fortify the technical bases, to reduce lingering uncertainties, and to provide opportunity to confirm elements of the existing information. They are also intended to apply more advanced measurement methods and test designs to improve the knowledge and confidence bases, and to be proactive regarding potential questions that might be posed during a licensing proceeding, if salt were eventually chosen as the disposal medium for commercial and or defense-related radioactive waste in the U.S.

Within the scope of DOE's generic approach to RD&D for geological disposal, DOE-NE began an effort in Fiscal Year 2012 (FY12) for a science-based scope of work related to geologic disposal of heat-generating waste in a salt formation at a generic site. This workscope was documented in a "Salt R&D Study Plan," dated March 23, 2012 and agreed upon by DOE-NE and DOE-EM (McMahon 2012). The 2012 Salt R&D Study Plan had six primary activities conducted in FY12-13 (see Appendix C of the present report, which is a reproduction of the Study Plan). The work described in the current report has a primary purpose of determining the best future plan for these activities in FY14 and out-years, and how to modify them based on the outcomes of the March 2013 Workshop.

2. BACKGROUND: GEOLOGIC DISPOSAL IN BEDDED SALT

Part of the promise and appeal of geologic disposal in a bedded (or domal) salt formation is the robustness of the natural barrier system for the undisturbed, expected-evolution scenario, i.e., for the scenario with no disruptions of the repository by human-intrusion events or unlikely natural events (see 40 CFR 191.12). Under these conditions, the salt host rock by itself ensures the successful operation of the "containment" safety function that is important to all geologic disposal systems. In particular, for the undisturbed scenario, reliance on robust engineered barriers is not necessary for long-term containment of the waste (but does provide for "defense in depth"—see 66 FR 55758 or IAEA 2011), due to the extremely low fluid permeability of the native host rock, which will only allow transport of radionuclides by the very slow process of molecular diffusion. Salt host rock also resists and restores perturbations to its containment function caused by (1) mechanical stresses induced by excavation of the emplacement tunnels (which could potentially cause fast fracture transport pathways) and (2) high levels of waste heat from the disposed radionuclide inventory (which could cause high fluid pressures and mechanical stresses). Excavation stresses are ameliorated by the visco-plastic properties of the salt, causing it to creep and consolidate to a near pristine condition, while heat-induced stresses are dissipated by the rapid dispersal of the waste heat due to the high thermal conductivity of the salt.

It should be recognized that knowledge of the expected postclosure evolution of these physical-chemical processes does not come from supposition but from an extensive prior knowledge base for disposal of non-heat-generating waste in salt at the WIPP (Hansen and Leigh 2011), as well as from multiple heater experiments in salt that have demonstrated the evolution of excavated and disturbed areas (e.g., see Stickney and Sambeek, 1984; Tyler et al. 1988; Rothfuchs et al. 1988; Bechthold et al. 2004).

2.1 Repository Safety Functions

Confidence in the long-term operation of *safety functions* is part of a successful safety strategy, which is the high-level approach pursued to assure safe long-term disposal, as documented in the Safety Case—see Section 3. Substantiation of the successful operation of the safety functions is provided by a quantitative postclosure safety assessment calculation (NEA 2012), which is an integral part of the volume of evidence presented in the safety case.

Safety functions identify key attributes of material barriers that are relied upon to prevent or limit contact of the emplaced waste with the biosphere, i.e., with humans, animals, and plants. These physical barriers fall into two major categories: natural (e.g., the host rock formation) and engineered (i.e., the waste container and other man-made barriers). Robust performance of physical barriers is facilitated when they work together, each complementing the other, which is the "multiple barrier" concept identified in various regulations (e.g., 10 CFR 63.115) and safety cases (see NEA 2004). The contributions of the various natural and engineered barriers to safety confidence can be organized according to multiple safety functions (IAEA 2011):

> "The host environment shall be selected, the engineered barriers of the disposal facility shall be designed and the facility shall be operated to ensure that safety is provided by means of multiple

> safety functions. Containment and isolation of the waste shall be provided by means of a number of physical barriers of the disposal system. The performance of these physical barriers shall be achieved by means of diverse physical and chemical processes together with various operational controls. The capability of the individual barriers and controls together with that of the overall disposal system to perform as assumed in the safety case shall be demonstrated. The overall performance of the disposal system shall not be unduly dependent on a single safety function."

While different terminology is used in different countries, safety functions fall into some general categories, as described by Bailey et al. (2011):

- **Stability/Isolation Safety Function**—Two subgroupings are identified:
    - Isolating the waste from non-anthropogenic future events and climate changes, and which thus contributes to the stability of the repositories' near-field conditions and to the longevity of the natural barriers. The deep borehole disposal concept is particularly robust with respect to this safety function.
    - Reducing the probability of and consequences from anthropogenic events such as future human actions that might result in inadvertent intrusions into the sealed repository.

- **Containment—**The prevention of groundwater from coming into contact with the waste. In the case of disposal in hard rock or argillaceous formations this safety function is provided by the engineered barrier system (EBS). In the case of disposal in salt formations much of the containment function is provided by the natural barrier system. [Note: If groundwater does not contact the waste there is, in general, no mobilization or release mechanism to transport radionuclides from the repository to the accessible environment, although gas-phase transport is a potentially minor release mechanism that must be investigated. An alternative definition of containment is provided at 10 CFR 60.2: "Containment means the confinement of radioactive waste within a designated boundary."]
- **Limited or Delayed Releases—**This safety function begins to dominate once the containment functions deteriorates, e.g. for example when waste packages are breached as a result of corrosion. This is a major function of the natural barrier system as well as components of the EBS and ensures the long-term barrier capability of geologic disposal.

The specific use of safety functions to prioritize RD&D is described in more detail in Section 5 of this report, which rates RD&D issues with respect to their importance to the postclosure safety objective.

2.2 Evolution of a Generic Bedded Salt Repository

This section provides a brief description of the evolution of a bedded salt repository for heat-generating waste and how the "containment" and "limited or delayed release" safety functions are expressed during this evolution. The "stability/isolation" safety function is not discussed in detail here, but is achieved through the depth beneath the ground surface (isolating the repository from humans), the effectiveness of the long-term seal system, and the host rock's resilience (stability) to the effects of natural disruptive events (e.g., seismicity). With regard to sealing and disruptive events, it is again the visco-plasticity and creep of the salt rock that helps ensure this type of function.

The purpose of this section is to provide a background for evaluating how a specific RD&D issue might impact safety confidence via its importance to one of the repository safety functions. By understanding the physical-chemical processes that evolve in a salt repository and how they potentially impact one of the three safety functions, a more formal assessment can be made regarding the importance of the issue. This assessment is informed by the large experience base for research and performance assessment in salt disposal systems (e.g., see DOE 1996; DOE 2006; Kuhlman et al. 2012; Kuhlman 2013).

Figure 2-1 shows the major features/barriers that must be evaluated to determine how the key safety functions operate in a salt repository. These are the waste form, waste container, backfill, open excavation, excavation disturbed zone (EDZ), and pristine salt host rock. The EDZ—sometimes called the disturbed rock zone (DRZ)—represents the transition or interface region between the excavation and host rock, caused by the induced mechanical and heat stresses from the mining operations and the emplacement of heat-generating waste. Relative to the foregoing features, Figure 2-2 schematically indicates the three major states of salt repository evolution in the nominal, undisturbed scenario: (1) an excavated state prior to waste emplacement, (2) an evolving state subsequent to waste emplacement when the heat pulse is most acute, and (3) a more stable state long after waste emplacement when the heat pulse has dissipated and the mechanical stresses have mostly returned to the pre-emplacement state. The following step-by-step description of the evolution of a generic salt-backfilled repository through these three major states explains the key processes and conditions that affect the barrier safety functions and, in particular, how the containment and limited/delayed release functions are ensured through naturally occurring circumstances in a bedded salt formation.

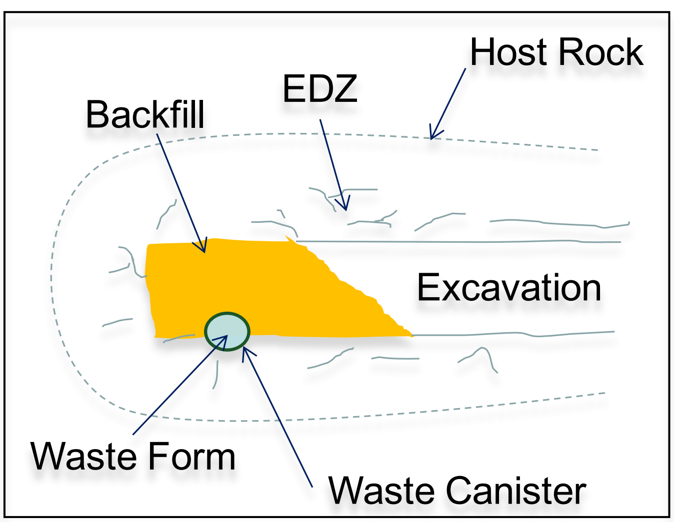


Figure 2-1. Schematic of Features of a Backfilled Repository Room.

For the nominal, undisturbed scenario, the evolutionary steps in the preclosure and postclosure phases of a bedded salt repository, relative to the functions of containment and limited/delayed releases, are as follows:

1. Initially, rock salt at depth is subjected to lithostatic stresses from the weight of overlying strata; prevailing *in situ* horizontal and vertical stresses are nearly equal or isostatic.
2. When an opening is excavated in the host rock, the *in situ* stress field is locally disturbed and a new set of stresses is induced in the rock surrounding the opening.
3. Deviatoric stresses give rise to dilatancy of the salt (volume increase by microfracturing and thus increase of porosity and permeability) forming an EDZ in the region surrounding the excavation.
4. The excavation boundaries (walls, roof, floor) will begin to converge (move inward) as the salt creeps.
5. Intercrystalline brine pressure gradients toward the excavation will cause brine to be released into the excavation from the EDZ and from any fractures that may communicate with overlying brine-bearing interbeds. Also fractures created by the stress differences allow gravity flow of the liberated brine.
6. Emplacement of heat-generating radioactive waste can further perturb the response of the host salt (increase the convergence rate) because salt creep increases as a strong function of temperature.

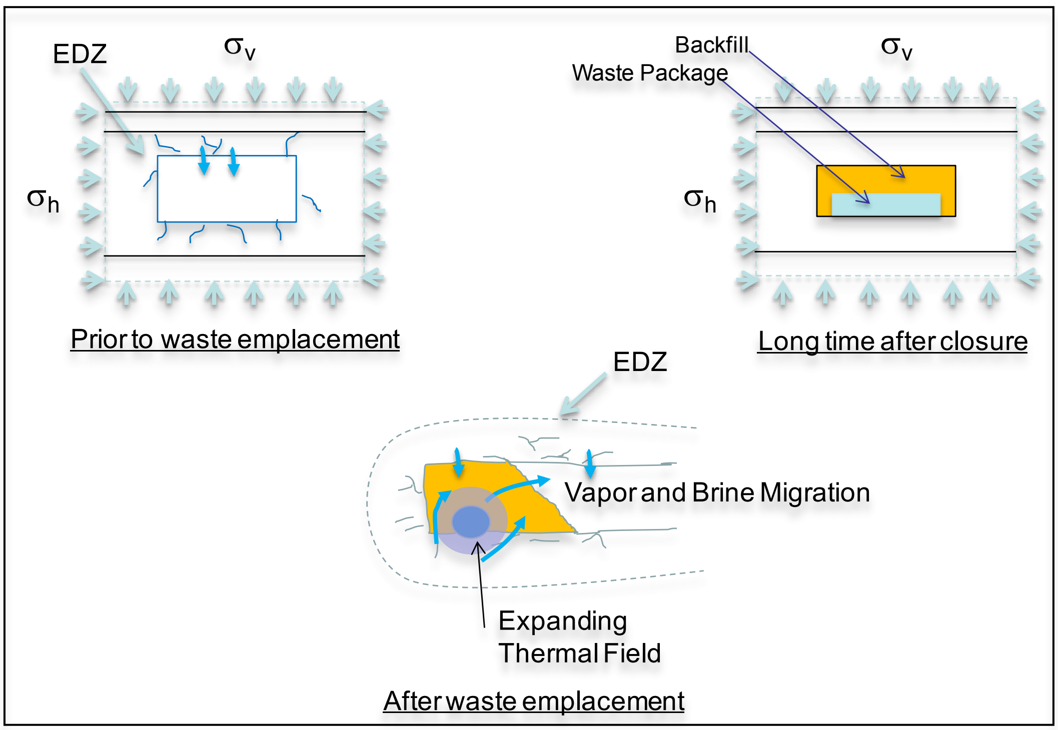


Figure 2-2. Three Major States in the Evolution of a Bedded Salt Repository for an Undisturbed Scenario.

7. Convergence of the excavation could compromise the *containment* function (i.e., via fracturing), particularly in salt formations that are not exceptionally thick and/or contain interbeds. Site selection should prefer thick salt formations.
8. A backfill of crushed salt emplaced around the waste containers will eventually limit convergence, promote healing of the damaged zones in the host rock to a state similar to intact salt, and entomb the emplaced waste, enhancing waste *containment*.
9. Backfill reconsolidation increases as the formation salt creeps into the excavation. Studies have shown that the natural water content of the run-of-mine salt is sufficient to promote fluid-assisted consolidation processes (Popp et al. 2011; Spiers and Brzesowsky 1993). Thermal activation of the creep processes in the formation salt will increase its creep rate and thereby increase the rate at which the granular salt reconsolidates. The backfill also serves to conduct heat away from the waste package, thereby reducing peak temperatures in the backfill.
10. Brine may continue to be released from the host salt into the excavation, leading to an increase in brine saturation of the backfill. The brine being drawn into the room by gravity will eventually migrate to areas beneath the floor.
11. Heat released from the emplaced waste package will tend to dry the backfill and host rock close to the waste package and cause the resulting water vapor to move outward. Heat that transfers into the host rock will tend to dry out the intercrystalline (or grain-boundary) water in the host rock and cause the water vapor to be liberated and evacuated by ventilation air or perhaps to condense in cooler regions of the repository; in local regions of potentially high thermal gradients, intracrystalline, brine-filled and brine-vapor inclusions may travel up or down the temperature gradient in the host rock, respectively.
12. Brine evaporation causes precipitation of the dissolved salts at the time of evaporation. If conditions elsewhere in the mine (>75% humidity, for example) favor condensation, local dissolution will occur.
13. The waste package prevents any brine available from contacting the waste and provides *containment* of the waste for an adequate period of time, such as for retrieval, but will eventually breach due to corrosion if sufficient brine is available, or by compaction from overburden stresses (depending on the design thickness of the waste package wall).
14. If brine is available, gas may be generated by corrosion of the waste package and, depending on the extent of the corrosion process, produce excessive gas pressure, resulting in possible fracturing or elongation of existing fractures (in the same sense as hydrofracture propagation perpendicular to the least principal stress). This could compromise the *containment* function if it were to result in enhanced communication with more permeable interbeds.
15. Assuming that some brine is available, the waste form itself can *limit the release rate* of radionuclides subsequent to container breach (depending on the waste form degradation rate).
16. The mobility of released radionuclides within and adjacent to the waste package will be influenced by the prevailing geochemistry, which in the presence of corrosion, would be strongly reducing, resulting in *limited and delayed releases* due to the higher stability of minerals in reduced form.
17. If the backfill and host rock function as intended, there would be essentially no releases from the repository and *containment* would be achieved.

18. After the waste heat has dissipated, and creep of the host rock and consolidation of the backfill has ceased, the system reaches a near equilibrium state, wherein mass transfer to geologic units beyond the host rock could at most occur via the slow process of mass diffusion (which still would require an interconnected network of pores—something unlikely in consolidated halite).

A key part of the overall safety case, outlined in Section 3, is a demonstration of the ability of the safety functions to continue to operate throughout the evolutionary steps described above. This requires demonstrable scientific knowledge about these evolutionary processes and the associated parameters that quantify the processes. While a large knowledge base exists for the emplacement of non-heat-generating, low-activity radioactive waste in salt (Kuhlman et al. 2012)—based on the successful operation of the WIPP—there are still some issues remaining with respect to repository evolution for heat-generating, high-activity waste. Prioritization of these remaining RD&D issues, according to their importance to the safety functions, is a key objective in establishing a successful RD&D program that will enhance safety confidence. Issue prioritization (or rating) was one of the primary inputs to the March 2013 workshop described in this report. The rating methodology and the associated importance values assigned to each issue are reviewed in Section 5. Much of the basis for the assigned importance values in Section 5 is predicated on the evolution of the repository described above and how it could either enhance or compromise safety functions, such as containment.

A final consideration in developing a successful RD&D program is the state of the scientific knowledge base relative to repository performance for disruptive scenarios, such as natural or human disruptions. While the work described here primarily focuses on the undisturbed scenario, which is appropriate at this stage of generic repository investigations, it is important to initiate and/or continue work on issues that may become important for disruptive scenarios. In the workshop considerations, human intrusion was considered to be a representative disruptive scenario. RD&D issues were evaluated relative to the primary safety function operative for the disruptive human-intrusion scenario, which is limited or delayed releases (Table 7-1)—since the containment function has been compromised in this scenario.

3. SAFETY CASE CONTEXT FOR RD&D ACTIVITIES

The formulation of a *safety case* for bedded salt host rock is consistent with DOE-NE's current generic approach to repository research and development and to the consent-based repository siting procedure recommended by the Blue Ribbon Commission on America's Nuclear Future (BRC 2012). A safety case for bedded salt will provide the structure by which to compare the merits of a bedded salt repository with the merits of generic repositories sited in other media. It also will provide a structured framework to (1) guide the activities of the implementer (e.g., DOE) through the various phases of repository development, including the planning and prioritization of RD&D activities, and (2) transparently communicate the current understanding of repository safety to a broad range of stakeholders, decision makers, and the general public, as well as explain the nature and potential impact of any remaining uncertainties (MacKinnon et al. 2012).

The development of any geologic repository takes place over a period of years and, as the repository program evolves, the level of completeness and rigor in the associated safety case becomes more robust with additional data from site characterization, repository design, and safety assessment activities. These three key activities combine to form an iterative process wherein the safety assessment from one development phase feeds site characterization and design at the next phase (Figure 3-1). Planning for, and transitioning to, each subsequent phase requires some form of decision-making process, as indicated in Figure 3-1, to prioritize RD&D activities designed to resolve remaining issues and uncertainties. Public and other stakeholder participation are important inputs to the decision-making process, before proceeding to the next phase of development (NRC 2003).

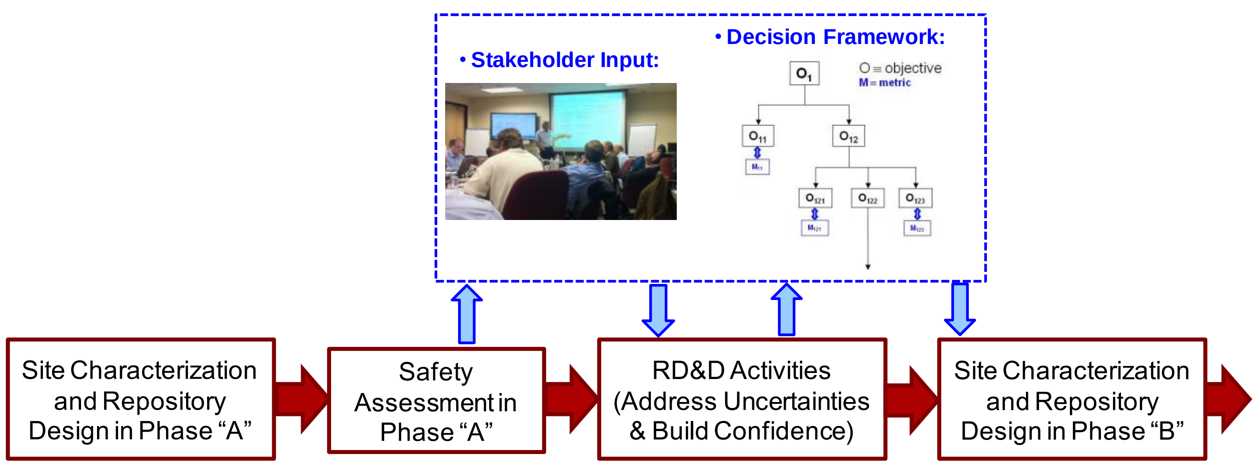


Figure 3-1. Iteration of Site Characterization, Repository Design, and Safety Assessment as Part of a Decision-Making Process to Prioritize RD&D Activities.
[Phase "A" and Phase "B" are generic phases such as "site suitability," "licensing", or "construction".]

The remainder of this section, and the next section, document the methodology of a decision-making process developed to help guide salt repository investigations at this generic stage. This formed part of the basis for an initial prioritization of potential salt RD&D needs, used as a starting point for Workshop discussions. However, as noted earlier, a significant national (and international) experience base exists with respect to this transitioning and prioritization process, based on the successful completion of all phases through construction for disposal of TRU waste at WIPP and all phases through license submittal for the proposed Yucca Mountain repository for SNF and HLW. Therefore, this methodology simply serves as a more formal method and aid for guiding future RD&D.

3.1 Major Elements of the Safety Case

As described in more detail in the next section, the major components or elements of a safety case can be used to structure a comprehensive objectives hierarchy that guides and evaluates science and engineering activities that help bolster safety confidence. With these safety case elements as the objectives or goals of RD&D activities, sound decisions can be made as to the relative importance of each activity, based on how well each one supports these goals or objectives. These elements or components of the safety case have been outlined elsewhere (NEA 2004; NEA 2009; Bailey et al. 2011; Schneider et al. 2011; Sevougian et al. 2013a), but are summarized as follows:

- *Statement of Purpose*. Describes the current stage or decision point within the program against which the current strength of the safety case is to be judged.
- *Safety Strategy*. This is the high-level approach adopted for achieving safe disposal, and includes the sub-elements of an overall management strategy, a siting and design strategy, and an assessment strategy.
- *Assessment Basis*. This element includes the sub-elements of site selection, site characterization, and repository design. It includes a description of (a) the primary characteristics and features of the selected repository site, (b) the location and layout of the repository, (c) a description of the engineered barriers, and (d) a discussion of how the engineered and natural barriers (i.e., the multiple-barrier concept) will function synergistically and how these barriers are expected to ensure the successful fulfillment of key safety (or barrier) functions such as containment, limited or delayed radionuclide releases, and isolation/stability of the repository with respect to external influences and events.
- *Disposal System Evaluation.* This element includes two major sub-elements for assessing repository behavior: a preclosure safety analysis and a postclosure safety (or performance) assessment (Sevougian et al. 2013b; NEA 2012). It is primarily a *quantitative* assessment of potential radiological consequences associated with a range of possible evolutions of the system over time, and includes an analysis of how well the barriers perform their functions. However, it also includes *qualitative* confidence-building arguments related to the intrinsic robustness of the site and design, as well as insights gained from natural and anthropogenic analogues. Sensitivity and uncertainty analyses to identify/quantify key remaining uncertainties and guide future RD&D are also an important aspect of this element of the safety case.
- *Statement of Confidence and Synthesis of Evidence*. The statement of confidence is based on a synthesis of safety arguments and analyses, and includes a discussion of "completeness" to ensure that no important issues have been overlooked in the safety

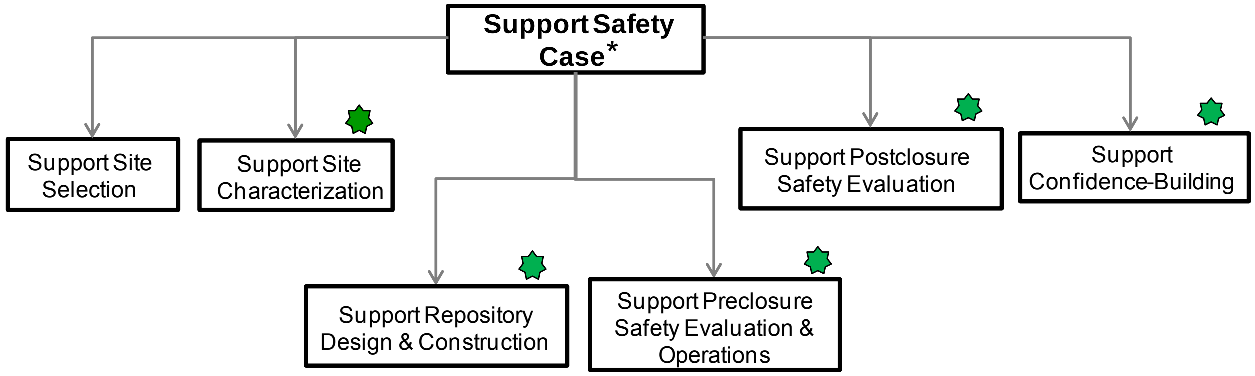
case. The statement of confidence recognizes the existence of any open issues and remaining uncertainties, and includes perspectives about how they can be addressed in the next phase(s) of repository development, if they are considered important to establishing safety.

3.2 Safety Case Objectives Hierarchy

Remaining technical, socio-political, and economic questions at any stage of repository development should be organized in a comprehensive *objectives hierarchy* that is a standard part of decision analysis (Keeney and Raiffa 1993). This objectives hierarchy, also called a "value tree" (von Winterfeldt and Edwards 1986; Weil and Apostolakis 2001), provides a logical structure for choosing between alternatives in a complex decision problem by assigning a *metric* or *performance measure* that quantifies the degree of achievement of each objective (Keeney 1980; Kenney 1992). An example of its application to the selection of a nuclear waste repository site may be found in Merkhofer and Keeney (1987). In the present context the highest objective to be achieved is to choose an appropriate set of RD&D activities that advance the safety case for a generic bedded salt repository. To evaluate the degree of that achievement with a logical and measurable construct, the elements and subelements of the safety case structure, described above, are used to formulate the appropriate objectives hierarchy. RD&D activities can then be measured against one or more of the objectives in this safety-case-based hierarchy for their potential value in supporting the overall safety case.

Figure 3-2 shows the top-level objectives hierarchy formulated to evaluate salt RD&D activities based on their importance to the safety case. Any activities that are planned and conducted should advance one or more of the objectives in Figure 3-2. As indicated in the figure, the primary RD&D being considered in this study, and in the associated March 2013 Workshop (see Section 7), is related to *sub*elements of the safety case under the major elements *assessment basis* and *disposal system evaluation*, namely, site selection, site characterization, repository design, preclosure safety, postclosure safety, and stakeholder acceptance (i.e., confidence building). R&D work on these subelements is the most beneficial for safety case confidence at this phase of generic repository investigations.

Beneath the top-level objectives in Figure 3-2, a more specific set of sub-objectives may be formulated for classifying and measuring the success of RD&D activities, such as "support the technical basis for EBS design." A complete list of these sub-objectives (i.e., the complete value tree) is presented in concise fashion in Figure 3-3.



* Safety case is for disposal of both DOE-owned and commercial heat-generating waste. (Note: Transportation system, waste receipt, and surface facilities are not considered in this report.)

Indicates objective considered in the March 2013 Workshop.

Figure 3-2. Safety Case Objectives Hierarchy.

Support Safety Case
(Assessment Basis & Disposal System Evaluation)

- **Support Site Selection**
- **Support Site Characterization**
- **Support Preclosure Safety Evaluation and Operations**
- **Support Repository Design and Construction**
  - Support Underground Layout and Drift Design
  - Support Ventilation and Drainage Systems Design
  - Support Access Shafts/Drifts Design
  - Support Backfill Design
  - Support Seal System Design
  - Support Ground Support Design
  - Support Power Supply Design
  - Support Waste Canister Design
- **Support Postclosure Safety Evaluation**
  - Support EBS Technical Basis
  - Support Geosphere Technical Basis
  - Support Biosphere Technical Basis
  - Support Total System Performance Assessment Model
- **Support Confidence-Building**
  - Support Peer Review
  - Support International Collaborations
  - Support *In Situ* Testing and Demonstrations
  - Support Natural and Anthropogenic Analogues
  - Support Verification, Validation, Transparency and Traceability

Figure 3-3. Safety Case Objectives Hierarchy Considered in the March 2013 Workshop.

3.3 Decision-Making Framework

A numerical value ranking of each proposed RD&D activity could be devised by assigning (1) a value rating to each RD&D activity relative to each objective in Figure 3-2, combined with (2) a normalized importance weight assigned to each of these six objectives. This type of prioritization exercise has previously been carried out within the UFD campaign for a set of generic RD&D "issues" applicable to the four main repository concepts, with a numerical value assigned to each issue (DOE 2012a, App. B). In the present study specific to bedded salt, and in the Workshop conducted to support this study, a less formal prioritization approach has been adopted, based more on expert judgment than a strict numerical ranking. Future prioritization efforts for salt RD&D are expected to use a decision analysis methodology, based on value or utility (Merkhofer and Keeney 1987), with the evaluation of postclosure objectives supported by future quantitative performance assessments (MacKinnon et al. 2012, Sec. 4.5).

It is important at this point to make a distinction between RD&D "issue" and RD&D "activity". The term "issue" is used in the present study to represent some type of remaining uncertainty that should be addressed to enhance safety confidence. This is a similar definition to that adopted in the UFD Roadmap (DOE 2012a):

> "Issues are, in the context of the UFDC Disposal R&D roadmap, opportunities to conduct R&D to fill information needs and knowledge gaps. The use of the word 'issue' does not necessarily imply that information is needed or a knowledge gap is present, but rather presents a topic that needs to be addressed to implement a geologic disposal system. This approach is similar to the 'issue resolution strategy' approach that has been utilized in the past U.S. site characterization programs."

The term "activity" is used in the present study to represent some type of work to resolve the issue or to advance the state of knowledge about the issue, with the goal being to reduce uncertainty and to build confidence in safety. Given these definitions of "issue" and "activity," the high-level decision-making method for prioritizing RD&D activities is the two-step process shown in Figure 3-4.

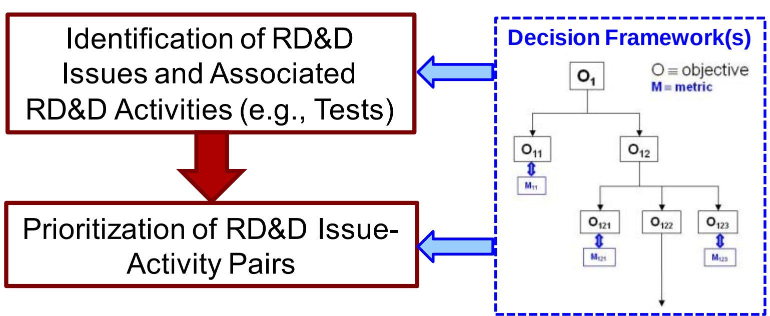


Figure 3-4. High-Level Decision-Making Process for Salt RD&D.

This process may be compared to a five-step process outlined in the UFD Roadmap, of which only the first two steps have been formalized to date (DOE 2012a):

1. Identify potential R&D issues (information needs and knowledge gaps)
2. Characterize and evaluate R&D issues to support prioritization
3. Identify overall UFDC issue priorities based on the evaluation
4. Identify R&D projects to address high-priority issues
5. Evaluate R&D projects and select projects for funding.

In particular, the process for identification, evaluation, and selection of R&D "projects" (or "activities," as they are termed here), shown in Steps 4 and 5, has not to date been formally documented (DOE 2012a, Sections 2.4 and 2.5). Nevertheless, science and engineering work has been funded by the UFD Campaign in topical areas related to the R&D *issues* that received the highest priority ratings in the UFD Roadmap (DOE 2012a, App. B). Thus, since only the underlying RD&D issues have been evaluated in the Roadmap, the metric used to evaluate RD&D issues (such as "importance to postclosure performance") are considered to be *proxy* metrics for evaluating or rating the importance of the associated R&D activities. (Recall that it is the actual RD&D activities that support or build confidence in the safety case.) This approach of using a proxy or indirect measurement of an objective is often adopted in decision analysis, when a direct metric cannot easily be assessed (Keeney and Gregory 2005). This same approach is adopted in this report, i.e., the importance ratings for salt RD&D issues is used as a proxy for the importance of the associated RD&D activities (testing, modeling, etc.) needed to resolve the issues.

As described in more detail in Section 5, at this stage of planning and prioritization the only "quantitative" metric used to evaluate issue importance is "importance to postclosure safety," which is quantified on a coarse scale of high ("H") importance, medium ("M") importance, and low ("L") importance—based on the impact of the underlying RD&D issue to a set of four repository safety/design functions (see Table 5-1). As noted by the NWTRB (2011, p. 53), "performance assessment is arguably the most important part of the safety case...," and it is not unreasonable at this stage of RD&D planning to emphasize a metric related to postclosure safety for prioritization of science and engineering. However, even though this is the sole "quantitative" metric applied, other safety objectives in Figure 3-2, such as "confidence-building," have been given strong consideration (see Section 5.2), since a safety case must present multiple lines of evidence and reasoning to support all elements of repository development and safety.

Besides an importance evaluation with respect to the objectives hierarchy in Figures 3-2 and 3-3, other types of information are either formally or informally used in the prioritization of RD&D activities. One of these is an evaluation of the current state-of-the-art or current state of knowledge for a particular RD&D issue. Issues or FEPs that have had little previous research conducted on them but are considered highly important to postclosure safety will be given a higher priority than either (1) issues with a lower importance to safety or (2) issues that may be highly important to safety but already have had extensive research conducted (such that associated uncertainties are minimal). This type of information was formalized in the UFD Roadmap, in the form of a seven-level "state-of-the-art" rating (DOE 2012a, Sec. 2.2.3), and evaluated for each of the UFD FEPs (DOE 2012a, App. A). Here, the state-of-the art for each RD&D issue is taken into consideration in the proposed RD&D activities in Section 8, but is not given a formal rating. For example, information regarding the state-of-the-art of many important RD&D issues is provided in the proposed RD&D test questionnaires (Question #6) in Appendix H of this report. [Also see Appendix A of the present report for a definition of the seven levels and a reproduction of the UFD Roadmap state-of-the-art ratings for salt-relevant FEPs.]

4. REMAINING SALT RD&D ISSUES/NEEDS

Based on the abundance of existing technical information from prior investigations in the U.S. and abroad (Kuhlman et al. 2012; Kuhlman 2013; GRS 2012), including the multiple performance assessment iterations at WIPP (DOE 1996; DOE 2004; DOE 2009), a strong technical basis already exists for a safety case for a bedded salt repository. However, phenomena caused by decay heat from heat-generating waste, such as HLW and UNF, could add some potentially beneficial and/or detrimental FEPs that are not necessarily important for the significantly cooler TRU waste that is disposed at WIPP. This includes material property changes coupled to fluid movement that is induced or enhanced by thermal-hydrologic-mechanical (THM) processes, especially in association with large deformations resulting from repository room closure and salt/or backfill consolidation. New chemistry related effects, deemed unimportant for low-temperature TRU waste, may also be important for heat-generating waste, such as the reaction of acidic brines with metal waste containers (Molecke 1983). These considerations also apply to FEPs related to the physical and chemical characteristics of the heat-generating waste, such as HLW and UNF, since these characteristics are likely to be appreciably different than TRU waste. In addition, site-specific considerations and differences in the disposal concept, container types, and performance period could give rise to potentially important FEPs, including site-specific human–intrusion FEPs.

Despite the fact that some potential issues related to heat-generating waste are site-specific, research for a “generic” salt site is beneficial at this time, in the event that a U.S. nuclear waste repository were to be sited in a salt formation. In order to focus this generic research on important topics, a number of past studies and literature sources have been considered. This large salt knowledge base (Kuhlman et al. 2012) is considered in combination with the assumed evolution of a heat-generating waste repository described in Section 2 to develop a set of remaining RD&D issues or uncertainties that might benefit from additional research.

An initial compilation of potential “issues” was taken from the UFD FEPs list for generic repositories (DOE 2012a, App. A), but modified slightly to be more specific for salt repositories (Sevougian et al. 2012, App. A). This list from Sevougian et al. (2012) was then culled to primarily those technical issues or FEPs related to Geosphere and EBS processes, in order to focus continuing and new salt RD&D on issues most amenable to the type of generic research being conducted at this time. In particular, FEPs related to External Factors (such as Geologic Processes, Climatic Processes, and Future Human Actions) and to the Biosphere were removed from consideration. The original list was also screened for certain FEPs that were thought unlikely to be of enough importance to warrant generic research, such as HLW glass recrystallization (2.1.02.04) and pyrophoricity (2.1.02.05). The remaining set of generic FEPs, listed in Appendix A of this report, helped inform the establishment of a consolidated “Salt RD&D Issue List” (Table 4-1) for the March 2013 Workshop.

In addition to the FEPs list in Appendix A, a number of other literature sources and previous salt research and testing were also accounted for in the compilation of the candidate list of salt RD&D issues to be investigated in the current context of generic repository investigations. Of particular interest are the issues outlined in Section 5.2 (Table 4) of Hansen and Leigh (2011), the set of goals in the Salt Defense Disposal Investigations (SDDI) proposal (DOE 2012b, Sec. 1), the issues and proposed *in situ* testing activities in Hansen (2013), and the issues considered in the 3rd U.S.-German Workshop (Hansen et al. 2013). These helped form the basis for developing the consolidated list of remaining issues that are candidates for salt RD&D activities (tests, modeling, etc.). This consolidated list of 48 "strawman" issues is presented below in Table 4-1, and is mapped in Appendix B, Table B-1, to the corresponding FEPs listed in Appendix A. Also given in Table 4-1, Column 2, are the safety objectives (Figure 3-4) to which the issues are most relevant.

Table 4-1. Strawman (Pre-Workshop) Salt RD&D Consolidated Technical Issues

Salt RD&D Technical Issue	**Safety Objective:** **D = Design & Construction** **PrSO = Preclosure Safety & Operations** **PoS = Postclosure Safety**
Wastes and Engineered Features (EBS) Feature/Process Issues	
1. Inventory and WP Loading	D, PrSO, PoS
2. Physical-chemical properties of crushed salt backfill at emplacement	D, PrSO, PoS
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	D, PrSO, PoS
4. Changes in chemical characteristics of brine in the backfill and EBS	D, PoS
5. Mechanical response of backfill	D, PrSO, PoS
6. Impact of mechanical loading on performance of the WP	D, PoS
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	D, PrSO, PoS
8. Corrosion performance of the waste package	D, PoS
9. Mechanical and chemical degradation of the waste forms	D, PoS
10. Brine flow through waste package	D, PoS
11. Changes in chemical characteristics of brine in the waste package	D, PoS
12. Radionuclide solubility in the waste package and EBS	D, PoS
13. Radionuclide transport in the waste package and EBS	D, PoS
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues	
14. Stratigraphy and physical-chemical properties of host rock	D, PrSO, PoS
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	D, PrSO, PoS
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	D, PrSO, PoS
17. The formation and evolution of the EDZ	D, PrSO, PoS
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	D, PoS
19. Chemical characteristics of brine in the host rock	PoS
20. Changes in chemical characteristics of brine in the host rock and EDZ	D, PoS
21. Radionuclide solubility in the host rock and EDZ	PoS
22. Radionuclide transport in the host rock and EDZ	PoS
Repository System (EBS and Geosphere combined) Feature/Process Issues	
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	D, PrSO, PoS
24. Buoyancy of the waste packages	D, PoS
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	D, PrSO, PoS
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	PoS
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	PoS
28. Performance of seal system	D, PoS

Salt RD&D Technical Issue	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations PoS = Postclosure Safety
29. Performance of ground support	D, PrSO, PoS
30. Performance and effects of ventilation	D, PrSO, PoS
Modeling Issues	
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	D, PoS
32. Appropriate representation of coupled processes in process models	D, PoS
33. Appropriate representation of coupled processes in TSPA model	PoS
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	D, PoS
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	D, PrSO, PoS
36. Efficient uncertainty quantification and sensitivity analysis methods	D, PrSO, PoS
37. Verification and validation	D, PrSO, PoS
38. Data and results management	D, PrSO, PoS
***In-Situ* Testing/Design/Operations Issues**	
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	PrSO, PoS
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	D, PrSO, PoS
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	D, PrSO, PoS
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	PrSO, PoS
Confidence-Building Issues	
43. Develop generic safety case	
44. Comparisons to natural and anthropogenic analogs	
45. International peer review and collaboration	
46. In-situ testing and demonstrations	
47. Verification, validation, transparency, and traceability	
48. Qualitative arguments about the intrinsic robustness of site and design	

[Note: The safety objective "support site characterization" is not explicitly included in Column 2 of Table 4-1 because the two workshop breakout groups—see Section 6—were aligned to the two main operational phases of a repository: preclosure and postclosure. However, site characterization is implicitly related to all of the Natural Barriers issues in Table 4-1. Also, the confidence-building safety objective and its sub-objectives in Figures 3-2 and 3-3 are essentially mapped directly to a set of "issues" (43 to 48) listed at the end of Table 4-1. Furthermore, although the Postclosure Safety sub-objectives "Support EBS Technical Basis" and "Support Geosphere Technical Basis" are not additionally listed in Figure 3-3 as sub-objectives under the higher-level "Design" and "Preclosure" objectives, they are clearly related to the latter, as indicated in Table 4-1. Similarly, the "Support TSPA" sub-objective, which only appears under the "Support Postclosure Safety Evaluation" objective in Figure 3-3, is clearly related to the major objectives of "Repository Design" and "Preclosure Safety" (as shown in Table 4-1 by the mapping of modeling issues 31 to 38 to either of these two objectives) because the repository design must support postclosure safety, and because processes that begin during the preclosure period subsequent to waste emplacement may need to be modeled to provide appropriate initial conditions for a postclosure safety assessment.]

5. RELATIVE IMPORTANCE RATINGS FOR THE CONSOLIDATED SALT RD&D ISSUES

An assessment of repository safety after closure addresses the ability of a site and repository facility to meet safety standards and to provide for the safety *functions* (Bailey et al. 2011) of the engineered and/or geological components (see Section 2), such as containment by engineered and natural barriers or reduction in the rate of movement of radionuclides in the engineered and natural barriers (cf. 10 CFR 63.2 and 40 CFR 191.13/14). In this section, these postclosure safety functions, as well as one design function, are used as a basis for rating the relative importance of RD&D issues and, by proxy, the testing/modeling activities proposed to reduce uncertainties associated with these issues.

5.1 Issue Importance Ratings by Safety/Design Function

The initial (pre-workshop or "strawman") importance ratings developed here are based on the expected repository performance for the nominal evolution scenario, i.e., for the scenario that does not have any human intrusions into the repository, such as borehole drilling, and does not encounter any natural disruptive events, such as seismicity or volcanism. During the March 2013 Workshop, these pre-workshop ratings were evaluated by the experts and a consensus (within each breakout group—see Section 7) was reached as to any recommended changes to these ratings.

The importance ratings presented below are based on a "high" heat load, i.e., a heat load more appropriate for hotter commercial HLW and UNF (at least above boiling at the outer wall of the waste container) than for lower heat DOE-managed HLW and SNF. This makes sense because it is a more "inclusive" way to prioritize RD&D issues and develop associated RD&D activities, since higher heat loads cause more complex physical-chemical interactions that will affect the performance of a repository for commercial radioactive waste, or a "commingled" radioactive waste repository (BRC 2011; BRC Staff 2011). However, even for a waste repository exclusively used for lower heat-load waste, such as only DOE-owned waste (Sevougian et al. 2013a), temperatures can approach boiling in the surrounding salt for the hottest Savannah River or Hanford HLW, and exceed boiling for DOE SNF and Naval fuel (Carter et al. 2012, Sec. 4.1).

The safety and design functions used to rate salt RD&D issues relative to the postclosure safety objective are defined in Table 5-1. Each function is associated with one or more key parameters or characteristics, which help better explain the purpose and operation of the particular function. There are two general significance levels for safety/design functions: primary or secondary, as defined in Table 5-1. A secondary function plays a subsidiary role to a primary function or plays no role until the primary function "fails."

The importance rating given to each of the 48 consolidated salt RD&D issues depends on both (1) its "impact" or relationship to one of the postclosure safety or design functions defined in Table 5-1 and (2) on the significance level of the function (whether primary or secondary). There are three impact levels for the issues (as defined in Table 5-2): direct (but potentially significant), indirect (but potentially significant), or weak (whether it is a direct or indirect impact). These impact levels apply both to the performance of a function (for the first 30 FEP-type issues) or to the confidence in the ability to demonstrate that performance, through either modeling or *in situ* testing (for the 8 modeling issues and the 4 *in situ* testing issues, respectively). The combination of significance level for a function and impact level for an issue provides a value rating ("H", "M", or "L") for each issue, as shown in Table 5-3. The evaluation of each RD&D issue, according to Tables 5-1 to 5-3, along with the brief explanation of the basis for the evaluation is given in Table 5-4. [Note: The confidence-building "issues" listed at the end of Table 5-4 are not amenable to the rating method given in Tables 5-1 to 5-3, but are rated instead by expert opinion.]

Table 5-1. Postclosure Safety and Design Functions

Function	Type	Significance Level	Definition	Examples of Key Associated Parameter(s) or Characteristic(s)
Isolation/stability	Safety	Primary (P)	Aspects of the repository that isolate the waste and the EBS from external events or changes, and therefore help maintain the integrity and longevity of the barriers.	• (high) seal integrity • (thick) host rock zone horizon • (non-) communication between salt beds and interbeds
Containment	Safety	Primary (P)	Aspects of the repository that prevent fluid contact with the waste.	• (very low) permeability
Limited or delayed releases	Safety	Secondary (S)	Aspects of the repository that reduce the transfer of radionuclides to the accessible environment after the containment function is compromised.	• (high) sorption • (low) solubility • (low) dissolution rates
Retrievability	Design	Primary (P)	Aspects of the repository that allow for retrievability of the emplaced waste without any releases, for a specified period of time after closure.	• (sufficient) WP thickness

Table 5-2. *Impact* of an R&D Issue on Performance of a Safety/Design Function (for Feature/Process issues), or on Confidence in the Demonstration of that Performance (for modeling or *in situ* tests)

Impact of an RD&D Issue on the Performance of a Postclosure Safety or Design Function	
D	Direct and potentially significant impact on the success of a safety or design function
I	Indirect but potentially significant impact on the success of a safety or design function
W	Weak impact (whether direct or indirect) on the success of a safety or design function

The importance rating methodology shown in Tables 5-1 to 5-3 could easily be adapted to a finer level of discretization than shown in Table 5-3. For example, as written, the matrix in Table 5-3 allows for six different value levels, so that numerical values of "1" through "6" (as an example) could be assigned to the six different combinations, instead of the three levels of "H", "M", and "L." Or, the impact levels could be more finely subdivided, say into five levels such as "very high," "medium-high," "medium," "medium-low," and "low" impact, to create a 5 × 2 =10 matrix of importance values (e.g., "1" through "10"). However, at this stage of generic research, a set of three value ratings ("H", "M", "L") is deemed to be sufficient.

Table 5-3. *Importance Value Ratings* for RD&D Issues (based on function significance and issue impact category)

Function Significance / Impact of Issue	Primary (P) safety/design function	Secondary (S) safety/design function
Direct (D) impact	High (H)	Low (L)
Indirect (I) impact	Medium (M)	Low (L)
Weak (W) impact	Low (L)	Low (L)

(Note: An RD&D Issue receives an importance rating according to its highest function-impact combination, i.e., it may receive an "L" rating for one function but if it gets an "H" for another function, it inherits that highest rating.)

Table 5-4. Consolidated Salt RD&D Technical Issues and Their Pre-Workshop Importance Ratings for Postclosure Safety and Design Functions for the Nominal Scenario and High Heat Load

[High "H" importance issues shaded in "light orange".]

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing
Wastes and Engineered Features (EBS) Feature/Process Issues			
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)	2
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)	1, 2
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability	1, 2
4. Changes in chemical characteristics of brine in the	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent gas	1

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing
backfill and EBS		generation (M) Indirectly related to limited and delayed releases (L)	
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)	2
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability	2
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation	1, 2
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository	1
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases	1
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases	1
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	Indirectly related to limited and delayed releases	1
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	1
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	1
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues			
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design	2
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)	1, 2
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)	2

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Explanation of Issue Importance Rating	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone	2
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion).	1, 2
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases	1
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)	1
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases	1
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases	1
Repository System (EBS and Geosphere combined) Feature/Process Issues			
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constitutive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).	2
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation	2
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing	1
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases	1
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases	1
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository	2
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions	2
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing)	2

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing
		Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides	
Modeling Issues			
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	1, 3
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	1, 3
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	1, 3
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	1, 3
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions	1, 3
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions	1, 3
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	1, 3
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)	1, 3
***In-Situ* Testing/Design/Operations Issues**			
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of *in situ* stresses and rock movement (H) and brine and vapor/gas movement (M)	2, 3
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function	2, 3
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host	H (= D,P)	May not be possible in the time frame of an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function	2, 3

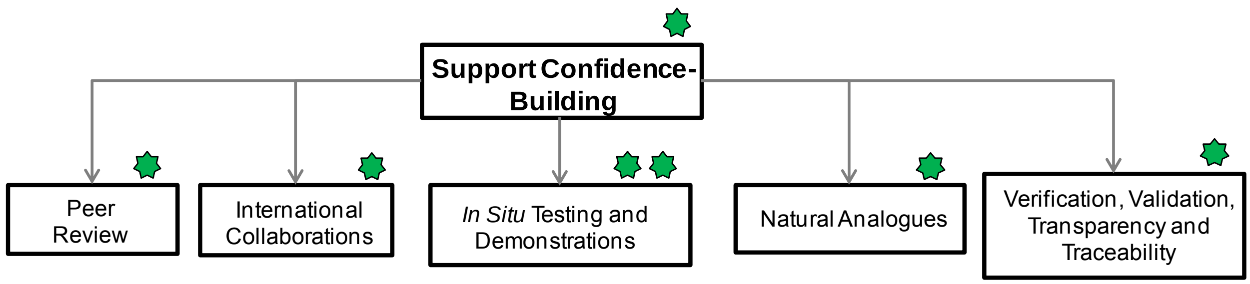
Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing
rock, and ventilation.			
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	2, 3
Confidence-Building Issues			
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety	1, 2, 3
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes	1, 2, 3
45. International peer review and collaboration	M	Adds credibility with the scientific community	1, 2, 3
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42	1, 2, 3
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs	1, 2, 3
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency	1, 2, 3

It should be noted that, as described in Section 7, the postclosure breakout group (Group #1), proposed a few changes to the above ratings for a human intrusion scenario (see Table 7-1). In particular, the "limited or delayed releases" safety function was changed to a "primary" function for the human intrusion scenario, with ratings of H, M, and L for direct, indirect, and weak impacts, respectively, because the containment function is compromised for the human intrusion scenario (i.e., it is no longer a primary function).

5.2 Confidence-Building Considerations

As indicated in Figure 3-2, confidence-building is a major goal of all RD&D activities, and should be given due consideration in the proposal and design of testing and/or modeling work. Depending on the stage of repository development and the interest of stakeholders and regulators, the confidence-building objective in Figure 3-2 may be given a higher weight than the postclosure safety objective for several types of RD&D activities. For example, for a repository concept that has a mature technical basis, such as bedded salt, large scale demonstration tests may be given a higher importance than further refinement of constitutive models. For a full-scale *in situ* demonstration test the goal may be less the acquirement of data to predict repository performance far into the future, than simply a demonstration that environmental conditions and physical-chemical processes stay within well-defined ranges. Or, the goal of the *in situ* test may be simply to demonstrate that heat-generating waste can be emplaced without any major adverse or unforeseen events.

Figure 5-1 shows the confidence-building objective and sub-objectives that were considered in the March 2013 workshop. [Note: Two "stars" are given to the *in situ* testing sub-objective because it was the subject of the entire second day of the March workshop—see Section 7.]



* Safety case is for disposal of both DOE-owned and commercial heat-generating waste. (Note: Transportation system, waste receipt, and surface facilities are not considered in this report.)

Indicates objective considered in the March 2013 Workshop.

Figure 5-1. Confidence-Building Objective and Sub-objectives.

For the reasons noted above, related to the stage of repository development and the perceived importance of issues and activities to stakeholders and regulators, the confidence-building objective can be used to refine or revise the importance ratings in Table 5-4, e.g., to move an issue with an "M" rating (and a proposed activity to address the issue) to an "H" rating. This specific instruction was given to the workshop participants prior to convening the breakout groups.

6. CURRENT SALT R&D ACTIVITIES

As mentioned in Section 1, a Salt Research and Development Study Plan was completed on March 23, 2012 and agreed upon by DOE-NE and DOE-EM (McMahon 2012). The Study Plan was developed in response to an agreement regarding the technical objectives and science-based scope of work for the study of salt geologic media for potential disposal of DOE-owned and civilian high-level waste and used nuclear fuel. This 2012 Salt R&D Study Plan is reproduced in Appendix C and its major RD&D activities are summarized at a high-level in Table 6-1. These RD&D activities are subject to modification for FY14 and out-years based on the outcomes of the March 2013 Workshop described below in Section 7, and these proposed modifications are outlined in Section 8.

Table 6-2 presents a mapping of the 2012 Salt R&D Study Plan activities in Table 6-1 to the consolidated list of RD&D issues from Table 5-4. It is apparent from this mapping that the majority of the currently funded salt RD&D activities map to high importance issues and that a few of the high importance (as well as some medium importance) issues in Table 5-4 have no associated activities. Based on this observation, and the outcomes of the March 2013 Workshop, some of the RD&D activities in Table 6-1 are candidates for not being continued beyond FY 13, while some new activities will be recommended. The recommended set of RD&D activities going forward is presented in Section 8, following a discussion of Workshop outcomes in Section 7. [Note: The issue prioritization or importance ratings developed as a result of the workshop are presented in Section 7 (Table 7-1). These are slightly changed from the pre-workshop importance ratings given in Table 5-4.]

Table 6-1. Current FY13 High-Level Salt R&D Activities (see Appendix C)

ACTIVITY 1: EXISTING SALT DATA COMPILATION AND ASSESSMENT
ACTIVITY 2: TEST PLANNING FOR RE-ENTRY INTO THE NORTH EXPERIMENTAL AREA OF WIPP
ACTIVITY 3: THERMAL, MECHANICAL, HYDROLOGIC, AND CHEMICAL LABORATORY STUDIES RELATED TO SALT
3.1 Hot Granular Salt Consolidation, Constitutive Model and Micromechanics
3.2 Thermal Conductivity as a Function of Porosity and Temperature
3.3 Laboratory Thermomechanical Testing
3.4 Brine Migration Experimental Studies
3.5 Study of Material Interactions In Heated Salt
3.6 Study of Thermodynamic Properties Of Brines, Minerals And Corrosion Products In High Temperature Systems
3.7 Radionuclide Solubility Measurements
ACTIVITY 4: MODELING STUDIES RELATED TO SALT
4.1 Safety Framework Development
4.2 Total System Performance Assessment (TSPA) Model Development
4.3 Generic Salt Repository Benchmarking
4.4 Thermomechanical-Hydrological and Chemical (TMHC) Model Development/Brine Migration
ACTIVITY 5: INTERNATIONAL COLLABORATION
ACTIVITY 6: SALT INSTRUMENTATION DEVELOPMENT AND TEST METHODOLOGIES

Table 6-2. Consolidated Salt RD&D Technical Issues (Table 5-4) Mapped to Current Salt R&D Activities (Table 6-1)
[High "H" importance issues shaded in "light orange".]

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Current UFD Salt R&D Activity
Wastes and Engineered Features (EBS) Feature/Process Issues		
1. Inventory and WP Loading	M (= I,P)	
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	3.1 3.2 4.4
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)	3.6 4.4
5. Mechanical response of backfill	H (= D,P)	3.1 3.2 4.4
6. Impact of mechanical loading on performance of the WP	H (= D,P)	
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	4.4
8. Corrosion performance of the waste package	M = (I,P)	2 3.5 3.6
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	
10. Brine flow through waste package	L (= D,S)	
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	3.6
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	3.7
13. Radionuclide transport in the waste package and EBS	L (= D,S)	
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues		
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Site-specific
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	2 3.3 4.3 4.4
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	3.3 4.3 4.4
17. The formation and evolution of the EDZ	H (= D,P)	4.4
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	2 3.4 4.4
19. Chemical characteristics of brine in the host rock	L (= I,S)	
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	4.4
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	3.7
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	
Repository System (EBS and Geosphere combined) Feature/Process Issues		
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and	H (= D,P)	3.2 4.4

Salt RD&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Current UFD Salt R&D Activity
Geosphere)		
24. Buoyancy of the waste packages	L (= W,P)	
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	
28. Performance of seal system	H (= D,P)	3.1
29. Performance of ground support	L = (W,P,S)	
30. Performance and effects of ventilation	M (= I,P)	
Modeling Issues		
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	3 4.4
32. Appropriate representation of coupled processes in process models	H (= D,P)	4.4
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	4.2 4.4
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	4.2 4.4
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	4.2
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	
37. Verification and validation	H (= D,P)	4.3
38. Data and results management	H (= D,P)	1
***In-Situ* Testing/Design/Operations Issues**		
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	2.1 6.1 6.2
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)	
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	4.3
Confidence-Building Issues		
43. Develop generic safety case	H	4.1
44. Comparisons to natural and anthropogenic analogs	H	
45. International peer review and collaboration	M	5
46. In-situ testing and demonstrations	H	
47. Verification, validation, transparency, and traceability	H	
48. Qualitative arguments about the intrinsic robustness of site and design	M	

7. WORKSHOP GOALS, TASKS, AND OUTCOMES

A planning workshop on "Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt" was held March 6-7, 2013 at Sandia National Laboratories in Albuquerque, New Mexico, and was well attended by staff with expertise in repository sciences from SNL, LANL, LLNL, LBNL, and SRNL. Representatives from DOE-CBFO, DOE-NE (UFD) and DOE-EM (HQ) also attended. The attendance list is presented in Appendix D (along with the assigned breakout group for each participant). The workshop was two days in length and followed the agenda shown in Appendix E. The overall goal of the workshop was to provide a basis for identifying RD&D activities that will have the greatest potential to contribute to the advancement of deep geologic disposal of nuclear waste in salt, which is equivalent to the highest-level safety-case objective stated above in Figure 3-3.

The morning of the first day was used to outline the specific goals and structure of the workshop, as indicated in the agenda in Appendix E (also see the presentation by R. MacKinnon in Appendix J). On the afternoon of the first day two breakout groups were convened to focus on technical issues relevant to the highlighted safety-case objectives shown in Figure 3-2, along with RD&D activities that can be designed to address these issues. Specifically, the consolidated RD&D issue list in Table 5-4 was used as a starting point for the two breakout groups, each of which had the goal of reaching a consensus on the relative importance of these technical issues.

The morning of the second day of the workshop focused on field testing/demonstration activities, including a background review of previous field testing performed for heat-generating waste in salt and a number of proposed *in situ* testing options for the new underground space at WIPP (see workshop presentations in Appendix J). The afternoon of the second day specifically examined the proposed Salt Defense Disposal Investigations (SDDI) test (DOE 2012b), an *in situ* test simulating emplacement of DOE-owned waste with nominal heat signature on the floor of the drift and covered with run-of-mine salt (Carter et al. 2012). Because the overriding purpose of the SDDI proposal is to address the expectations of stakeholders for a field demonstration of the on-floor emplacement concept, *confidence-building* (see Section 5.2) is a major objective to which the SDDI could contribute if planned and designed in a technically rigorous manner.

7.1 Day 1 Workshop Activities and Results

As mentioned, the goals of the first afternoon of the workshop were to reach consensus on the set of key technical issues and their importance ratings, and to propose additional RD&D activities (see Section 6) to resolve these issues. Two breakout groups were convened, one called the "postclosure breakout group (Group 1)" and the other called the "preclosure breakout group (Group 2)." Although both groups were to consider all the RD&D issues listed in Table 5-4, each group was to concentrate on a subset of those issues, as indicated by the last column of Table 5-4. [Note: Group 3 in Table 5-4 refers to the group discussion in the afternoon of the second day of the workshop regarding field testing.]

The four major instructions given to the two Day 1 breakout groups were (also see the presentation by D. Sevougian in Appendix J):

1) Review consolidated RD&D issue list (Table 5-4) and the associated importance ratings—provide comments/revisions as necessary
2) For high importance ("H") issues that are *not* currently being addressed by UFD R&D tasks (see Table 6-2), define specific activities (tests/modeling) needed to advance the state of the art
3) If any medium importance ("M") or low importance ("L") issue is moved to a high ("H") ranking, define specific activities (tests/modeling) to address these issues (if these items are not currently being addresses by UFD R&D activities)
4) Answer the test questionnaire (see Appendix F) for each newly proposed RD&D test or activity

Instructions specific to each breakout group were:

5) Group 1 (Postclosure) assignments:
   - Concentrate on issues and test design from a postclosure perspective (EBS postclosure processes within the excavation and NBS postclosure processes in the host salt formation)
   - Look at all feature/process issues (the first 30 issues) but concentrate on your assigned feature/process issues ("1")
   - Modeling issues are also assigned to your group
   - If there is time, look at confidence-building issues
6) Group 2 (Preclosure) assignments:
   - Concentrate on issues and test design from a preclosure perspective (design, demonstration, and preclosure)
   - Look at all feature/process issues (the first 30 issues) but concentrate on your assigned feature/process issues ("2")
   - *In-Situ* Testing/Design/Operations issues are also assigned to your group
   - If there is time, look at confidence-building issues

As shown in the agenda in Appendix E, the two groups rejoined at the end of the day to report their findings. These findings and the proposed adjustments to the pre-workshop importance ratings in Table 5-4 are presented in detail in Appendix G, Tables G-1, G-2, and G-3. Two importance rating tables are presented in Appendix G for Group 1 because this group determined that it was essential to rate issues not only for the nominal evolution postclosure scenario but also for a human intrusion postclosure scenario. The latter causes an elevation in importance for issues related to radionuclide mobilization and transport, since the containment function is breached. In particular, the safety function called "limited or delayed releases" (Table 5-1) becomes a primary function in the human intrusion scenario. A combined table with the importance ratings of both breakout groups (from Appendix G) is given below in Table 7-1.

A few comments on potential RD&D testing activities were made by participants of the two breakout groups, as indicated by some of the notes in the last column of the three tables in Appendix G. However, in general, the groups felt there was not enough time to fill out the test questionnaire shown in Appendix F. Thus, newly proposed test activities and the completion of corresponding test questionnaires was assigned as a post-workshop activity. The suite of more than twenty proposed tests and questionnaires received following the workshop is documented in Appendix H.

7.2 Day 2 Workshop Activities and Results

As mentioned above, the second day of the workshop was dedicated to *in situ* field testing, with the morning session comprised of background presentations (see Appendix J, F. Hansen and K. Kuhlman presentations) on previous *in situ* testing (both national and international, and including large-scale demonstrations), and the afternoon session being devoted to a "combined breakout group—Group 3" (i.e., all workshop participants) that had two main goals:

1) Review the RD&D technical issues and reach a consensus on those technical issues that *in situ* field tests, such as the proposed SDDI test, could potentially inform or address (DOE 2012b; also see Appendix J, M. Schuhen and D. Weaver presentations; also see Appendix H, Table H-4).
2) Develop input on potential additional research activities in the newly mined underground area in the Salado Formation at WIPP.

To achieve these goals, the workshop participants as a whole went through each issue in Table 5-4 to evaluate whether the proposed SDDI test was currently designed to address the issue and, if not, whether it had the potential to address the issue without adding too much complication and uncertainty to the test. Particular emphasis was placed on "H"-rated issues in Table 7-1. The participants reached a consensus opinion on each issue and the results are presented below in Table 7-2. This consensus opinion was based on test concept given in DOE (2012b) and in the D. Weaver workshop presentation (Appendix J), and is subject to change as the test design is refined.

In addition to evaluating the potential of the proposed SDDI test to address RD&D issues, the workshop participants as a whole were asked to reach a consensus on which safety case objectives (see Figure 3-3) may be supported by the proposed SDDI test. These results are presented in Figure 7-1 below. In a broad sense, as indicated in Figure 7-1, a large-scale *in situ* test, such as the conceptual SDDI test, is potentially able to support a number of safety case objectives. When preceded by appropriate process model evaluations regarding test design and test behavior, *in situ* large-scale demonstrations have the ability to build confidence for both the repository implementer (i.e., DOE) and a variety of stakeholders, such as Federal regulatory agencies, state and local government oversight agencies, and various public interest groups. Choosing when to initiate such a test during a phased repository project (Figure 3-2) depends on the knowledge basis for the given repository concept, and the perceptions of stakeholders, as described in Section 5.2. When such a test has a clearly articulated and demonstrable set of goals that are related to the safety case, its success is much more likely. Part of the purpose of the March 2013 Workshop was to develop input on a path toward setting these goals and ensuring that they have a sound basis and a high priority given the current state of knowledge for bedded salt repository science and engineering. [Note: Following the workshop, more detail on the SDDI test was proposed in a test questionnaire documented in Table H-4.]

Support Safety Case
(Assessment Basis & Disposal System Evaluation)

- **Support Site Selection**
- **Support Site Characterization**
- **Support Preclosure Safety Evaluation and Operations**
  - Support Transfer of Waste Canisters Underground
  - Support Emplacement of Backfill
  - Support Receipt of Waste Canisters Underground
  - Support Pre-closure Safety Evaluation
  - Support Transport of Waste Canisters to Emplacement Area
  - Support Operation of Ventilation System
  - Support Emplacement of Waste Canisters
- **Support Repository Design and Construction**
  - Support Underground Layout and Drift Design
  - Support Ventilation and Drainage Systems Design
  - Support Access Shafts/Drifts Design
  - Support Backfill Design
  - Support Seal System Design
  - Support Ground Support Design
  - Support Power Supply Design
  - Support Waste Canister Design
- **Support Postclosure Safety Evaluation**
  - Support EBS Technical Basis
  - Support Geosphere Technical Basis
  - Support Biosphere Technical Basis
  - Support Total System Performance Assessment Model
- **Support Confidence-Building**
  - Support Peer Review
  - Support International Collaborations
  - Support *In Situ* Testing and Demonstrations
  - Support Natural and Anthropogenic Analogues
  - Support Verification, Validation, Transparency and Traceability

Figure 7-1. Safety Case Objectives Potentially Supported by the SDDI Test, based on Consensus of the Workshop Participants.
[“green shading” = direct support; “pink shading” = indirect support; “no shading” = minimal or no support]

As described in Section 3, the safety case framework offers a transparent way to communicate the current understanding of repository safety to a diverse group of stakeholders. The National Research Council‘s Committee on Principles and Operational Strategies for Staged Repository Systems (NRC 2003, p. 126), whose work was cited several times by the Blue Ribbon Commission (e.g., BRC 2012, Sec. 6.4), stated: “The safety case includes a broad and understandable (to stakeholders and the general public) explanation of how safety is achieved and a similar discussion of the uncertainties that result from limitations in the scientific understanding of system behavior.” A prominent component of communicating safety confidence to governmental and public stakeholders can be a successful large-scale *in situ* field test carried out in an underground research laboratory (URL), as has been done previously at WIPP. This approach of using URLs to build safety confidence is supported by the Blue Ribbon Commission (BRC 2012, Sec. 6.4): “…pilot, test, and demonstration facilities (including an *in situ* research and demonstration laboratory)…will make it possible to conduct tests aimed at improving operational efficiency and safety and signal a continuing commitment to R&D to reduce residual uncertainties. These facilities have also been used as excellent public communication tools in Sweden and France, for example, to explain to the interested public exactly how a repository operates."

7.3 Summary of Workshop Outcomes

7.3.1 Workshop Day 1 Summary

A high-level evaluation of Table 7-1 indicates that modeling, confidence-building, and *in situ* testing issues (Issues 31 to 48) are viewed as high importance to the safety case in bedded salt. These types of RD&D issues would be expected to be of similar importance in any geologic media or repository concept, based both on technical expertise and on past experience with such facilities in the U.S. (e.g., WIPP and Yucca Mountain). Thus, they are likely to receive high attention in any RD&D funding profile. In addition to these categories, a certain set of feature/process issues was viewed as important by both breakout groups, and should be funded at an appropriate high priority level to enhance safety confidence. Most of these had to do with the thermal effects of heat-generating waste emplaced in salt, and its affect on other processes such as fluid movement and material deformation. These thermal-hydrologic and thermal-mechanical issues/processes are important to the primary safety function in the nominal or expected evolution postclosure scenario for a salt repository, which is containment.

Chemical and thermal-chemical issues are more important in an intrusion scenario, which can only be viewed as highly important if it has a high enough probability of occurrence to result in a high expected risk or dose (cf. 10 CFR 63). The siting process for a national repository (DOE 2013) would presumably have some disqualification criteria (BRC 2012, Sec. 6.4) applied to sites that are located in areas with an unacceptably high frequency of intrusions, whether natural or human-induced. For this reason, and because most bedded salt and domal salt sites are in areas that are not tectonically active, more focus is placed on the nominal scenario at this stage of generic RD&D than on disruptive/intrusion scenarios. However, the latter cannot be completely ignored, since research programs designed to test chemical effects on radionuclide transport are complicated to initiate and/or to terminate (e.g., considering the health, safety, and QA aspects of such research). Given this, it is appropriate to keep some level of active funding for lab tests and accompanying modeling activities that examine chemical conditions and chemical evolution associated with heat-generating high-level waste, including potential interactions of different engineered materials that can result in oxidation-reduction reactions that influence the mobilization of radionuclides.

Table 7-1. Combined Issue Ratings: Pre-workshop Nominal Scenario, Breakout Group 1 Nominal Scenario, Breakout Group 2 Nominal Scenario, and Breakout Group 1 Human Intrusion Scenario

Salt RD&D Technical Issue	**Pre-workshop Issue Importance Rating** **Nominal Scenario**	**Breakout Group 1 Revisions to Issue Importance Ratings** **Nominal Scenario**	**Breakout Group 2 Revisions to Issue Importance Ratings** **Nominal Scenario**	**Breakout Group 1 Revision to Importance Ratings for** **Human Intrusion Scenario**
Wastes and Engineered Features (EBS) Feature/Process Issues				
1. Inventory and WP Loading	M (= I,P)			
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)		**H (= D,P)**	
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)			
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)			
5. Mechanical response of backfill	H (= D,P)			
6. Impact of mechanical loading on performance of the WP	H (= D,P)		**M (= I,P)**	
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	**M (= I,P)**		**M (= I,P)**
8. Corrosion performance of the waste package	M = (I,P)			
9. Mechanical and chemical degradation of the waste forms	L (= D,S)			**H (= D,P)**
10. Brine flow through waste package	L (= D,S)			**M (= I,P)**
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)			**H (= D,P)**
12. Radionuclide solubility in the waste package and EBS	L (= D,S)			**H (= D,P)**
13. Radionuclide transport in the waste package and EBS	L (= D,S)			**M (= I,P)**
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues				
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)		**M (=I,P)**	
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)			
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)			
17. The formation and evolution of the EDZ	H (= D,P)			
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	**M (= I,P)**		**M (= I,P)**
19. Chemical characteristics of brine in the host rock	L (= I,S)			
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)			

Table 7-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating <u>Nominal Scenario</u>	Breakout Group 1 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 2 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 1 Revision to Importance Ratings for <u>Human Intrusion Scenario</u>
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)			
22. Radionuclide transport in the host rock and EDZ	L (= D,S)			
Repository System (EBS and Geosphere combined) Feature/Process Issues				
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)			
24. Buoyancy of the waste packages	L (= W,P)			
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)		**H (= D,P)**	
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)			
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)			**H (= D,P)**
28. Performance of seal system	H (= D,P)			
29. Performance of ground support	L = (W,P,S)			
30. Performance and effects of ventilation	M (= I,P)			
Modeling Issues				
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)			
32. Appropriate representation of coupled processes in process models	H (= D,P)			
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)			
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)			
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)			
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)			
37. Verification and validation	H (= D,P)			
38. Data and results management	H (= D,P)			
***In-Situ* Testing/Design/Operations Issues**				
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)			
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply	H (= D,P)			

Table 7-1 (continued).

Salt RD&D Technical Issue	**Pre-workshop Issue Importance Rating** **<u>Nominal Scenario</u>**	**Breakout Group 1 Revisions to Issue Importance Ratings** **<u>Nominal Scenario</u>**	**Breakout Group 2 Revisions to Issue Importance Ratings** **<u>Nominal Scenario</u>**	**Breakout Group 1 Revision to Importance Ratings for** **<u>Human Intrusion Scenario</u>**
with preclosure and postclosure safety requirements.				
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)			
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)			
Confidence-Building Issues				
43. Develop generic safety case	H			
44. Comparisons to natural and anthropogenic analogs	H		**M**	
45. International peer review and collaboration	M		<u>Peer Review</u>: **M** <u>Collaboration</u>: **H**	
46. In-situ testing and demonstrations	H			
47. Verification, validation, transparency, and traceability	H			
48. Qualitative arguments about the intrinsic robustness of site and design	M			

Table 7-2. Combined Issue Ratings from Day 1, and the Day 2 Breakout Group Evaluation of the Potential of the Proposed SDDI Test to Address these Issues
[Green color indicates that the SDDI will address some facet of the issue, while a yellow color with a "TBD" means it is "to be determined" at a later date.]

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] <u>Nominal Scenario</u>	Breakout Group 1 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 2 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 1 Revision to Importance Ratings for <u>Human Intrusion Scenario</u>	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from <u>Day 1 Breakout Groups</u>, where indicated)
Wastes and Engineered Features (EBS) Feature/Process Issues						
1. Inventory and WP Loading	M (= I,P)				Yes	
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)		**H (= D,P)**		TBD	- SDDI measurements of these properties may only be weakly related to actual repository conditions
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)				No	- SDDI will not test this. Porosity redistribution cannot be seen under *in situ* conditions that in the field. - A lab test would be more appropriate, and a null result in the lab provides useful information.
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)				Yes	- R&D on the effects of acidic brines are not currently proposed for the SDDI but could be included in SDDI
5. Mechanical response of backfill	H (= D,P)				No	- SDDI test conditions will not provide enough mechanical stress to investigate this - According to <u>Day 1 Group 2</u>, full scale, *in situ* test would require too long of a time period but shorter term lab testing will confirm models, which may be used to predict longer term behavior.
6. Impact of mechanical loading on performance of the WP	H (= D,P)		**M (= I,P)**		No	- According to <u>Day 1 Group 2</u>, modeling would be sufficient to understand WP degradation that could impact retrievability
7. Brine and vapor movement in the	H (= D, P)	**M (= I,P)**		**M (= I,P)**	Yes	- Key goal of the SDDI

Table 7-2 (continued).

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] Nominal Scenario	Breakout Group 1 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 2 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from Day 1 Breakout Groups, where indicated)
backfill and emplacement drift, including evaporation and condensation						
8. Corrosion performance of the waste package	M = (I,P)				Yes	- Could potentially be addressed by SDDI, with metal coupons, composed of a variety of waste package materials (e.g., mild steel, stainless steel, etc.). - Could also be confirmed in the lab but with more stringent environmental controls (chemical exposure history).
9. Mechanical and chemical degradation of the waste forms	L (= D,S)			**H (= D,P)**	No	
10. Brine flow through waste package	L (= D,S)			**M (= I,P)**	No	
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)			**H (= D,P)**	No	
12. Radionuclide solubility in the waste package and EBS	L (= D,S)			**H (= D,P)**	No	
13. Radionuclide transport in the waste package and EBS	L (= D,S)			**M (= I,P)**	No	
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues						
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)		**M (= I,P)**		No	
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)				TBD	- Uncertain as to whether this can/will be addressed by SDDI
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)				Yes	- Day 1 Group 2 commented that these are fundamental aspects of URL investigations

Table 7-2 (continued).

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] Nominal Scenario	Breakout Group 1 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 2 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from Day 1 Breakout Groups, where indicated)
17. The formation and evolution of the EDZ	H (= D,P)				Yes	- Day 1 Group 2 comments: • Fundamental aspect of SDDI • No salt healing expected in the SDDI test, but we want to observe EDZ evolution from heating • Consider a mine-by experiment, and a seal-design test that applies load to the wall • Consider a heated fluid inclusion test for model validation—try to accelerate healing of the EDZ
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	**M (= I,P)**		**M (= I,P)**	Yes	- Could measure fluid movement in the SDDI test with electrical resistance tomography (ERT). However, a complimentary ERT lab test (started prior to the field test) would be important - Day 1 Group 2 commented that we should test the preliminary simulation result that the EDZ under heated packages behaves as a permeable, porous layer that becomes saturated
19. Chemical characteristics of brine in the host rock	L (= I,S)				Yes	
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)				Yes	- Need to collect brine to do this. Is this possible? Yes, via collection holes in the floor. - Accompanying lab testing will be useful
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)				No	
22. Radionuclide transport in the host rock and EDZ	L (= D,S)				No	

Table 7-2 (continued).

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] Nominal Scenario	Breakout Group 1 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 2 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from Day 1 Breakout Groups, where indicated)
Repository System (EBS and Geosphere combined) Feature/Process Issues						
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)				Yes	- However, no further testing is needed, according to the Day 1 Group 2 breakout group (see Table G-3)
24. Buoyancy of the waste packages	L (= W,P)				No	
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)		**H (= D,P)**		No	- Amenable to testing *in situ* (but SDDI does not address this) - Currently the topic of international R&D
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)				Yes	- As currently conceived (DOE 2012b), the SDDI proposal does not include measurements related to microbial activity
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)			**H (= D,P)**	No	
28. Performance of seal system	H (= D,P)				No	- R&D and testing has already been done for this issue, according to the Day 1 Group 1 breakout group - No further R&D needed, according to the Day 1 Group 2 breakout group
29. Performance of ground support	L = (W,P,S)				No	
30. Performance and effects of ventilation	M (= I,P)				TBD	- There will be significant moisture movement through the backfill "plug" at the end of the test drifts. This must be controlled and/or accurately instrumented
Modeling Issues						
31. Appropriate constitutive models	H (= D,P)				Yes	

Table 7-2 (continued).

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] Nominal Scenario	Breakout Group 1 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 2 Revisions to Issue Importance Ratings Nominal Scenario	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from Day 1 Breakout Groups, where indicated)
(e.g., Darcy flow; effective stress)						
32. Appropriate representation of coupled processes in process models	H (= D,P)				Yes	
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)				Yes	
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)				Yes	- According to Day 1 Group 2, this is beyond the scope of R&D; need process models informed and incorporated or abstracted for PA.
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)				Yes	- According to Day 1 Group 2, 3-D TM modeling will be needed to design a repository for heat-generating waste, especially a large one
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)				Yes	
37. Verification and validation	H (= D,P)				Yes	
38. Data and results management	H (= D,P)				Yes	
***In-Situ* Testing/Design/Operations Issues**						
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)				Yes	- According to Day 1 Group 2, instrumentation is still a challenge for field testing, repository monitoring, etc
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to	H (= D,P)				Yes	

Table 7-2 (continued).

Salt R&D Technical Issue	Pre-workshop Issue Importance Rating[1] <u>Nominal Scenario</u>	Breakout Group 1 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 2 Revisions to Issue Importance Ratings <u>Nominal Scenario</u>	Breakout Group 1 Revision to Importance Ratings for <u>Human Intrusion Scenario</u>	Potential of Current SDDI Plan to Address this Issue (Day 2 "Breakout Group 3" Consensus) (Yes/No/TBD)	Day 2 Breakout Group 3 Comments on SDDI and other Potential Testing Activities (Additional Comments from <u>Day 1 Breakout Groups</u>, where indicated)
comply with preclosure and postclosure safety requirements.						
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)				Yes	- <u>According to Day 1 Group 2</u>, this should *not* be considered *only* in the context of the current SDI or SDDI proposals—to be taken up later; not a topic for R&D at this time.
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)				Yes	- <u>According to Day 1 Group 2</u>, this should *not* be considered *only* in the context of the current SDI or SDDI proposals—to be taken up later; not a topic for R&D at this time.
Confidence-Building Issues						
43. Develop generic safety case	H				Yes	
44. Comparisons to natural and anthropogenic analogs	H		**M**		No	
45. International peer review and collaboration	M		<u>Peer Review</u>: **M**		Yes	
			<u>Collaboration</u>: **H**		Yes	
46. In-situ testing and demonstrations	H				Yes	
47. Verification, validation, transparency, and traceability	H				Yes	
48. Qualitative arguments about the intrinsic robustness of site and design	M				N/A	

7.3.2 Workshop Day 2 Summary

A high-level evaluation of Table 7-2 indicates that the proposed SDDI test (see Table H-4) has the potential to reduce uncertainties related to the high-importance modeling, confidence-building, and *in situ* testing issues (Issues 31 to 48). It also has the potential to support many but not all of the high-importance feature/process issues (Issues 1 to 30). However, as evidenced by some of the notes/comments in the last column of Table 7-2, and also by consensus agreement reached during Day 2 of the workshop, the SDDI test as currently conceived is conceptual only, with much work needed to support test planning and design before its ability to address important technical issues can be confirmed.

There was a consensus at the end of the workshop that a key goal of an *in situ* test such as the SDDI is to support the confidence-building objective by demonstrating to stakeholders (such as local and State governments) that bedded salt formations (such as the Salado or a similar formation—see Appendix I) are an appropriate geologic medium for safely emplacing and isolating heat-generating waste. It was recognized that because the SDDI is designed for lower heat-load DOE-owned waste (Carter et al. 2012), additional field tests would likely be appropriate if high-heat load commercial waste is eventually sited in a bedded salt repository. However, because of the overlap between heat output for some defense and commercial wastes (see Robinson presentation in Appendix J), the results of a SDDI or similar low-heat-load test would have value for designing an *in situ* test for high-heat-load commercial waste. It was also recognized that the SDDI is a test proposal for the newly mined area at WIPP in the Salado bedded salt formation of the Permian Basin but will provide generic information and concepts for media beyond the Salado. As shown in Appendix I of this report, due to the similar depositional environment of all major bedded salt deposits in the U.S., the Salado is demonstrably representative of these deposits, meaning that such a test can help resolve RD&D issues that are amenable to generic research.

It was agreed that this test will only indirectly illustrate operational aspects of the in-drift waste emplacement concept of Carter et al. (2012)—see the “indirect” rating in Table 7-1—given the special care that will be required when emplacing the heaters and covering them with run-of-mine salt in order to protect the instruments and sensors. Primarily this test will illustrate something about what might happen after emplacement (rather than during emplacement). Also, given that the primary value of the SDDI or similar test will be in its confidence building aspects, the principle of “less is more” was adopted as sound advice by the working group and recommended as a tenant for planning and conducting the test. Consensus was reached to focus test objectives on the basics of brine and water vapor movements, corrosion (possibly), and thermal profiles from varying placements/groupings of the heaters on the floor. Adding complex measurements to the demonstration would likely undermine the confidence-building value of the test.

7.3.3 Post-Workshop Test Proposals

As mentioned in Section 7.1, new RD&D test/activity proposals were assigned to the workshop participants as a post-workshop effort. This resulted in twenty-three RD&D test proposals from workshop participants, documented in detail in Appendix H and summarized below in Table 7-3. In addition, there was one proposal provided by researchers who were not present at the workshop (see Table H-24). The proposals are organized into six major categories: (1) primarily *in situ*, large-scale field testing (with modeling), (2) laboratory testing, followed by *in situ* testing (with modeling), (3) laboratory testing, followed by *in situ* testing (no modeling), (4) laboratory testing (with modeling), (5) laboratory testing (no modeling), and (6) modeling and simulation studies only (no physical tests). A description of the integration of these new RD&D test/activity proposals with current RD&D activities (see Table 6-1 and Appendix C), as well as the recommended disposition of each new proposal, is presented in Section 8. [Note: Within each of the six major categories, the tests listed in Table 7-3 are not given in any particular order.]

Table 7-3. Summary of RD&D Test Proposals/Questionnaires Received after the Salt RD&D Integration Workshop

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation
Primarily *in situ*, large-scale field testing (with modeling)			
H-1	Clay Seam Shear Testing	*In situ* tests in the new URL; Laboratory tests; Constitutive modeling; International collaborations	Frank Hansen (SNL)
H-2	Single Heater Test	Generic *in situ* tests in the new URL; International collaborations; Modeling prediction and validation	Frank Hansen (SNL), Carlos Jove-Colon (SNL)
H-3	Large-Scale Seal Test	*In situ* tests in the new URL; International collaborations; Modeling; Lab—ACI concrete testing	Frank Hansen (SNL)
H-4	Salt Defense Disposal Investigations (SDDI) Thermal Test	*In situ* thermal test; Laboratory tests; THM and THMC model validation	Doug Weaver (LANL)
H-5	Water migration tracer test during the proposed SDDI experiment	*In situ* field test with lab analysis; including pre-, during, and post-test transport modeling	Philip Stauffer (LANL), Florie Caporuscio (LANL), Paul Reimus (LANL), Ernie Hardin (SNL)
Laboratory testing, followed by *in situ* testing (with modeling)			
H-6	Salt Decrepitation Effects	Laboratory tests initially; borehole & *in situ* field testing later; THM process and constitutive modeling	Kris Kuhlman (SNL)
H-7	Development of an Integrated Geophysical Imaging System for Field-Scale Monitoring of Brine Migration and Mechanical Alteration in Salt Repositories	Laboratory tests; Field testing at LBNL Geophysical Measurement Facility (GMF); (no modeling initially but later some pre-test modeling)	T.M. Daley, Y. Wu, J. Birkholzer, and J.B. Ajo-Franklin (LBNL)
Laboratory testing, followed by *in situ* testing (no modeling)			
H-8	Geophysical and acoustical monitoring of fluid migration and fracture evolution for WIPP salt thermal tests	Initial lab sensitivity experiments; followed by *in situ* field tests at WIPP during SDDI thermal tests (no modeling)	Peter Roberts (LANL)
H-9	*In situ* and laboratory testing of moisture monitoring methods	Laboratory tests; *In situ* field tests (no simulation modeling mentioned)	Dan Levitt (LANL)

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation
Laboratory testing (with modeling)			
H-10	Thermo-Hydro-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay on Permeability and Brine Migration in Salt at High Temperatures and Pressures	Complex THMC laboratory experiments; coupled process modeling to predict/interpret the results	Tim Kneafsey and Seiji Nakagawa (LBNL)
Laboratory testing (no modeling)			
H-11	Long-term steel corrosion analyses from Room A1/B re-entry	Laboratory test; (no simulation modeling mentioned)	Pat Brady (SNL)
H-12	Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography	Laboratory tests (no simulation modeling)	Hongwu Xu (LANL), Jonathan Ajo-Franklin (LBL)
H-13	Validation of constitutive models and parameterization of unsaturated brine flow in intact and crushed salt	Laboratory test (no simulation modeling)	Kris Kuhlman (SNL); Bwalya Malama (SNL)
H-14	Stability of Polyhalite in the Salado Formation	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)
H-15	Stability of hydrous phases (corrensite, bassanite) in the Salado Formation	Laboratory test (applicable for SDDI waste emplacement studies)— (no simulation modeling)	Florie Caporuscio (LANL)
H-16	Use of ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)) to map and quantify brine content in an undisturbed salt core.	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)
H-17	Elevated-Temperature Measurements of Plutonium (III) and Neodymium(III) Solubility in Low to Moderate Ionic Strength Aqueous Solutions	Laboratory tests (no modeling)	Jonathan Icenhower and David Shuh (LBNL); Donald Reed (LANL)
H-18	Laboratory Study on the Long-term Porosity and Permeability Reduction in Salt Backfill Under Elevated Temperature Conditions	Laboratory tests (no modeling)	Tim Kneafsey and Seiji Nakagawa (LBNL)
Modeling and simulation studies only (no physical tests)			
H-19	Mechanistic modeling of brine and vapor movement	Theoretical and modeling study	Qinjun Kang (LANL)
H-20	THM Optimization of Preclosure Repository Design	Coupled process modeling	Jonny Rutqvist and Laura Blanco-Martin (LBNL); Phil Stauffer and Florie Caporuscio (LANL)
H-21	Benchmarking Simulations for THM Behavior of Rock Salt	THM(C) benchmark modeling—model-to model comparisons for a simplified repository, for a lab/field THM experiment; and for the planned SDDI test	Jonny Rutqvist and Jens Birkholzer (LBNL); Phil Stauffer and Bruce Robinson (LANL); Carlos Jove-Colon, Kristopher Kuhlman, and Ernest Hardin (SNL)

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation
H-22	THM Model of Salt Rock Microstructural Damage and Healing	Mechanistic microstructure modeling of coupled processes in salt	Daisuke Asahina and Jim Houseworth (LBNL)
H-23	Brine Migration in Salt: Review and Constitutive Model Development	Constitutive models	Jim Houseworth, Jonny Rutqvist, Hui-Hai Liu, Jens Birkholzer (LBNL)
Proposals from researchers not present at the Workshop			
H-24	Validation Experiments Using a Geocentrifuge to Examine Canister Movement in a Salt Repository	Lab testing	Earl D. Mattson, Mitchell A. Plummer (INL)

8. PROPOSED RD&D STUDY PLAN

This section identifies and summarizes the RD&D activities recommended for future funding consideration. Each of these activities addresses high-importance ("H") or medium-importance ("M") technical issues (see Tables 6-2 and 7-1). Most of these recommended activities continue ongoing work from FY13 (Appendix C), with a few representing new activities resulting from the Workshop recommendations and post-Workshop test/modeling proposals. The recommend dispositions for all post-Workshop proposals (compiled in Appendix H) are given at the end of this Section in Table 8-1.

Following is a high-level outline of the recommended activities going forward. Laboratory, modeling, and field testing activities are all represented in this suite of proposed activities. These are numbered according to the numbering scheme in Appendix C, but with new activities indicated by <u>underlining</u>. Details about these RD&D activities are described after the high-level outline.

1. Existing Salt Data Compilation and Assessment

2. Test Planning for Re-Entry Into the North Experimental Area of WIPP

3. Laboratory Studies
    - 3.1. Hot Granular Salt Consolidation, Constitutive Model and Micromechanics
    - 3.2. <u>Laboratory Interbed Shear Testing</u>
    - 3.3. Laboratory Thermomechanical Testing of Intact Salt
    - 3.4. Brine Migration Experimental Studies
    - 3.5. <u>Thermal-Hydrologic-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay Interbeds on Permeability and Brine Migration in Salt at High Temperatures and Pressures</u>
    - 3.6. Study of Thermodynamic Properties of Brines, Minerals and Corrosion Products in High Temperature Systems
    - 3.7. Radionuclide Solubility Measurements

4. Modeling Studies Related to Salt
    - 4.1. Safety Framework
    - 4.2. Total System Performance Assessment (TSPA) Model Development
    - 4.3. Generic Salt Repository Benchmarking – US/German Collaborative Effort
    - 4.4. Thermomechanical-Hydrological and Chemical (TMHC) Model Development
    - 4.5. <u>Brine Migration Modeling in Rock Salt</u>

5. International Collaboration

6. Salt Instrumentation Development and Test Methodologies

7. <u>Thermal Field Testing</u>

1. Existing Salt Data Compilation and Assessment: SNL, LANL

The objective of this activity is to compile and assess existing data sources into a comprehensive salt testing database that supports resolution of RD&D issues. This database and associated bibliography will make readily available reports and data for supporting future testing and safety case activities related to a nuclear waste repository in salt. Construction of the database was completed in FY12 and a User's Guide was issued. In FY13, a Level 2 Milestone Report *Establishing the Technical Basis for Disposal of Heat-Generating Waste in Salt* will be completed that describes the current technical basis for disposal in salt. Work in FY14 and beyond for this activity would include maintenance of the database and an end-of-year update. The next revision to the FY13 Level 2 report is recommended for FY15. This activity is consistent with the NEA-sanctioned Salt Club objective of knowledge preservation and transference. This activity directly addresses nominal-scenario "H" Issue 38, and indirectly supports many of the other issues.

2. Test Planning for Re-Entry Into the North Experimental Area of WIPP: LANL, SNL

Heated room experiments were conducted in Rooms A, B, and H in the North Experimental Area of WIPP in the late 1980s and early 1990s (see K. Kuhlman presentation in Appendix J). These tests were abruptly terminated, and some heaters and canisters were abandoned in place. The objective of this activity is to determine if useful information can be developed from examination of the reconsolidated salt attached to the heater (nominal-scenario "H" Issue 15), possible evidence of brine migration in the intact salt adjacent to the heater (nominal-scenario "H" Issue 18), and possible corrosion on the heaters and canisters themselves (nominal-scenario "M" Issue 8). Two plans will be developed, a physical recovery plan and a re-entry plan. The physical recovery plan will determine the type, location, and number of proposed tests to perform (nominal-scenario "H" Issue 39) in the North Experimental Area and will be completed in FY13. The re-entry plan will be developed in FY14 to accommodate the proposed tests that would potentially be initiated in FY15. Entry into the north end and associated forensic reconnaissance would not jeopardize the space in the newly mined URL area. (The new URL rooms should be excavated on a just-in-time basis to preserve as much of the time-sensitive transient behavior as possible.)

3. Laboratory Studies – Thermal, Mechanical, Hydrologic, and Chemical Laboratory Studies Related To Salt

The focus of this set of activities is to use laboratory studies to reduce remaining uncertainties in the technical bases that support disposal of heat-generating waste in salt. New experimental data will be developed for (1) the thermomechanical behavior of run-of-mine granular salt and its thermal conductivity as a function of porosity and temperature, (2) the shear behavior of interbeds, including clay seams, (3) the thermomechanical behavior of intact salt and corroboration of the German test results on WIPP salt, (4) brine migration through intact salt, (5) the thermal-mechanical-hydrologic-chemical behavior of the EDZ under high temperatures and stresses, (6) thermodynamic properties of brines, minerals and corrosion products in high temperature systems and (7) radionuclide solubilities at elevated temperatures in bedded salt.

3.1. Hot Granular Salt Consolidation, Constitutive Model and Micromechanics: SNL

This activity is a continuation of FY13 Activity 3.1 (see Appendix C). The focus of this activity has been to develop the parameters for a salt consolidation constitutive model that describe consolidation as a function of stress and temperature (nominal-scenario "H" Issues 3 and 5), based on UFD laboratory work on hot granular salt. In FY14 this work will extend the compaction model to include thermal conductivity (nominal-scenario "H" Issue 23) and permeability as a function of porosity. Funding for this effort includes the work associated with milestone reports and expenses to create and present appropriate technical papers at conferences. The micromechanics of consolidation will be documented and summarized in a state-of-the-art report. This activity is consistent with the NEA-sanctioned Salt Club objective and was an identified area of uncertainty in the U.S.-German Workshops on Salt Repository Research Design and Operations (Hansen et al. 2013). The performance function of sealing systems comprising granular salt reconsolidation is paramount to salt repository design; therefore, this work is of high priority (see Table 7-1, nominal-scenario "H" Issue 28).

3.2. Laboratory Interbed Shear Testing: SNL

This is a new activity for FY14 and replaces the FY12 and FY13 experimental work on the thermal conductivity of salt, which is expected to be completed at the end of FY13 and combined into the constitutive model developed under Activity 3.1 (see above). This new Activity 3.2 is based on the proposed testing in Table H-1. The presence of interbeds and, in particular, clay seams in bedded rock salt can have a significant influence on the structural stability and creep closure of an excavation (nominal-scenario "H" Issues 15, 16, and 17). The objective of this laboratory study is to measure shear strength parameters of rock salt containing interbeds. These data are essential for repository excavation and layout design and assurance of preclosure and postclosure safety requirements. Standard laboratory tests or near standard (direct shear, torsion, triaxial compression) on small and large scale samples will be conducted. This is an identified data gap. Although clay seams impart first-order effects on room closure, mechanical tests have not been made. Collaboration with the Germans helped identify this data gap and the information will be used to enhance constitutive models. This testing supports international collaboration and goals of the NEA Salt Club.

3.3. Laboratory Thermomechanical Testing of Intact Salt: SNL

A specific request by DOE-NE was made to conduct a suite of high-temperature laboratory tests on intact salt. A suite of such testing was put forward as one of the primary efforts to be conducted before a high-temperature field test would be attempted. Efforts in FY12 involved shake-down testing that is needed to develop a suitable testing protocol and test plan. In FY13 a formal test plan has been written and testing is underway. Funding in FY14 will allow initiation of a formal suite of tests to corroborate some 140 thermomechanical tests conducted by the Germans on WIPP cores. This work has been arranged and supported by international collaborations and the overarching memoranda of understanding (MOU) established between the German Federal Ministries and DOE as well as the MOU of the Joint Partners to compare current constitutive models and simulation procedures for calculations of the thermomechanical behavior and healing of rock salt. This collaboration will be applicable to bedded and domal salt (generic in its application) and ultimately identify the best-in-the-world codes and models for salt repository design or design and analysis of any field-scale tests in salt (see Activity 4.3 below). This activity helps address nominal-scenario "H" Issues 15, 16, 17, and 23.

3.4. Brine Migration Experimental Studies: LANL, SNL

This activity is a continuation of FY13 Activity 3.4 (see Appendix C) and focuses on brine migration in intact salt at generic salt repository pressure and temperature (P, T) conditions (nominal-scenario "H" Issue 18). It will be integrated with the modeling proposal described below in Activity 4.5. Literature surveys will be conducted to identify relevant information on thermally-driven brine migration (both inter- and intragranular). Based on these surveys, laboratory experiments will be designed to target areas of uncertainty. It is expected that these lab experiments will impose various temperature and stress gradients on salt cores to analyze how intragranular water (in fluid inclusions) migrates to grain boundaries and whether the water crosses the boundary or accumulates and flows along intergranular spaces. Mineral dehydration studies will also be conducted to investigate the movement of water released by this process and the associated effects of mineral volume changes, such as changes in permeability, porosity, and rock strength.

3.5. <u>Thermal-Hydrologic-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay Interbeds on Permeability and Brine Migration in Salt at High Temperatures and Pressures</u>: LBNL, SNL

This is a new activity for FY14. As described in Table H-10, the new FY14 activity proposes to conduct laboratory experiments to measure the coupled thermal-hydro-mechanical processes in the near-field EDZ at conditions representative of a repository for heat-producing defense *and* civilian waste (nominal-scenario "H" Issues 15, 17, and 18). Experiments will measure the evolution of permeability and mechanical properties of salt (containing clay) and how they are influenced by high temperature, different stress conditions, and different levels of pressure of the intruding fluid as would be experienced by salt in the EDZ. The fate of water/brine will also be evaluated. Because these processes are dependent on the presence, abundance, and distribution of clay, samples with and without clay will be tested. Any predictive or confirmative modeling associated with this new testing activity should be conducted under Activities 4.4 and 4.5 below (test proposals H-21 and H-23). Before initiating this activity it is recommended that a test plan be developed for peer review.

3.6. Study of Thermodynamic Properties of Brines, Minerals and Corrosion Products in High Temperature Systems: SNL

In FY12, SNL produced a Test Plan for Study of Thermodynamics of Brines, Minerals and Corrosion Products at High Temperatures. In FY 13, SNL is establishing a high-temperature thermodynamics research laboratory in support of this project. The equipment for the laboratory is on loan to SNL from the University of Idaho and has arrived at Sandia's laboratory in Carlsbad, NM. FY14 funding will be used to be used to initiate the suite of experiments discussed in the Test Plan. This activity addresses nominal-scenario "M" Issues 4, 8, and 20, and also human-intrusion "H" Issue 11 (see Table 7-1).

3.7. Radionuclide Solubility Measurements: LANL, LBNL

This activity is in part a continuation of FY13 Activity 3.7 (see Appendix C) but would also include aspects of the proposal in Table H-17. The overall goal of this study is to establish the magnitude of the temperature effect on radionuclide solubility to guide the development of future performance assessment solubility models. New to this activity would be experiments to generate solubility data for Pu(III) over a temperature range (50 to 200°C) and ionic strength range (0 to 0.01 m NaCl, $MgCl_2$) pertinent to disposal of heat-emanating radioactive waste in a salt repository. These data would become important in any repository scenario in which water contacts the waste and mobilizes radionuclides, such as a disturbed or intrusion scenario. 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. This activity addresses nominal scenario "L" Issue 21 and human-intrusion "H" Issue 12.

4. Modeling Studies Related To Salt

The March 2013 Workshop rated all modeling issues (31-38) as either high or medium importance for the nominal scenario, with most being rated as high (see Table 7-1). Activity 4 addresses many of those modeling issues and develops a set of evaluation and integration tools to guide salt RD&D test activities via a safety-case-informed approach. These modeling tools can play a major role in transparently informing customers and stakeholders of Salt R&D results. The five major elements of this work are (1) a safety framework that integrates modeling and testing activities; (2) a methodology for developing a system performance assessment model; (3) an international benchmarking collaboration to compare TM(H) constitutive models and simulation methods for the thermomechanical behavior and healing of rock salt; (4) THMC coupled process model development; and (5) development of a brine migration model for intact rock salt.

4.1 Safety Framework: SNL

This activity is a continuation of FY13 Activity 4.1 (see Appendix C) and addresses "H" Issue 43. As described in Section 3 of this report, the safety case provides the framework for prioritizing RD&D activities, with the postclosure safety/performance assessment model being a primary tool for providing quantitative guidance to this prioritization. The two major roles of the safety case, as described earlier are as a management tool to guide Salt RD&D activities and as information tool to communicate with stakeholders. In particular, the safety framework developed in this work activity will update the Safety Framework report completed on 11/16/2012 (Freeze et al. 2012). This FY13 update will include information from Activity 1 and Activity 4.2.

4.2 Total System Performance Assessment (TSPA) Model Development: SNL

The Salt Repository TSPA model, advanced under this activity, will leverage existing TSPA modeling capability (e.g., from WIPP performance assessment models) and the model development work currently being conducted for UFD's Generic Disposal System Model (GDSM). An important step in the development of the Salt Repository TSPA Model will be the identification and evaluation of coupled processes important to overall system performance, and how the important coupled processes will be included in the TSPA model in a defensible way. An important aspect of this evaluation will be to conduct sensitivity and uncertainty analyses, based on analyses from the underlying THMC process model(s), to determine those parameters and processes most important to the safety of a salt repository. These assessments will lead to specification of the methods and approach to be used for Salt Repository TSPA model development. Information from the TSPA sensitivity and uncertainty analyses, based on studies with process model(s)—see Activities 4.3, 4.4, and 4.5, will be integrated into the safety framework at various key decision points to inform, prioritize, and focus test design and data gathering activities.

In FY12, an initial list of FEPs for disposal of heat-generating waste in bedded salt was compiled. Those FEPs underwent an initial screening and a more compact list of FEPs was developed. That FEPs analysis was documented in the Level 2 Milestone: *TSPA Model Development and Sensitivity Analysis of Processes Affecting Performance of a Salt Repository for Disposal of Heat-Generating Nuclear Waste* (Sevougian et al. 2012; also see Sevougian et al. 2013b). The original M2 milestone document for FY13, *Methodology and Requirements for Post-Closure Safety Assessment of Disposal of Heat-Generating Waste in Salt*, is replaced by this present report/milestone documenting recommended future RD&D activities in bedded salt. However, the design of the Salt Repository TSPA model for heat-generating waste continues in FY13, with the development and incorporation of a salt reference case (Vaughn et al. 2013) into the UFD's Generic/Advanced Disposal System Models, informed by FEPs analysis and screening. Activity 4.2 addresses "H" Issues 33 and 34 and "M" Issue 35.

4.3. Generic Salt Repository Benchmarking—U.S.-German Collaborative Effort: SNL, LBNL, German researchers

This activity is a continuation of FY13 Activity 4.3 (see Appendix C), which addresses "H" Issues 15, 16, 37, and 42. In FY12, SNL proceeded with the evaluation of modeling capabilities, constitutive models, and validation against benchmark tests. These collaborative benchmark calculations have continued in FY13 and a report on the collaborative benchmark studies will be issued at the end of FY13. In October 2013 the next stage of the Joint Project will officially begin (see Activity 3.3 above). The purpose of the extension of the Joint Project is to include benchmark calculations against Room B&D experiments. An international benchmarking collaboration with German partners has been arranged via a memorandum of understanding (MOU) to compare current constitutive models and simulation procedures for calculations of thermomechanical behavior and healing of rock salt. The goal of these studies is to evaluate the best models for TM(H) salt behavior that exist in the world and use this information to advance generic salt repository capabilities for U.S. programs. This work will add to our understanding of generic salt phenomenology across the range of salt types and characteristics—hence will reduce uncertainty while adding to salt database. Extension of the Joint Project may provide an opportunity to add partners to the existing MOU.

A tentative matrix comprises well over 100 tests, which would be conducted at no expense to the U.S. salt programs. We would be obligated to acquire the core from the WIPP site, ensure its QA pedigree, and ship it to Germany. Sandia has shipped over four tons of large-diameter WIPP salt to date. We are also acquiring additional core for backup and potential corroboration testing by U.S. labs at Sandia and RESPEC.

4.4. Thermomechanical-Hydrological and Chemical (TMHC) Model Development: SNL, LANL, LBNL

This activity is a continuation of FY13 Activity 4.4 (see Appendix C), which addresses "H" Issues 3, 5, 7, 15, 16, 17, 18, 23, 31, 32, 33, and 34. It will leverage existing computational models and tools to couple TM, TH, and C phenomena in salt under subsurface repository conditions, with the added focus on brine accessibility and moisture transport. The coupling between native salt deformation, damage accumulation that makes the brine accessible, compaction/consolidation of granular salt, and their cumulative effect on physical properties and fluid transport are key aspects of this work. As described in Table H-21, this activity will also ask different modeling teams with their different THM codes to simulate a series of THM rock salt modeling problems in a benchmarking exercise. The objective of this exercise is to compare advanced models and methodologies, evaluate importance of individual modeling choices (i.e., specific conceptual models, weak or strong coupling, complexity), demonstrate validity of assumptions and approaches, and increase confidence in results. Testing results from laboratory activities described above should be used for model validation under this activity.

4.5. Brine Migration Modeling in Rock Salt: LBNL, LANL

As proposed in detail Table H-23, this new activity will focus on brine migration in intact salt appropriate for generic salt repository pressure and temperature (P, T) conditions and will be a companion activity to the *Brine Migration Experimental Studies* (Activity 3.4) described above. The goal of this modeling component would be to review existing models for brine movement in intact salt and develop a constitutive model appropriate for bedded salt that describes brine movement as a function of pressure, stress, and temperature conditions. The experimental and modeling components of this activity will be integrated to ensure that necessary model physical and chemical parameters are developed and the model is validated. This activity addresses the "H" Issues 18, 31, 34, and 37.

5. International Collaboration: LANL, LBNL, SNL

This activity is a continuation of Activity 5 from FY13 and addresses nominal-scenario "H" Issue 45 (see Table 7-1). International collaborations with the German researchers will continue to leverage their considerable expertise while enhancing our generic salt program credibility. Collaborations will have the goal of advancing the science and technology on important issues such as constitutive modeling, granular salt consolidation, brine migration, and seal strategy.

This scope includes workshops, publication, technical and logistical support, collaboration of state-of-the-art review papers and organizational activities. The Nuclear Energy Agency's Integration Group for the Safety Case (NEA IGSC) recently sanctioned a Salt Club for advancing salt repository options for member states and the U.S. Initial meetings will set up the rules of engagement, deliverable goals, and a business model. Salt Club meetings will continue through FY14 and have the goals of advancing understanding of FEPs associated with heat generating waste, tools for total system performance assessment, constitutive modeling, and the safety case for disposal of heat generating waste.

In FY13, international collaboration included active follow-up to the International Salt Mechanics VII conference, with the intent to hold the next such conference in the USA and participation in the IGD Technology Platform, which includes all repository media and a wide range of potential R&D. International collaboration builds upon the co-authoring of state-of-the-art position papers.

Specific activities encompass:

- The 3rd US/German workshop on salt repository research in October 2012 at Sandia National Laboratories in Albuquerque, New Mexico.
- Publishing of the Proceeding of 3rd US/German workshop in February 2013 (Hansen et al. 2013).
- Support development, review, and concurrence on a FEPs catalogue for HLW disposal in salt, consistent with the conclusions of the 2nd and 3rd US/German workshops. Initiated in December 2012 and continuing through FY14.
- Participate in the NEA IGSC Salt Club meeting in Paris in December 2012, and a subsequent Salt Club meeting in Germany in September 2013.
- Organize and participate in the 4th US/German workshop on salt repositories held in Germany. September 2013.
- Participate in the IGD-TP strategic initiative on seal systems for generic repositories.
- Provide independent technical review upon request.

6. Salt Instrumentation Development and Test Methodologies: LANL, SNL, LBNL

This activity provides the resources necessary to develop the generic salt measurement and data collection techniques and to make useful benefit of the unique skill sets and resources currently available from past WIPP studies, the Yucca Mountain Project, and from salt testing performed internationally. The instrumentation of any future thermal test in salt is expected to be a complex process and beginning the development of both classical measurement techniques and geophysics techniques will greatly aid in the planning and eventual deployment of a salt field test and will help inform the planning efforts as to the feasibility of certain techniques. Underground deployment of instrumentation may be conducted in the construction and forensics of the WIPP compaction tests (e.g. instrumentation emplacement and survivability studies), bringing significant value in the planning and designing of any future thermal testing salt, including the data gathering techniques. A small effort is being conducted in this area in FY13, but as indicated in Table 8-1, various other new efforts should be contingent on detailed planning for an *in situ* large-scale field test such as the SDDI (e.g., see the testing proposals in Tables H-7, H-8, and H-9). This activity addresses "H" Issue 39.

7. Thermal Field Testing: LANL, SNL, LBNL

As discussed in Section 7.2, a large-scale *in situ* field test, such as the SDDI concept outlined in Table H-4, has the potential to support a number of safety case objectives, if it is designed appropriately. A consensus was reached that once the field test is designed and adequately instrumented to measure and monitor thermal and brine-related parameters, it has the potential to address several RD&D technical issues for lower heat-load waste (see Section 7.3.2 and Table 7-2). It should be emphasized that the specific SDDI proposal still requires detailed test modeling and planning before its technical merits and operational requirements can be finalized. Therefore, it is recommended that sufficient analysis and test planning be funded and conducted to finalize the specific objectives and details of the proposed SDDI test (described in greater detail in Table H-4), prior to its implementation. It is also recommended that other individual lab or *in situ* tests (heated and non-heated) be conducted with simpler, more focused data objectives. An example of these more focused tests that received consideration during the workshop was an *in situ*, single-heater test (see Table H-2), which would allow measurement and monitoring of thermally driven processes in a shorter timeframe, while gaining experience in Test Plan development and field deployment.

Several new testing and monitoring methods have been discussed and proposed in Appendix H that are intended to support a thermal field test. These methods should be evaluated for suitability as part of the detailed test planning for the SDDI, and possibly incorporated into its final design.

8. "H" and "M" Issues Without Recommended Activities

Tables 8-2 and 8-3 indicate the subset of high- or medium-importance issues that do not currently have ongoing RD&D activities or that have not as yet been recommended for RD&D activities in the foregoing list. Table 8-2 is for nominal-scenario issues (pre-Workshop ratings) and Table 8-3 is for human intrusion issues (post-Workshop ratings). These various issues should be considered in future years for appropriate research to support the safety case, as needed.

Table 8-1. Recommendations for Disposition of RD&D Test Proposals (listed in Appendix H).

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation	Comments
Primarily *in situ*, large-scale field testing (with modeling)				
H-1	Clay Seam Shear Testing	*In situ* tests in the new URL; Laboratory tests; Constitutive modeling; International collaborations	Frank Hansen (SNL)	Recommend lab testing portion of this activity, defer field testing.
H-2	Single Heater Test	Generic *in situ* tests in the new URL; International collaborations; Modeling prediction and validation	Frank Hansen (SNL), Carlos Jove-Colon (SNL)	Recommend that this test be considered as part of planning for the SDDI test.
H-3	Large-Scale Seal Test	*In situ* tests in the new URL; International collaborations; Modeling; Lab—ACI concrete testing	Frank Hansen (SNL)	Recommend deferring this test until a decision is made on whether or not to pursue a salt repository.
H-4	Salt Defense Disposal Investigations (SDDI) Thermal Test	*In situ* thermal test; Laboratory tests; THM and THMC model validation	Doug Weaver (LANL)	Recommend that further analysis and test planning be conducted before the technical merits, data quality objectives, and operational requirements can be finalized; this test concept has merit to support confidence building.
H-5	Water migration tracer test during the proposed SDDI experiment	*In situ* field test with lab analysis; including pre-, during, and post-test transport modeling	Philip Stauffer (LANL), Florie Caporuscio (LANL), Paul Reimus (LANL), Ernie Hardin (SNL)	This activity should be evaluated in the context of the design of the SDDI and associated field tests.
Laboratory testing, followed by *in situ* testing (with modeling)				
H-6	Salt Decrepitation Effects	Laboratory tests initially; borehole & *in situ* field testing later; THM process and constitutive modeling	Kris Kuhlman (SNL)	This activity should be deferred until the completion of ongoing thermomechanical testing (FY13 Activity 3.3, i.e., new Activity 3.2) and, if a decision is made to implement a SDDI or single-heater thermal field test, it should also be evaluated in the context of the design of those field tests.
H-7	Development of an Integrated Geophysical Imaging System for Field-Scale Monitoring of Brine Migration and Mechanical Alteration in Salt Repositories	Laboratory tests; Field testing at LBNL Geophysical Measurement Facility (GMF); (no modeling initially but later some pre-test modeling)	T.M. Daley, Y. Wu, J. Birkholzer, and J.B. Ajo-Franklin (LBNL)	This activity should be evaluated in the context of the design of the SDDI and associated field tests.

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation	Comments
Laboratory testing, followed by *in situ* testing (no modeling)				
H-8	Geophysical and acoustical monitoring of fluid migration and fracture evolution for WIPP salt thermal tests	Initial lab sensitivity experiments; followed by *in situ* field tests at WIPP during SDDI thermal tests (no modeling)	Peter Roberts (LANL)	This activity should be evaluated in the context of the design of the SDDI and associated field tests.
H-9	*In situ* and laboratory testing of moisture monitoring methods	Laboratory tests; *In situ* field tests (no simulation modeling mentioned)	Dan Levitt (LANL)	This activity should be evaluated in the context of the design of the SDDI and associated field tests.
Laboratory testing (with modeling)				
H-10	Thermo-Hydro-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay on Permeability and Brine Migration in Salt at High Temperatures and Pressures	Complex THMC laboratory experiments; coupled process modeling to predict/interpret the results	Tim Kneafsey and Seiji Nakagawa (LBNL)	Recommend development of a test plan for peer review.
Laboratory testing (no modeling)				
H-11	Long-term steel corrosion analyses from Room A1/B re-entry	Laboratory test; (no simulation modeling mentioned)	Pat Brady (SNL)	Recommend that a decision on this activity be deferred until test plan for re-entry is completed.
H-12	Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography	Laboratory tests (no simulation modeling)	Hongwu Xu (LANL), Jonathan Ajo-Franklin (LBL)	Recommend activity be deferred for consideration until brine migration experiments and modeling be further developed.
H-13	Validation of constitutive models and parameterization of unsaturated brine flow in intact and crushed salt	Laboratory test (no simulation modeling)	Kris Kuhlman (SNL); Bwalya Malama (SNL)	Recommend activity be deferred for consideration until after constitutive model benchmarking activity (new FY13 Activity 4.3, i.e., new Activity 4.2) and brine migration modeling activity (new Activity 4.3) are completed.
H-14	Stability of Polyhalite in the Salado Formation	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)	Too specific to WIPP and not strongly supportive a generic salt applications. No tie to issues.
H-15	Stability of hydrous phases (corrensite, bassanite) in the Salado Formation	Laboratory test (applicable for SDDI waste emplacement studies)— (no simulation modeling)	Florie Caporuscio (LANL)	Too specific to WIPP and not strongly supportive a generic salt applications. No tie to issues.
H-16	Use of ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)) to map and quantify brine	Laboratory test (no simulation modeling)	Florie Caporuscio (LANL)	Recommend including this as part of ongoing brine experiments (FY13 Activity 3.4, i.e., new Activity 3.5)

Table ID	Test Name	Test Type(s)	Principal Investigator(s) and Lab Affiliation	Comments
	content in an undisturbed salt core.			
H-17	Elevated-Temperature Measurements of Plutonium (III) and Neodymium(III) Solubility in Low to Moderate Ionic Strength Aqueous Solutions	Laboratory tests (no modeling)	Jonathan Icenhower and David Shuh (LBNL); Donald Reed (LANL)	Recommend initiation as part of the ongoing actinide solubility activity (FY13 Activity 3.7, i.e, new Activity 3.6).
H-18	Laboratory Study on the Long-term Porosity and Permeability Reduction in Salt Backfill Under Elevated Temperature Conditions	Laboratory tests (no modeling)	Tim Kneafsey and Seiji Nakagawa (LBNL)	This activity is similar to ongoing crushed salt backfill experimental studies and not recommended for initiation (FY13 Activities 3.1 and 3.2).
Modeling and simulation studies only (no physical tests)				
H-19	Mechanistic modeling of brine and vapor movement	Theoretical and modeling study	Qinjun Kang (LANL)	This activity is recommended for initiation in association with the test proposal in Table H-23.
H-20	THM Optimization of Preclosure Repository Design	Coupled process modeling	Jonny Rutqvist and Laura Blanco-Martin (LBNL); Phil Stauffer and Florie Caporuscio (LANL)	This activity is important but should be done after the THM benchmarking activity and/or as an element of the THM modeling activity (H-21).
H-21	Benchmarking Simulations for THM Behavior of Rock Salt	THM(C) benchmark modeling—model-to model comparisons for a simplified repository, for a lab/field THM experiment; and for the planned SDDI test	Jonny Rutqvist and Jens Birkholzer (LBNL); Phil Stauffer and Bruce Robinson (LANL); Carlos Jove-Colon, Kristopher Kuhlman, and Ernest Hardin (SNL)	This activity is recommended for initiation (new Activity 4.4).
H-22	THM Model of Salt Rock Microstructural Damage and Healing	Mechanistic microstructure modeling of coupled processes in salt	Daisuke Asahina and Jim Houseworth (LBNL)	This activity should be deferred for consideration until after constitutive models are assessed in the generic salt benchmarking activity (FY13 Activity 4.3, i.e., new Activity 4.2).
H-23	Brine Migration in Salt: Review and Constitutive Model Development	Constitutive models	Jim Houseworth, Jonny Rutqvist, Hui-Hai Liu, Jens Birkholzer (LBNL)	Recommended for initiation (new Activity 4.3)
Proposals from researchers not present at the Workshop				
H-24	Validation Experiments Using a Geocentrifuge to Examine Canister Movement in a Salt Repository	Lab testing	Earl D. Mattson, Mitchell A. Plummer (INL)	Not recommended for initiation at this time because this issue (Issue 24) had a consensus ranking of “L” by the workshop participants

Table 8-2. Nominal Scenario, High- and Medium-Importance Consolidated Salt RD&D Technical Issues Not Currently Funded or Not Yet Recommended for Funding.
[High "H" importance issues shaded in "light orange".]

Salt RD&D Technical Issue	Pre-Workshop Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) Nominal Scenario High Heat Load ratings	Current or Recommended UFD Salt R&D Activity
Wastes and Engineered Features (EBS) Feature/Process Issues		
1. Inventory and WP Loading	M (= I,P)	
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Design-specific
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues		
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Site-specific
Repository System (EBS and Geosphere combined) Feature/Process Issues		
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	
30. Performance and effects of ventilation	M (= I,P)	
Modeling Issues		
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	
***In-Situ* Testing/Design/Operations Issues**		
Confidence-Building Issues		
44. Comparisons to natural and anthropogenic analogs	H	
48. Qualitative arguments about the intrinsic robustness of site and design	M	

Table 8-3. Human-Intrusion Scenario, High- and Medium-Importance Consolidated Salt RD&D Technical Issues Not Currently Funded or Not Yet Recommended for Funding.
[High "H" importance issues shaded in "light orange".]

Salt RD&D Technical Issue	**Post-Workshop Issue Importance Rating (Table 7-1)** (H = High, M = Medium, L = Low) **Based on** (impact, function type) **H.I. Scenario** **High Heat Load ratings**	**Current or Recommended UFD Salt R&D Activity**
Wastes and Engineered Features (EBS) Feature/Process Issues		
9. Mechanical and chemical degradation of the waste forms	**H (= D,P)**	
10. Brine flow through waste package	**M (= I,P)**	
13. Radionuclide transport in the waste package and EBS	**M (= I,P)**	
Repository System (EBS and Geosphere combined) Feature/Process Issues		
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	**H (= D,P)**	

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Appendix A: CANDIDATE FEPs FOR GENERIC SALT RD&D

This appendix contains the FEPs compilation that formed the initial basis for the consolidated list of candidate salt RD&D "issues" contained in Table 4-1. It is reduced from the full set of UFD FEPs contained in Sevougian et al. (2012, App. A). In particular, the full list of FEPs in Sevougian et al. was first reduced to primarily those technical issues or FEPs related to Geosphere and EBS processes, i.e., FEPs related to External Factors (such as Geologic Processes, Climatic Processes, and Future Human Actions) and to the Biosphere were removed from consideration at this time. The reduced list was then screened for certain FEPs that were thought unlikely to be of enough importance to repository safety to warrant generic research at this time, such as HLW glass recrystallization (2.1.02.04) and pyrophoricity (2.1.02.05). Also presented with the list of basis FEPs in Table A-1 is their "state-of-the-art" categorization from the UFD Roadmap (DOE 2012a, App. A). Specifically, in the UFD Roadmap the "state-of-the-art" of each issue is categorized as one of the following:

- Well Understood: the representation of an issue (process) is well developed, has a strong technical basis, and is defensible. Additional R&D would add little to the current understanding
- Fundamental Gaps in Method: the representation of an issue (conceptual and/or mathematical, experimental) is lacking
- Fundamental Data Needs: the data or parameters in the representation of an issue (process) is lacking
- Fundamental Gaps in Method, Fundamental Data Needs: Both
- Improved Representation: The representation of an issue may be technically defensible, but improved representation would be beneficial (i.e., lead to more realistic representation).
- Improved Confidence: Methods and data exist, and the representation is technically defensible but there is not widely-agreed upon confidence in the representation (scientific community and other stakeholders).
- Improved Defensibility: Related to confidence, but focuses on improving the technical basis, and defensibility, of how an issue (process) is represented

A crosswalk to WIPP FEPs (Hansen and Leigh 2011, App. A) is also given below in Table A-1.

Table A-1. FEPs considered as "included" (candidates for RD&D) for the Salt R&D Workshop
[From Sevougian et al. (2012, App. A), based on Freeze et al. (2011). **Reddish brown** typeface indicates changes specific to salt that are not mentioned in DOE (2012a).]

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
1.1.00.00	1. REPOSITORY ISSUES			
1.1.02.01	Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Water contaminants (explosives residue, diesel, organics, etc.) - Water chemistry different than host rock (e.g., oxidizing) - Undesirable materials left - Accidents and unplanned events	***Not evaluated/ranked in UFD Roadmap***	
1.1.02.02	Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Creation of excavation-disturbed zone (EDZ) - Stress relief - Boring and blasting effects - Rock reinforcement effects (drillholes) - Accidents and unplanned events - Enhanced flow pathways [see also Evolution of EDZ in 2.2.01.01]	***Not evaluated/ranked in UFD Roadmap***	
1.1.02.03	Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Site flooding - Preclosure ventilation - Accidents and unplanned events	***Not evaluated/ranked in UFD Roadmap***	
1.1.08.01	Deviations from Design and Inadequate Quality Control	- Error in waste emplacement (waste forms, waste packages, waste package support materials) - Error in EBS component emplacement (backfill, seals, liner)	***Not evaluated/ranked in UFD Roadmap***	

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		- Inadequate excavation / construction (planning, schedule, implementation) - Aborted / incomplete closure of repository - Material and/or component defects - Undetected manufacturing defects in waste packages and other EBS components		
1.1.10.01	Control of Repository Site	- Active controls (controlled area) - Retention of records - Passive controls (markers)	***Not evaluated/ranked in UFD Roadmap***	H57 – Loss of Records
1.1.13.01	Retrievability		*Improved Confidence* The issue of retrievability has been evaluated for some time. IAEA/NEA effort underway (December 2010 workshop)	
2.0.00.00	2. DISPOSAL SYSTEM FACTORS			
2.1.00.00	1. WASTES AND ENGINEERED FEATURES		**For the EBS, these evaluations are generally not media specific**	
2.1.01.00	1.01. INVENTORY			
2.1.01.01	Waste Inventory - Radionuclides - Non-Radionuclides **Priority 2.05 out of 8 (generic)**	- Composition - Enrichment / Burn-up	*Fundamental Data Needs* Inventories have been estimated for UNF and HLW generated from different recycling processes. Additional data is needed for other fuel cycle scenarios under consideration by FCT program	W2 Waste Inventory Incl.
2.1.01.03	Heterogeneity of Waste Inventory - Waste Package Scale - Repository Scale **Priority 1.92 out of 8**	- Composition - Enrichment / Burn-up - Damaged Area	*Fundamental Data Needs* Waste forms and repository configuration is not known	W3 Heterogeneity of Waste Forms Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	(generic)			
2.1.02.00	1.02. WASTE FORM			
2.1.02.01	SNF (Commercial, DOE) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release **Priority 4.01 out of 8 (generic)**	Degradation is dependent on: - Composition - Geometry / Structure - Enrichment / Burn-up - Surface Area - Gap and Grain Boundary Fraction - Damaged Area - THC Conditions [see also Mechanical Impact in 2.1.07.06 and Thermal-Mechanical Effects in 2.1.11.06]	*Fundamental Gaps in Method* *Fundamental Data Needs* U.S. program evaluated the long-term behavior of LWR UOX in oxidizing environments. Other programs have evaluated and are modeling the degradation of UOX and MOX in reducing environments. Little information is available regarding the degradation/alteration of other UNF types.	W4 Container Form Excl. W5 Container Material Inventory Incl.
2.1.02.02	HLW (Glass, Ceramic, Metal) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release	Degradation is dependent on: - Composition - Geometry / Structure - Surface Area - Damaged / Cracked Area - Mechanical Impact - THC Conditions [see also Mechanical Impact in 2.1.07.07 and Thermal-Mechanical Effects in 2.1.11.06]	***Not evaluated/ranked in UFD Roadmap***	W4 Container Form Excl. W5 Container Material Inventory Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.02.06	SNF Cladding Degradation and Failure **Priority 5.33 out of 8 (generic)**	- Initial damage - General Corrosion - Microbially Influenced Corrosion - Localized Corrosion - Enhanced Corrosion (silica, fluoride) - Stress Corrosion Cracking - Hydride Cracking - Unzipping - Creep - Internal Pressure - Mechanical Impact	*Fundamental Gaps in Method* *Fundamental Data Needs* U.S. program evaluated the performance attributes of LWR - UOX cladding, but decided not to take credit for cladding in the Yucca Mountain License Application. Other programs directly disposing LWR SNF have taken no credit for cladding. Nothing is known about cladding or other "outer barrier" behavior for other waste forms.	
2.1.03.00	1.03. WASTE CONTAINER			
2.1.03.02	General Corrosion of Waste Packages **Priority 4.34 out of 8 (generic)**	- Dry-air oxidation in anoxic condition - Humid-air corrosion in anoxic condition - Aqueous phase corrosion in anoxic condition - Passive film formation and stability - Chemistry of brine contacting WP - Salt deliquescence - Hydrogen gas buildup - Effect of close contact with salt undergoing creep deformation	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable studies in the corrosion of a variety of metallic materials both in the U.S. and abroad that can be leveraged. Some knowledge gaps exist regarding degradation modes for various alloys under various conditions. Little/no information available regarding new/novel materials Uncertainty in extrapolating short-term laboratory tests to long-time periods and spatially variable conditions. Interest in gas generation resulting from corrosion in some programs (Europe) Potential for novel alloys with increased resistance to corrosion - little information known.	

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.03.03	Stress Corrosion Cracking (SCC) of Waste Packages **Priority 4.34 out of 8 (generic)**	- Residual stress distribution in WP from fabrication - Stress development and distribution in contact with salt undergoing creep deformation - Crack initiation, growth and propagation - Stress distribution and evolution around advancing cracks	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable studies in the corrosion of a variety of metallic materials both in the U.S. and abroad. SCC may not be an issue for some materials in specific environments. Need to identify conditions which SCC can occur (materials and environments).	
2.1.03.04	Localized Corrosion of Waste Packages **Priority 4.34 out of 8 (generic)**	- Pitting - Crevice corrosion - Salt deliquescence - Effect of close contact with salt undergoing creep deformation [see also 2.1.09.06 Chemical Interaction with Backfill]	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable studies in the corrosion of a variety of metallic materials both in the U.S. and abroad. Improved understanding of localized corrosion effects, in particular stress corrosion cracking, pitting, and crevice corrosion would lead to improved modeling and understanding of waste package performance.	
2.1.03.05	Hydride Cracking of Waste Packages **Priority 4.34 out of 8 (generic)**	- Hydrogen diffusion through metal matrix - Crack initiation and growth in metal hydride phases	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable studies in the corrosion of a variety of metallic materials both in the U.S. and abroad. Long-term effects such as hydrogen embrittlement, de-alloying, creep, segregation, radiation damage, oxide wedging, and the effect of radiolysis on the potential aqueous phase in contact with metallic barrier materials. Identify modeling feasibility of radiolytic effects	

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
			on corrosion.	
2.1.03.06	Microbially Influenced Corrosion (MIC) of Waste Packages	- Viable colonies of halophilic bacteria - EBS environments promoting and sustaining microbial colonies	***Not evaluated/ranked in UFD Roadmap***	
2.1.03.08	Evolution of Flow Pathways in Waste Packages **Priority 1.96 out of 8 (generic)**	- Evolution of physical form of waste package degradation - Plugging of cracks in waste packages [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impacts in 2.1.07.05, 2.1.07.06, and 2.1.07.07, Thermal-Mechanical Effects in 2.1.11.06 and 2.1.11.07]	*Improved representation* Typically conservative models applied to flow through perforated waste packages.	
2.1.04.00	1.04. BUFFER / BACKFILL			
2.1.04.01	Evolution and Degradation of Backfill **Priority 3.50 out of 8 (generic)**	- Alteration - Thermal expansion / Degradation - Swelling / Compaction - Erosion / Dissolution - Evolution of backfill flow pathways [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impact in 2.1.07.04, Thermal-Mechanical Effects in 2.1.11.08, Chemical Interaction in 2.1.09.06]	*Fundamental Gaps in Method* *Fundamental Data Needs* Other countries have performed considerable investigations into different backfill and buffer materials (bentonite and cementitious materials). Additional R&D needed to better understand processes associated with backfill/buffer for these materials. Little/no information available regarding new/novel buffer/backfill materials	W9 Backfill Physical Properties Excl. W31 Differing Thermal Expansion of Repository Components Excl. W75 Chemical Degradation of Backfill Excl.
2.1.05.00	1.05. SEALS			

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.05.01	Degradation of Seals **Priority 2.76 out of 8 (generic)** **This is better stated as "Evolution of Seal Components"**	- Alteration / Degradation / Cracking - Erosion / Dissolution - Asphalt seals: degradation as function of temperature and degassing [see also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.08]	*Fundamental Gaps in Method* *Fundamental Data Needs* Various countries, including USA and international repository programs, have conducted investigations on the stability and degradation of concretes and other sealing materials. WIPP has a certified seal design and the Swedish and Finnish programs are well advanced in granite environments. A collaborative research program has been developed by DOE-EM Office of Waste Processing named the "Cementitious Barriers Partnership". The UFD EBS program will focus mainly on the development of thermodynamic database to be used in the prediction of solubilities of cementitious phases and a computational tool to perform these calculations. It will also evaluate model concepts of cement corrosion and degradation processes. Modeling of solid solution phenomena is key to the accurate representation of cement barrier degradation.	W36 Consolidation of Shaft Seals Incl. W37 Mechanical Degradation of Shaft Seals Incl. W74 Chemical Degradation of Shaft Seals Incl. W76 Microbial Growth on Concrete Incl. W113 Consolidation of Panel ClosuresInc W114 Mechanical Degradation of Panel Closures Incl. W115 Chemical Degradation of Panel Closures Incl.
2.1.06.00	1.06. OTHER EBS MATERIALS			
2.1.06.01	Degradation of Liner / Rock Reinforcement Materials in EBS **Priority 2.62 out of 8 (generic)**	- Alteration / Degradation / Cracking - Corrosion - Erosion / Dissolution / Spalling [see also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.07]	*Improved Representation* Other countries have investigated a variety of disposal system designs, including other engineered barriers system materials Improved understanding of other EBS material degradation and impacts on other EBS processes (i.e., chemistry) are needed. For example, degradation modes at the cement / rock and cement/ metal barrier interfaces.	

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.07.00	1.07. MECHANICAL PROCESSES			
2.1.07.02	Drift Collapse **Priority 2.70 – generic** In UFD Roadmap the description was changed to: - Drift collapse - Drift deformation (EDZ)	- Alteration of seepage - Alteration of EBS flow pathways - Alteration of EBS thermal environment [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Chemical Effects of Drift Collapse in 2.1.09.12, and Effects of Drift Collapse on TH in 2.1.11.04, Mechanical Effects on Host Rock in 2.2.07.01]	*Fundamental Gaps in Method* *Fundamental Data Needs* Mechanical effects in emplacement tunnels, rooms, etc. have been investigated in other geologic disposal programs. Being investigated as part of EDZ R&D. Relevant to construction operations, waste emplacement, and the emplacement of backfill material. THM processes could enhance the excavated damage zone thus influencing the hydraulic properties of the EBS backfill/buffer materials.	W20 Salt Creep Incl.
2.1.07.03	Mechanical Effects of Backfill **Priority 3.29 out of 8 (generic)**	- Crushed salt backfill should consolidate during room closure process - Static and dynamic loading on EBS structures - Restricts displacement of EBS components during ground motion and fault displacement - Protection of ~~other~~ EBS components from rockfall / drift collapse caused by ground motion and fault displacement	*Fundamental Gaps in Method* *Fundamental Data Needs* Relevant to construction operations, waste emplacement, and the emplacement of backfill material. THM processes could enhance the excavated damage zone thus influencing the hydraulic properties of the EBS backfill/buffer materials.	W9 Backfill Physical Properties Excl. W35 Mechanical Effects of Backfill Incl.
2.1.07.04	Mechanical Impact on Backfill **Priority 2.94 out of 8 (generic)**	- Rockfall / Drift collapse - Hydrostatic/lithostatic pressure of drift walls on any backfill present - Internal gas pressure - H2 gas buildup from anoxic corrosion of WP and other EBS components	*Fundamental Gaps in Method* *Fundamental Data Needs* Relevant to emplacement of backfill material and potential impact on the expected hydraulic properties of the backfill/buffer material. THM processes could enhance the excavated damage zone thus influencing the hydraulic	W20 Salt Creep Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		[see also Degradation of Backfill in 2.1.04.01 and Thermal-Mechanical Effects in 2.1.11.08]	properties of the EBS backfill/buffer materials but long-term 'healing' is expected to mitigate these perturbations.	
2.1.07.05	Mechanical Impact on Waste Packages Could be generalized to **Mechanical Response of Waste Package.** Internal gas pressure and swelling of corrosion products affect the mechanical response, but are not related to "impact". **Priority 2.76 out of 8 (generic)**	- Rockfall / Drift collapse - Waste package movement - Lithostatic pressure from salt creep - Hydrostatic pressure as repository is fully saturated - Internal gas pressure from anoxic corrosion of internal components - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.07]	*Fundamental Gaps in Method* *Fundamental Data Needs* Data needs on the effect of loading on waste package surface and corrosion. Evolution and characterization of degradation modes at the waste package interface in the presence of hydrated buffer/backfill materials. Potential emplacement issues	W20 Salt Creep Incl. W33 Movement of Containers Excl. W64 Effects of Metal Corrosion Excl.
2.1.07.06	Mechanical Impact on SNF Waste Form **Priority 3.27 out of 8 (generic)**	- Drift collapse - Swelling corrosion products - Breakage following WP structural collapse under lithostatic pressure from salt creep [see also Thermal-Mechanical Effects in 2.1.11.06]	*Fundamental Gaps in Method* *Fundamental Data Needs* Mechanical effects could be associated with waste form degradation (volume changes) but these are expected to minimal.	W20 Salt Creep Incl. W32 Consolidation of Waste Incl. W64 Effects of Metal Corrosion Excl.
2.1.07.07	Mechanical Impact on HLW Waste Form	- Drift collapse - Swelling corrosion products - Breakage following WP structural collapse under lithostatic pressure from salt creep [see also Thermal-	***Not evaluated/ranked in UFD Roadmap***	W20 Salt Creep Incl. W32 Consolidation of Waste Incl. W64 Effects of Metal Corrosion Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		Mechanical Effects in 2.1.11.06]		
2.1.07.08	Mechanical Impact on Other EBS Components - Seals - Liner / Rock Reinforcement Materials - Waste Package Support Materials **Could be generalized to: Mechanical Response of Other EBS Components** **Priority 2.16 out of 8 (generic)**	- Rockfall / Drift collapse - Movement - Hydrostatic pressure as repository is fully saturated - Lithostatic pressure from salt creep - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.09]	*Fundamental Gaps in Method* *Fundamental Data Needs* Other countries have investigated a variety of disposal system designs, including other engineered barriers system materials Improved understanding of other EBS material degradation and impacts on other EBS processes. Specific to repository environment and design.	W20 Salt Creep Incl. W36 Consolidation of Shaft Seals Incl. W113 Consolidation of Panel Closures Incl. W64 Effects of Metal Corrosion Excl.
2.1.07.09	Mechanical Effects at EBS Component Interfaces **Priority 2.56 out of 8 (generic)**	- Component-to-component contact (static or dynamic) - Volume changes - Thermal expansion	*Fundamental Gaps in Method* *Fundamental Data Needs* Identification of key interaction at EBS barrier interfaces needs to be established. Clay-metal barrier interfaces can be subjected to metal barrier degradation (e.g., metal corrosion) due to the presence of hydrous phases (clays) that could dehydrate at elevated temperatures. Models and experiments need to be developed to assess these interactions with fluids at barrier interfaces and their effects to barrier performance.	W31 Differing Thermal Expansion of Repository Components Excl. W64 Effects of Metal Corrosion Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.07.10	Mechanical Degradation of EBS	- Roof buckling and floor heave - Fault displacement - Initial damage from excavation / construction - Consolidation of EBS components - Degradation of waste package support structure and drift support structures - Alteration of EBS flow pathways [see also Mechanical Effects from Preclosure in 1.1.02.02, Evolution of Flow Pathways in EBS in 2.1.08.06, Drift Collapse in 2.1.07.02, Degradation in 2.1.04.01, 2.1.05.01, and 2.1.06.01, and Mechanical Effects on Host Rock in 2.2.07.01]	***Not evaluated/ranked in UFD Roadmap***	
2.1.08.00	1.08. HYDROLOGIC PROCESSES			
2.1.08.01	Flow Through the EBS	- Saturated / Unsaturated flow - Preferential flow pathways - Density effects on flow - Initial hydrologic conditions - Flow pathways out of and into EBS [see also Open Boreholes in 1.1.01.01, Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Flow in Waste Packages in 2.1.08.02, Flow in Backfill in 2.1.08.03, Flow through Seals 2.1.08.04, Flow	***Not evaluated/ranked in UFD Roadmap***	W9 Backfill Physical Properties Excl. N27 Effects of Preferential Pathways Incl. W7 Shaft Seal Physical Properties Incl. W90 Advection Incl. W110 Panel Closure Physical Properties Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		through Liner in 2.1.08.05, Thermal Effects on Flow in 2.1.11.10, Effects of Gas on Flow in 2.1.12.02]		
2.1.08.02	Flow In and Through Waste Packages **Priority 0.86 out of 8 (generic)**	- Saturated / Unsaturated flow - Movement as thin films or droplets	*Improved Representation* Typically conservative models applied to flow through perforated waste packages.	N27 Effects of Preferential Pathways Incl. W90 Advection Incl.
2.1.08.03	Flow in Backfill **Priority 2.76 out of 8 (generic)**	- Saturated / Unsaturated flow - Fracture / Matrix flow – fracture flow does not occur in crushed salt - Preferential flow pathway as crushed salt backfill undergoes consolidation	*Fundamental Gaps in Method* Other countries have evaluated flow through buffer/backfill materials. Improved models of flow through breaches could increase understanding of releases from the engineered barriers.	N27 Effects of Preferential Pathways Incl. W90 Advection Incl.
2.1.08.04	Flow Through Seals **Priority 2.80 out of 8 (generic)**	- Saturated / Unsaturated flow - Fracture / Matrix flow - Gas transport (in UFD, Appendix A list) - Preferential flows in non-salt portion - Brine formation by salt deliquescence	*Fundamental Gaps in Method* *Fundamental Data Needs* Improved models of flow through breaches could increase understanding of releases from the engineered barriers. For cementitious barriers, reactive transport models need to be developed to assess barrier seal performance from processes such as carbonation, sulfate attack, and coupled phenomena influencing gas transport.	N25 Fracture Flow Incl. N27 Effects of Preferential Pathways Incl. W6 Shaft Seal Geometry Incl. W7 Shaft Seal Physical Properties Incl. W90 Advection Incl. W109 Panel Closure Geometry Incl. W110 Panel Closure Physical Properties Incl.
2.1.08.05	Flow Through Liner / Rock Reinforcement Materials in EBS **Priority 0.85 out of 8 (generic)**	- Saturated / Unsaturated flow - Flow pathways along rock bolts - Fracture / Matrix flow	*Fundamental Gaps in Method* *Fundamental Data Needs* Reactive transport models need to be developed to assess barrier seal performance and interactions with fluids at barrier interfaces that could influence gas generation and	N27 Effects of Preferential Pathways Incl. W90 Advection Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
			transport.	
2.1.08.06	Alteration and Evolution of EBS Flow Pathways	- Drift collapse - Degradation/consolidation of EBS components - Plugging of flow pathways - Formation of corrosion products - Water ponding - Brine formation by salt deliquescence [see also Evolution of Flow Pathways in WPs in 2.1.03.08, Evolution of Backfill in 2.1.04.01, Drift Collapse in 2.1.07.02, and Mechanical Degradation of EBS in 2.1.07.10]	***Not evaluated/ranked in UFD Roadmap***	W64 Effects of Metal Corrosion Excl. H35 Borehole-Induced Mineralization Excl.
2.1.08.07	Condensation Forms in Repository - On Tunnel Roof / Walls - On EBS Components **Priority 1.73 out of 8 (generic)**	- Heat transfer (spatial and temporal distribution of temperature and relative humidity) - Dripping - Moisture movement - Brine formation by salt deliquescence - Release and migration of inclusion brine [see also Heat Generation in EBS in 2.1.11.01, Effects on EBS Thermal Environment in 2.1.11.03 and 2.1.11.04]	*Improved Representation* Expected to be of low impact in backfilled repositories. Highly dependent on EBS barrier design and components that would allow flow capture and/or diversion.	
2.1.08.08	Capillary Effects in EBS **Priority 1.87**	- Wicking - Capillary barrier - Osmotic binding	*Improved Representation* Expected to be of low impact in backfilled repositories. For salt importance rises because	W41 Wicking Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	(generic)		capillary effects in the backfill are important for determinng how much brine contacts the waste package. Highly dependent on EBS barrier design and components. For example, the presence of a Richards barrier.	
2.1.08.09	Influx/Seepage Into the EBS **Priority 1.89 out of 8 (generic)**	- Water influx rate (spatial and temporal distribution) [see also Open Boreholes in 1.1.01.01, Thermal Effects on Flow in EBS in 2.1.11.10, Flow Through Host Rock in 2.2.08.01, Effects of Excavation on Flow in 2.2.08.04]	*Fundamental Gaps in Method* *Fundamental Data Needs* Expected to be of medium impact in backfilled repositories. Highly dependent on EBS barrier design and components. For example, the presence of a Richards barrier.	W40 Brine Inflow Incl. W42 Fluid Flow Due to Gas Production Incl. H31 Natural Borehole Fluid Flow Excl. H32 Waste-Induced Borehole Flow Excl. H34 Borehole-Induced Solution and Subsidence Excl. H37 Changes in Groundwater Flow Due To Mining Incl. H39 Changes in Groundwater Flow Due To Explosions Excl.
2.1.09.00	1.09. CHEMICAL PROCESSES - CHEMISTRY			
2.1.09.01	Chemistry of Water Flowing into the Repository **Priority 2.64 out of 8 (generic)**	- Chemistry of influent water (spatial and temporal distribution) - Thermal effect - Chemistry of brine originated from inclusion brine - Chemistry of brine originated from intrusion groundwater - Chemistry of brine formed from salt deliquescence - Effect of anoxic condition [See also Chemistry in Host Rock 2.2.09.01]	*Fundamental Gaps in Method* Methods to obtain water chemistry exist and have been applied in many different programs. However, obtaining water chemistry information can be difficult in certain situations (i.e., highly charged systems, deep boreholes).	H24 Drilling-Induced Geochemical Changes Incl. H30 Fluid-Injection-Induced Geochemical Changes Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.09.02	Chemical Characteristics of Water in Waste Packages **Priority 2.76 out of 8 (generic)**	- Water composition (radionuclides, dissolved species, …) - Initial void chemistry (air / gas) - Water chemistry (pH, ionic strength, pCO2, pO2.pH2.) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from tunnels and/or backfill) - Effect of corrosion of waste canister and internal components - Effect of waste form corrosion - Evolution of water chemistry / interaction with waste packages [see also Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	*Fundamental Gaps in Method* *Fundamental Data Needs* Some work has been done in this respect in terms of modeling (see Wang et al. 2010) and experimental work on miniature waste packages (Ferris et al. 2009). Studies like this can provide important information as to constrain water chemistries inside the waste packages. Still, the information is limited to low temperatures and this might be an important knowledge gap. Limited/no information or methods available for advanced waste forms and alternative spent fuels.	W51 Chemical Effects of Corrosion Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W58 Dissolution of Waste Incl. W59 Precipitation of Secondary Excl. Minerals Excl. W60 Kinetics of Precipitation and Excl. Dissolution W64 Effects of Metal Corrosion Incl. W65 Reduction-Oxidation Fronts Excl. W66 Reduction-Oxidation Kinetics Incl. W67 Localized Reducing Zones Excl.
2.1.09.03	Chemical Characteristics of Water in Backfill **Priority 1.47 out of 8 (generic)**	- Water composition (radionuclides, dissolved species, …) - Water chemistry (pH, ionic strength, pCO2, pO2.pH2.) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from tunnels and/or waste package) - Brine originated from inclusion brine - Brine originated from intrusion groundwater	*Fundamental Gaps in Method* *Fundamental Data Needs* In backfilled repositories, water chemistry will be highly dependent on rock pore water chemistry, local conditions of pressure and temperature, and specific interactions with the barrier/buffer materials. Some modeling work on cation exchange and anion exclusion phenomena in clay has been initialized. Still, there are significant data gaps regarding dependencies on local ionic strength and temperature effects on diffusive transport in clay barriers.	W10 Backfill Chemical Composition Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Excl. Minerals W60 Kinetics of Precipitation and Excl. Dissolution

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		- Brine formed from salt deliquescence - Effect of gas formed from WP anoxic corrosion - Effect of anoxic condition - Evolution of water chemistry / interaction with backfill [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Tunnels in 2.1.09.04]	There are also knowledge gaps in cementitious backfills. Little/no information available regarding new/novel buffer/backfill materials.	
2.1.09.04	Chemical Characteristics of Water in Tunnels **Priority 1.77 out of 8 (generic)**	- Water composition (radionuclides, dissolved species, …) - Initial void chemistry (air/gas) - Water chemistry (pH, ionic strength, pCO2, pO2.pH2.) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from near-field host rock) - Initial chemistry (from construction / emplacement) - Evolution of water chemistry / interaction with seals, liner/rock reinforcement materials, waste package support materials [see also Chemical Effects from Preclosure in 1.1.02.01, Chemistry of Water Flowing in 2.1.09.01, Chemistry in Waste Packages in 2.1.09.02, Chemistry in	*Fundamental Gaps in Method* *Fundamental Data Needs* Expected to be of low impact in backfilled repositories. Could affect interactions with liner, seal, and other EBS barrier components.	W10 Backfill Chemical Composition Incl. W51 Chemical Effects of Corrosion Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl. W64 Effects of Metal Corrosion Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		Backfill in 2.1.09.03]		
2.1.09.05	Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels Possibly included in 2.1.09.02, 2.1.09.03, and 2.1.09.04	- Corrosion product formation and composition (waste form, waste package internals, waste package) - Evolution of water chemistry in waste packages, in backfill, and in tunnels - Effect of water chemistry on corrosion products characteristics [contributes to Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	***Not evaluated/ranked in UFD Roadmap***	W51 Chemical Effects of Corrosion Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W58 Dissolution of Waste Incl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl. W64 Effects of Metal Corrosion Incl. W65 Reduction-Oxidation Fronts Excl. W66 Reduction-Oxidation Kinetics Incl. W67 Localized Reducing Zones Excl.
2.1.09.06	Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels Possibly included in 2.1.09.02, 2.1.09.03, and 2.1.09.04	- Backfill composition and evolution (bentonite, crushed rock, ...) - Evolution of water chemistry in backfill, and in tunnels - Enhanced degradation of waste packages (crevice formation) - Brine originated from inclusion brine - Brine originated from	***Not evaluated/ranked in UFD Roadmap***	W10 Backfill Chemical Composition Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		intrusion groundwater - Brine formed from salt deliquescence - Effect of gas formed from EBS anoxic corrosion - Effect of anoxic condition [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04, Localized Corrosion of WPs in 2.1.03.04]		
2.1.09.07	Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS - In Backfill - In Tunnels **Priority 2.80 out of 8 (generic)**	- Liner composition and evolution (Portland cement, special concrete formulations for salt, metal, ...) - Rock reinforcement material composition and evolution (grout, rock bolts, mesh, ...) - Composition and evolution of other cementitious materials, including any special formulations for salt - Evolution of water chemistry in backfill, and in tunnels [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	*Fundamental Gaps in Method* *Fundamental Data Needs* Could potential be of high impact in repositories depending on materials chosen and design. Highly dependent on interactions with liner, seal, and other EBS barrier components. Reactive transport models need to be developed to assess barrier seal performance and interactions with fluids at barrier interfaces that could influence fluid transport and chemistry.	W51 Chemical Effects of Corrosion Incl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W58 Dissolution of Waste Incl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl. W64 Effects of Metal Corrosion Incl. W65 Reduction-Oxidation Fronts Excl. W66 Reduction-Oxidation Kinetics Incl. W67 Localized Reducing Zones Excl.
2.1.09.08	Chemical Interaction of Water with Other EBS Components - In Waste Packages - In Tunnels	- Seals composition and evolution - Waste Package Support composition and evolution (Portland cement, special concrete formulations for salt, metal, ...) - Other EBS components	***Not evaluated/ranked in UFD Roadmap***	W8 Shaft Seal Chemical CompositionExc W111 Panel Closure Chemical Composition Excl. W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		(other metals (copper), ...) - Evolution of water chemistry in backfill, and in tunnels [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]		Dissolution
2.1.09.09	Chemical Effects at EBS Component Interfaces **Priority 2.61 out of 8 (generic)**	- Component-to-component contact (chemical reactions) - Consolidation of EBS components - Barrier degradation at interfaces	*Fundamental Gaps in Method* *Fundamental Data Needs* Identification of key interaction at EBS barrier interfaces needs to be established. Clay-metal barrier interfaces can be subjected to metal barrier degradation (e.g., metal corrosion) due to the presence of hydrous phases (clays) that could dehydrate at elevated temperatures. Models and experiments need to be developed to assess these interactions with fluids at barrier interfaces and their effects to barrier performance.	W50 Galvanic Coupling (within The repository) Excl.
2.1.09.10	Chemical Effects of Waste-Rock Contact	- Waste-to-host rock contact (chemical reactions) - Component-to-host rock contact (chemical reactions)	***Not evaluated/ranked in UFD Roadmap***	W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl.
2.1.09.12	Chemical Effects of Drift Collapse	- Evolution of water chemistry in backfill and in tunnels (from altered seepage, from altered thermal-hydrology) [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	***Not evaluated/ranked in UFD Roadmap***	

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.09.13	Radionuclide Speciation and Solubility in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 4.86 out of 8 (generic)**	- Dissolved concentration limits - Limited dissolution due to inclusion in secondary phase - Enhanced dissolution due to alpha recoil - Complexation with organic ligands - Formation of various types of colloids [controlled by Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	*Improved Representation* Considerable work has been done in the U.S. and in other countries regarding radionuclide speciation and dissolved concentration limits. Improved understanding of solubility controls and dissolved concentration limits would lead to improved radionuclide transport models and better understanding of disposal system performance. Large knowledge gaps on radionuclide solubilities at elevated temperatures and in concentrated electrolyte solutions. Accurate redox speciation chemistry of important radionuclides such as Pu and Np are still a matter of investigation. Improved understanding of potential solubility-controlling phases for radionuclides with mixed compositions (i.e., not necessarily pure end-members). Complex water chemistry / solid solutions in EBS Methods - Experimental and representation (model) Phases / controls for advanced fuel compositions - data and methods needs	W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W58 Dissolution of Waste Incl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl. W99 Alpha Recoil Excl.
2.1.09.50	1.09. CHEMICAL PROCESSES - TRANSPORT			

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.09.51	Advection of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 3.06 out of 8 (generic)**	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Level of Saturation [see also Gas Phase Transport in 2.1.12.03]	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable work has been done in the U.S. and in other countries regarding EBS transport. Improved understanding of EBS transport processes would lead to improved radionuclide transport models and better understanding of disposal system performance. For backfilled repositories, focus should be given to diffusive transport through barriers and waste package. Thermal loading from WF is important	W77 Solute Transport Incl. W83 Rinse Excl. W90 Advection Incl.
2.1.09.52	Diffusion of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 3.06 out of 8 (generic)**	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Brine Saturation	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable work has been done in the U.S. and in other countries regarding EBS transport. Improved understanding of EBS transport processes would lead to improved radionuclide transport models and better understanding of disposal system performance. For backfilled repositories, focus should be given to diffusive transport through barriers and waste package. Thermal loading from WF is important	W91 Diffusion Incl. W92 Matrix Diffusion Incl. W97 Chemical Gradients Excl. W98 Osmotic Processes Excl. W100 Enhanced Diffusion Excl.
2.1.09.53	Sorption of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Surface complexation properties - Flow pathways and velocity - Brine Saturation - Sorption on EBS degradation products	*Fundamental Gaps in Method* *Fundamental Data Needs* Considerable work has been done in the U.S. and in other countries regarding EBS transport and sorption processes relevant to	W61 Actinide Sorption Incl. in Culebra and Dewey Lake Excl. elsewhere W62 Kinetics of Sorption Excl. W63 Changes in Sorptive SurfacesExcl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	Priority 3.06 out of 8 (generic)	- Sorption in anoxic condition - Effect of brine ionic strength [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	radionuclides. Improved understanding of EBS transport processes, in particular sorption, would lead to improved radionuclide transport models and better understanding of disposal system performance. Current modeling work on reactive-transport through barriers is being considered and will be expanded to include radionuclides.	
2.1.09.55	Formation of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 1.79 out of 8 (generic)**	- Formation of intrinsic colloids - Formation of pseudo colloids (host rock fragments, waste form fragments, corrosion products, microbes, and humics) - Formation of co-precipitated colloids - Sorption/attachment of radionuclides to colloids (clay, silica, waste form, FeOx, microbes)	*Fundamental Gaps in Method* *Fundamental Data Needs* Although colloids might form, their role in transport will be highly dependent on other parameters of the EBS. Colloidal phases may have an important effect of radionuclide solubility but their stability under various conditions and their role as solubility-controlling phases is still a matter of research. The role of humics, fulvics and other organic materials has been widely studied in the EU.	W64 Effects of Metal Corrosion Incl. W79 Colloid Formation and Stability Incl. W82 Suspension of Particles Incl.
2.1.09.56	Stability of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 1.79 out of 8 (generic)**	- Chemical stability of attachment (dependent on water chemistry) - Mechanical stability of colloid (dependent on colloid size, gravitational settling)	*Fundamental Gaps in Method* *Fundamental Data Needs* Same as FEP 2.1.09.55	W79 Colloid Formation and Stability Incl. W82 Suspension of Particles Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.09.57	Advection of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 1.42 out of 8 (generic)**	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Saturation - Colloid concentration	*Fundamental Gaps in Method* *Fundamental Data Needs* Same as FEP 2.1.09.55	W78 Colloid Transport Incl. W80 Colloid Filtration Incl. W87 Microbial Transport Incl.
2.1.09.58	Diffusion of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 1.42 out of 8 (generic)**	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Saturation - Colloid concentration	*Fundamental Gaps in Method* *Fundamental Data Needs* Same as FEP 2.1.09.55	W78 Colloid Transport Incl. W97 Chemical Gradients Excl. W98 Osmotic Processes Excl.
2.1.09.59	Sorption onto Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel **Priority 1.42 out of 8 (generic)**	- Surface complexation properties - Flow pathways and velocity - Saturation - Colloid concentration [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	*Fundamental Gaps in Method* *Fundamental Data Needs* Same as FEP 2.1.09.55	W81 Colloid Sorption Incl. W88 Biofilms Excl.
2.1.09.61	Filtration of Colloids in EBS **Priority 1.42 out of 8 (generic)**	- Physical filtration or trapping (dependent on flow pathways, colloid size) - Electrostatic filtration	*Fundamental Gaps in Method* *Fundamental Data Needs* Same as FEP 2.1.09.55	W80 Colloid Filtration Incl.
2.1.09.62	Radionuclide Transport Through Liners and Seals	- Advection - Dispersion - Diffusion - Sorption	***Not evaluated/ranked in UFD Roadmap***	W6 Shaft Seal Geometry Incl. W109 Panel Closure Geometry Incl. W61 Actinide Sorption Excl. W62 Kinetics of Sorption Excl. W63 Changes in Sorptive Surfaces Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		[contributes to Radionuclide release from EBS in 2.1.09.63]		W77 Solute Transport Incl. W78 Colloid Transport Incl. W87 Microbial Transport Incl.
2.1.09.63	Radionuclide Release from the EBS - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the host rock (due to varying flow pathways and velocities, varying component degradation rates, varying transport properties) [contributions from Dissolved in 2.1.09.51/52/53, Colloidal in 2.1.09.57/58/59, Gas Phase in 2.1.12.03, Liners and Seals in 2.1.09.62]	***Not evaluated/ranked in UFD Roadmap***	W34 Container Integrity Excl. W61 Actinide Sorption Excl. W77 Solute Transport Incl. W78 Colloid Transport Incl. W80 Colloid Filtration Incl. W81 Colloid Sorption Incl. W87 Microbial Transport Incl.
2.1.10.00	1.10. BIOLOGICAL PROCESSES			
2.1.10.01	Microbial Activity in EBS - Natural - Anthropogenic	- Effects on corrosion - Formation of complexants - Formation of microbial colloids - Formation of biofilms - Gas generation by biodegradation - Biomass production - Bioaccumulation [see also Microbiallly Influenced Corrosion in 2.1.03.06, Complexation in EBS in 2.1.09.54, Radiological Mutation of Microbes in 2.1.13.03]	***Not evaluated/ranked in UFD Roadmap***	N71 Microbes Incl./Excl. Incl. for colloids & gas generation; other impacts Excl. W44 Degradation of Organic MaterialIncl. W45 Effects of Temperature on Microbial Gas Generation Incl. W46 Effects of Pressure on Microbial Gas Generation Excl. W47 Effects of Radioactivity on Microbial Gas Generation Excl. W48 Effects of Biofilms on Microbial Gas Generation Incl. W76 Microbial Growth on ConcreteExcl.
2.1.11.00	1.11. THERMAL PROCESSES			

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.11.01	Heat Generation in EBS **Priority 2.59 out of 8 (generic)**	- Radionuclide decay - Heat transfer (spatial and temporal distribution of temperature and relative humidity) [see also Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Waste Inventory in 2.1.01.01]	*Fundamental Data Needs* Work has been done in the U.S. and in other countries regarding to the effect of heat on EBS performance. Strong influence to THCM coupled processes in the EBS. Thermal management criteria is strongly tied to barrier concept and performance. THCM models and data needs are essential to the assessment of barrier performance.	W13 Heat from Radioactive Decay Excl.
2.1.11.03	Effects of Backfill on EBS Thermal Environment **Priority 2.22 out of 8 (generic)**	- Thermal conductivity of backfill - Thermal blanket - Condensation	*Fundamental Gaps in Method* *Fundamental Data Needs* Work has been done in the U.S. and in other countries regarding to the effect of heat transport on EBS performance. Strong influence to THCM coupled processes in the EBS. Thermal management criteria is strongly tied to barrier concept and performance. THCM models and data needs are essential to the assessment of barrier performance. Little/no information regarding new/novel backfill/buffer materials	W9 Backfill Physical Properties Excl. W29 Thermal Effects on Material Properties Excl.
2.1.11.04	Effects of Drift Collapse on EBS Thermal Environment **Priority 2.39 out of 8 (generic)**	- Thermal conductivity of rubble - Thermal blanket - Condensation	*Fundamental Gaps in Method* *Fundamental Data Needs* Relevant to construction operations, waste emplacement, and the emplacement of backfill material. THM processes could enhance the excavated damage zone thus influencing the hydraulic properties of the EBS backfill/buffer materials.	W20 Salt Creep Incl. W29 Thermal Effects on Material Properties Excl.
2.1.11.05	Effects of Influx (Seepage) on Thermal Environment	- Temperature and relative humidity (spatial and temporal distribution)	***Not evaluated/ranked in UFD Roadmap***	N28 Thermal Effects on Groundwater Flow Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		[see also Influx/Seepage into EBS in 2.1.08.09]		
2.1.11.06	Thermal-Mechanical Effects on Waste Form and In-Package EBS Components	- Mechanical loads from room closure due to salt creep - Alteration - Cracking - Thermal expansion / stress	***Not evaluated/ranked in UFD Roadmap***	W20 Salt Creep Incl. W31 Differing Thermal Expansion of Repository Components Excl.
2.1.11.07	Thermal-Mechanical Effects on Waste Packages	- Mechanical loads from room closure due to salt creep - Thermal sensitization / phase changes - Cracking - Thermal expansion / stress / creep	***Not evaluated/ranked in UFD Roadmap***	W20 Salt Creep Incl. W31 Differing Thermal Expansion of Repository Components Excl.
2.1.11.08	Thermal-Mechanical Effects on Backfill	- Mechanical loads from room closure due to salt creep - Consolidation of backfill - Alteration - Cracking - Thermal expansion / stress - Movement of WP due to the negative buoyance	***Not evaluated/ranked in UFD Roadmap***	W20 Salt Creep Incl. W31 Differing Thermal Expansion of Repository Components Excl. W35 Mechanical Effects of Backfill Excl.
2.1.11.09	Thermal-Mechanical Effects on Other EBS Components - Seals - Liner / Rock Reinforcement Materials - Waste Package Support Structure	- Mechanical loads from room closure due to salt creep - Alteration - Cracking - Thermal expansion / stress	***Not evaluated/ranked in UFD Roadmap***	W20 Salt Creep Incl. W31 Differing Thermal Expansion of Repository Components Excl.
2.1.11.10	Thermal Effects on Flow in EBS	- Altered influx/seepage - Altered saturation / relative humidity (dry-out, resaturation) - Condensation	***Not evaluated/ranked in UFD Roadmap***	N28 Thermal Effects on Groundwater Flow Excl. W29 Thermal Effects on Material Properties Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.11.11	Thermally-Driven Flow (Convection) in EBS	- Convection	***Not evaluated/ranked in UFD Roadmap***	N28 Thermal Effects on Groundwater Flow Excl. W43 Convection Excl.
2.1.11.12	Thermally-Driven Buoyant Flow / Heat Pipes in EBS	- Vapor flow	***Not evaluated/ranked in UFD Roadmap***	N28 Thermal Effects on Groundwater Flow Excl. W43 Convection Excl. W89 Transport of Radioactive Gases Excl
2.1.11.13	Thermal Effects on Chemistry and Microbial Activity in EBS		***Not evaluated/ranked in UFD Roadmap***	W45 Effects of Temperature on Microbial Gas Generation Incl.
2.1.11.14	Thermal Effects on Transport in EBS	- Thermal diffusion (Soret effect) - Thermal osmosis	***Not evaluated/ranked in UFD Roadmap***	W93 Soret Effect Excl. W98 Osmotic Processes Excl.
2.1.12.00	1.12. GAS SOURCES AND EFFECTS			
2.1.12.01	Gas Generation in EBS **Priority 0.98 out of 8 (generic)**	- Repository Pressurization - Mechanical Damage to EBS Components - He generation from waste from alpha decay - H_2 generation from anoxic corrosion of waste package and other EBS components - H_2 generation from radiolysis - CO_2, CH_4, and H_2S generation from microbial activity - Vaporization of water - Influence of gas pressure on room closure by salt creep - Influence of gas pressure on advective flows toward and away from the repository	*Fundamental Gaps in Method* *Fundamental Data Needs* There are needs for modeling approaches and experimental data to accurately assess the importance of gas transport through EBS.	W26 Pressurization Incl. W44 Degradation of Organic Material Incl. W45 Effects of Temperature on Microbial Gas Generation Incl. W46 Effects of Pressure on Microbial Gas Generation Excl. W47 Effects of Radioactivity on Microbial Gas Generation Excl. W48 Effects of Biofilms on Microbial Gas Generation Incl. W49 Gases from Metal Corrosion Incl. W54 Helium Gas Production Excl. W55 Radioactive Gases Excl. W99 Alpha Recoil Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.1.12.02	Effects of Gas on Flow Through the EBS **Priority 0.98 out of 8 (generic)**	- Two-phase flow - Gas bubbles - Corrosion gas buildup [see also Buoyant Flow/Heat Pipes in 2.1.11.12]	*Fundamental Gaps in Method* *Fundamental Data Needs* There are needs for modeling approaches and experimental data to accurately assess the importance of gas transport through EBS.	W42 Fluid Flow Due To Gas Production Incl.
2.1.12.03	Gas Transport in EBS **Priority 1.02 out of 8 (generic)**	- Gas phase transport - Gas phase release from EBS - Corrosion gas buildup	*Fundamental Gaps in Method* *Fundamental Data Needs* There are needs for modeling approaches and experimental data to accurately assess the importance of gas transport through EBS.	W89 Transport of Radioactive Gases Excl. W90 Advection Incl.
2.2.00.00	2. GEOLOGICAL ENVIRONMENT			
2.2.01.00	2.01. EXCAVATION DISTURBED ZONE			
2.2.01.01	Evolution of EDZ **Priority 2.58 out of 8 (salt)**	- Lateral extent, heterogeneities - Physical properties - Flow pathways - Chemical characteristics of groundwater in EDZ - Radionuclide speciation and solubility in EDZ - Thermal-mechanical effects, particularly healing of fractures in the EDZ - Thermal-chemical alteration, particularly diffusion of sulfates from the host rock into the disposal rooms (affects gas generation) [see also Mechanical Effects of Excavation in 1.1.02.02, Seismic Activity Impacts EBS and/or EBS Components in	*Fundamental Data Needs* Need to know the evolution of the characteristics of the EDZ under the thermal-mechanical and wetting changes (clay and salt). Need to understand the coupled evolution of near-field host rock (EDZ) and backfill. Considerable work has been done for WIPP and European programs. European programs starting multi-year projects investigating thermal-mechanical and moisture effects in the EDZ. This issue includes other disturbances (e.g., ventilation) beyond just excavation effects.	W18 Disturbed Rock Zone Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		1.2.03.01]		
2.2.02.00	2.02. HOST ROCK			
2.2.02.01	Stratigraphy and Properties of Host Rock **Priority 3.74 out of 8 (salt)**	- Rock units - Thickness, lateral extent, heterogeneities, discontinuities, contacts - Physical properties - Flow pathways [see also Fractures in 2.2.05.01 and Faults in 2.2.05.02]	*Fundamental Gaps in Method* Many site characterization methods have been developed for repository and other related programs (EM, carbon sequestration). More refined methods can be developed to define flow paths (discontinuities, heterogeneities, fracture connectivity, and uncertainty quantification).	N1 Stratigraphy Incl.
2.2.05.00	2.05. FLOW AND TRANSPORT PATHWAYS			
2.2.05.01	Fractures - Host Rock - Other Geologic Units **Priority 3.65 out of 8 (salt)**	- Rock properties - Hydrologic properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]	*Fundamental Gaps in Method* Modeling sparsely fractured media is challenging. Need to develop improved modeling tools to represent fractures/fracture sets as discrete features. Need information to characterize/model connectivity, channelization (e.g., tracer tests).	N25 Fracture Flow Incl. N27 Effects of Preferential Pathways Incl. N31 Hydrological Response to Earthquakes Excl.
2.2.05.02	Faults - Host Rock - Other Geologic Units	- Rock properties - Hydrologic properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]		N25 Fracture Flow Incl. N27 Effects of Preferential Pathways Incl. N31 Hydrological Response to Earthquakes Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.2.05.03	Alteration and Evolution of Geosphere Flow Pathways - Host Rock - Other Geologic Units **Priority 2.46 out of 8 (salt)**	- Changes In rock properties - Changes in faults - Changes in fractures - Changes in flow pathways, aquifers, and aquitards, including potential for plugging and dissolution - Changes in saturation - Evolution of properties (porosity, permeability, etc.) in interbeds [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01, Fractures in 2.2.05.01, and Faults in 2.2.05.02] [see also Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]	*Improved Confidence* Data for validation is lacking. Some gaps may exist in modeling the interaction of chemical (alkaline) plume with the surrounding rocks. Column experiments and natural analogues could be used for understanding the alkaline plume.	N8 Formation of Fractures Incl. in near-field; Excl. in far-field N9 Changes in Fracture Properties Incl. in near-field; Excl. in far-field N10 Formation of New Faults Excl. N11 Fault Movement Excl. N16 Shallow Dissolution Incl. N18 Deep Dissolution Excl. N22 Fracture Infills Excl. N31 Hydrological Response to Earthquakes Excl. N32 Natural Gas Intrusion Excl. W23 Subsidence Excl. W24 Large-Scale Rock Fracturing Excl. W25 Disruption Due to Gas Effects Incl. H25 Oil and Gas Extraction Excl. H26 Groundwater Extraction Excl. H27 Liquid Waste Disposal Outside Boundary of Site Excl. H28 Enhanced Oil and Gas Production Outside Boundary of Site Excl. H29 Hydrocarbon Storage Outside Boundary of Site Excl. H34 Borehole-Induced Solution and Subsidence Excl. H35 Borehole-Induced Mineralization Excl. H37 Changes in Groundwater Flow Due To Mining Incl. H39 Changes in Groundwater Flow Due To Explosions Excl. H58 Solution Mining for Potash Excl. H59 Solution Mining for Other Resources Excl. H60 Liquid Waste Disposal Inside Boundary of Site Excl. H61 Enhanced Oil and Gas Production Inside Boundary of Site Excl. H62 Hydrocarbon Storage Inside Boundary of Site Excl.
2.2.07.00	2.07. MECHANICAL			

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	PROCESSES			
2.2.07.01	Mechanical Effects on Host Rock **Priority 3.83 out of 8 (salt)**	- From subsidence due to repository-related excavations - From salt creep - From healing of the EDZ - From dissolution of halite - From solution mining of other strata - From fracturing caused by gas pressurization - Chemical precipitation / dissolution [see also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]	*Fundamental Gaps in Method* *Fundamental Data Needs* European programs starting multi-year projects investigating thermal-mechanical and moisture effects. Note that there are also international collaborations in EM Need to interface with EBS.	W18 Disturbed Rock Zone Incl. W19 Excavation-Induced Changes in Stress Incl. W20 Salt Creep Incl. W21 Changes in the Stress Field Incl. W22 Roof Falls Incl. W23 Subsidence Excl. W24 Large-Scale Rock Fracturing Excl. W25 Disruption Due To Gas Effects Incl. W26 Pressurization Incl. W27 Gas Explosions Excl. W28 Nuclear Explosions Excl. W30 Thermally Induced Stress Changes Excl.
2.2.08.00	2.08. HYDROLOGIC PROCESSES			
2.2.08.01	Flow Through the Host Rock **Priority 7.73 out of 8 (salt)**	- Saturated flow - Fracture flow / matrix imbibition (probably not applicable to salt) - Unsaturated flow (fingering, capillarity, episodicity, perched water) - Preferential flow pathways (including flow in interbed) - Density and thermal effects on flow - Flow pathways out of Host Rock [see also Influx/Seepage into EBS in 2.1.08.09, Alteration of Flow Pathways in	*Fundamental Gaps in Method* *Fundamental Data Needs* Need to develop improved modeling tools to represent fractures/fracture sets as discrete features in crystalline. Need information to characterize/model connectivity, channelization (e.g., tracer tests). Need to understand fracturation and healing in clays and salt. Water migration in salt is a unique process that needs to be better understood. Need to understand thermal and pressure gradients and gas generation and migration.	N23 Saturated Groundwater Flow Incl. N24 Unsaturated Groundwater Flow Incl. N25 Fracture Flow Incl. N26 Density Effects on Groundwater Flow Excl. N27 Effects of Preferential Pathways Incl. N28 Thermal Effects on Groundwater Flow Excl. W40 Brine Inflow Incl. W90 Advection Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
		2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02]	Need to capture and validate uncertainty.	
2.2.08.04	Effects of Repository Excavation on Flow Through the Host Rock **Priority 7.10 out of 8 (salt)**	- Saturated flow (flow sink) - Unsaturated flow (capillary diversion, drift shadow) - Influx/Seepage into EBS (film flow, enhanced seepage) [see also Influx/Seepage into EBS in 2.1.08.09]	*Fundamental Gaps in Method* Requires same R&D as FEP 2.2.08.01.	H37 Changes in Groundwater Flow Due To Mining Incl.
2.2.08.05	Condensation Forms in Host Rock	- Condensation cap - Shedding - Deliquescence of mixed salts [see also Thermal Effects on Flow in Geosphere in 2.2.11.01]	***Not evaluated/ranked in UFD Roadmap***	
2.2.08.06	Flow Through EDZ **Priority 7.73 out of 8 (salt)**	- Saturated / Unsaturated flow - Fracture / Matrix flow	*Fundamental Gaps in Method* *Fundamental Data Needs* Flow in the EDZ is closely tied to the evolution of the EDZ. R&D related to FEP 2.2.01.01	W18 Disturbed Rock Zone Incl. W90 Advection Incl.
2.2.08.07	Mineralogic Dehydration **Priority 6.49 out of 8 (salt)**	- Dehydration reactions release water and may lead to volume changes	*Fundamental Gaps in Method* *Fundamental Data Needs* Significant work has been done. But significant gaps exist in modeling the coupled THMC processes. This is most important in clay. R&D related to FEP 2.2.01.01	H35 Borehole-Induced Mineralization Excl.
2.2.09.00	2.09.CHEMICAL PROCESSES - CHEMISTRY			
2.2.09.01	Chemical Characteristics of Groundwater in Host	- Water composition (radionuclides, dissolved species, …)	*Fundamental Gaps in Method* *Fundamental Data Needs*	N33 Groundwater Geochemistry Incl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	Rock **Priority 2.40 out of 8 (salt)**	- Water chemistry (temperature, pH, Eh, ionic strength, pO2 …) - Reduction-oxidation potential - Reaction kinetics - Interaction with EBS - Origin of brine (inclusion brine, intrusion groundwater brine, brine formed from salt deliquescence, etc.) - Effect of gas formed from EBS anoxic corrosion - Effect of anoxic condition [see also Chemistry in Tunnels in 2.1.09.04, Chemical Interactions and Evolution in 2.2.09.03] [contributes to Chemistry of Water Flowing into Repository in 2.1.09.01]	Methods for characterizing groundwater chemistry and models to predict water chemistry evolution in the near field need to be further improved. Need to define a generic chemistry for each geologic environment. Need to identify interactions with EBS materials (e.g., introduced fluids, alkaline plume from the near field). R&D to determine potential for identification of favorable and/or unfavorable groundwater chemistries. Need to characterize effect of microbial activity on water chemistry. Need to identify chemical sampling methods to characterize initial fluid composition (e.g., clay, unsaturated rock). Evaluate interactions of various waste forms/waste streams with various chemical environments. Identify method to characterize groundwater composition - spatial and temporal variability, scale dependence Salt - Need to understand brine chemistry, interaction of high ionic strength brine with EBS components Need better characterization of deep crystalline water chemistry (deep boreholes).	
2.2.09.03	Chemical Interactions and Evolution of Groundwater in Host	- Host rock composition and evolution - Evolution of water chemistry	*Fundamental Gaps in Method* *Fundamental Data Needs*	N35* Freshwater Intrusion Excl. N36 Changes in Groundwater Eh Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	Rock **Priority 2.10 out of 8 (salt)**	in host rock - Chemical effects on density - Interaction with EBS - Reaction kinetics - Mineral dissolution/precipitation - Redissolution of precipitates after dry-out - Origin of brine (inclusion brine, intrusion groundwater brine, brine formed from salt deliquescence, etc.) - Evolution of gas generation from EBS anoxic corrosion - Effect of anoxic condition [contributes to Chemistry in Host Rock in 2.2.09.01]	See FEP 2.2.09.01	N37 Changes in Groundwater pH Excl. N38 Effects of Dissolution Excl. H24 Drilling-Induced Geochemical Changes Excl. H30 Fluid-Injection-Induced Geochemical Changes Excl. H35 Borehole-Induced Mineralization Excl. H36 Borehole-Induced Geochemical Changes Incl. H38 Changes in Geochemistry Due To Mining Excl. *Geochemical Effects
2.2.09.05	Radionuclide Speciation and Solubility in Host Rock **Priority 2.40 out of 8 (salt)**	- Dissolved concentration limits - Water composition - Water chemistry (temperature, pH, Eh, ionic strength, pO2,pH2 …) - Reduction-oxidation potential [controlled by Chemistry in Host Rock in 2.2.09.01]	*Fundamental Gaps in Method* *Fundamental Data Needs* Accurate prediction radionuclide of speciation in a natural system under various conditions remains challenging. Thermodynamic data for modeling speciation/solubility for high ionic strength and high temperature environments is needed. Need methods to fill in thermodynamic data gaps. Need methods to measure *in situ* redox conditions, characterize actinide/radionuclide speciation, and model radionuclide speciation for a range of redox conditions. Significant work has been done on simple systems. Better characterization of complexants is needed.	W56 Speciation Incl. W57 Kinetics of Speciation Excl

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.2.09.50	2.09. CHEMICAL PROCESSES - TRANSPORT			
2.2.09.53	Diffusion/Dispersion of Dissolved Radionuclides in Host Rock **Priority 2.40 out of 8 (salt)**	- Gradients (concentration, chemical potential) - Diffusive properties (porosity, tortuosity, diffusion coefficients) - Flow pathways and velocity - Saturation	*Fundamental Gaps in Method* *Fundamental Data Needs* The effects of geologic formation heterogeneity and their scale dependence is not fully understood. Need to consider/characterize scale dependence of properties for all physical transport processes. Effect of saturation on physical transport properties has additional uncertainty that could be reduced. Need to better understand bentonite/host rock interface (bentonite saturation) Advection follows flow, see FEP 2.2.08.01. Need to better understand the effect of channeling and advective flow-wetted surfaces on diffusion and sorption. Dispersion - Evaluate alternative advection/dispersion conceptual models. Diffusion - Need better characterization / conceptualization of diffusion in small pores (e.g., clays) - membrane effect (EDL overlap). Need generic experimental work (e.g., engineered materials). Dilution - Well understood.	W91 Diffusion Incl. W92 Matrix Diffusion Incl. W97 Chemical Gradients Excl. W98 Osmotic Processes Excl. W100 Enhanced Diffusion Excl.
2.2.09.55	Sorption of Dissolved Radionuclides in Host Rock	- Surface complexation properties - Flow pathways and velocity - Saturation	*Fundamental Gaps in Method* *Fundamental Data Needs* Need to develop improved sorption models	W61 Actinide Sorption Incl. in Culebra, Dewey Lake Excl. elsewhere W62 Kinetics of Sorption Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
	Priority 2.40 out of 8 (salt)	- Mineralogical composition of host rock - Brine ionic strength - Brine redox condition - Effect of H2 gas buildup [see also Chemistry in Host Rock in 2.2.09.01]	(beyond Kd) - consider kinetics (irreversibility) Need to develop surface complexation models that account for forces that are non-electrostatic in nature. Need improved models of sorption changes along flow paths (speciation) - also need data (leverage work from EM and Office of Science and International). Need to separate spatial variability from uncertainty in Kd values. Improve measurement of multiple samples. Need to be able to extrapolate models/data from simple systems to actual systems. Need to quantify reactive surface area. Field demo sites exist for validation. Data gaps for Kds for elevated temperature and high ionic strength media. Need to incorporate these processes in reactive transport models.	W63 Changes in Sorptive SurfacesExcl.
2.2.09.59	Colloidal Transport in Host Rock **Priority 2.22 out of 8 (salt)**	- Flow pathways and velocity - Saturation - Advection - Dispersion - Diffusion - Sorption - Colloid concentration - Colloid stability	*Fundamental Gaps in Method* *Fundamental Data Needs* Significant work has been done. But the puzzle is yet to be put together. Evidence suggests that Pu travels further than Kd models would predict. Need improved models that can reproduce this observed behavior. Need improved techniques for *in situ* characterization and quantification of colloids. Leverage info from NAGRA working group on colloids.	W78 Colloid Transport Incl. W80 Colloid Filtration Incl. W81 Colloid Sorption Incl. W87 Microbial Transport Incl. W88 Biofilms Excl. W97 Chemical Gradients Excl. W98 Osmotic Processes Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
			Colloid formation - Better understand formation from clay materials, sorption/desorption (attachment/detachment). Colloid instability in high ionic strength environments. Colloid transport - Need to reduce uncertainty in infiltration. Need to better represent heterogeneous behavior of colloids. Need better understanding of colloid transport behavior in unsaturated environments to reduce conservatisms in current models. Muliple rate kinetics and irreversibility of radionuclide sorption onto colloids - better understand size dependence.	
2.2.09.61	Radionuclide Transport Through EDZ	- Advection - Dispersion - Diffusion - Sorption	*Fundamental Gaps in Method* *Fundamental Data Needs* More thermodynamic data are needed for elevated temperatures.	W77 Solute Transport Incl. W78 Colloid Transport Incl. W87 Microbial Transport Incl.
2.2.10.00	2.10. BIOLOGICAL PROCESSES			
2.2.10.01	Microbial Activity in Host Rock **Priority 1.32 out of 8 (generic)**	- Formation of complexants - Formation and stability of microbial colloids - Biodegradation - Bioaccumulation - - Nutrients availability and replenishment [see also Complexation in Host Rock in 2.2.09.57]	*Fundamental Gaps in Method* *Fundamental Data Needs* Better methods for quantify mircobial activity in a subsurface environments and its impact on water chemistry (see FEP 2.2.09.01). Try to leverage work from EM, Office of Science, and WIPP. Better understand how microbes may be limited by environment	N71 Microbes Incl./Excl. Incl. for colloids & gas generation; Other impacts Excl. W44 Degradation of Organic Material Incl. W45 Effects of Temperature on Microbial Gas Generation Incl. W46 Effects of Pressure on Microbial Gas Generation Excl. W47 Effects of Radioactivity on Microbial Gas Generation Excl. W48 Effects of Biofilms on Microbial Gas Generation Incl. W79 Colloid Formation and StabilityIncl. W88 Biofilms Excl.
2.2.11.00	2.11. THERMAL PROCESSES			

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
2.2.11.02	Thermally-Driven Flow (Convection) in Geosphere **Priority 2.10 out of 8 (salt)**	- Convection	*Improved Representation* Much can be learned from geothermal studies. Improved representation would be needed for unsaturated sites. Current approach relies on multi-scale model implementation. HPC may provide for more transparent model implementation. Need to collaborate with EBS	N28 Thermal Effects on Groundwater Flow Excl. W43 Convection Excl.
2.2.11.03	Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere **Priority 1.66 out of 8 (salt)**	- Vapor flow	*Improved Representation* Same as FEP 2.2.11.02	N28 Thermal Effects on Groundwater Flow Excl. W43 Convection Excl.
2.2.11.04	Thermal Effects on Chemistry and Microbial Activity in Geosphere **Priority 2.40 out of 8 (salt)**	- Mineral precipitation / dissolution - Altered solubility [contributes to Chemistry in 2.2.09.01 and 2.2.09.02]	*Fundamental Gaps in Method* *Fundamental Data Needs* Likely to be screened out in far field, but is important in near field/EDZ. Large gap in thermodynamic data at elevated temperatures. Specification of thermodynamic approach for modeling clay dehydration and alteration.	W45 Effects of Temperature on Microbial Gas Generation Incl.
2.2.11.06	Thermal-Mechanical Effects on Geosphere **Priority 2.30 out of 8 (salt)**	- Thermal expansion / compression - Altered properties of fractures, faults, rock matrix	*Fundamental Data Needs* No additional data needed for far field. See FEPs 2.2.07.01 and 2.2.01.01 for state of the art discussion	W29 Thermal Effects on Material Properties Excl. W30 Thermally Induced Stress Changes Excl.
2.2.11.07	Thermal-Chemical Alteration of Geosphere **Priority 2.30 out of 8 (salt)**	- Mineral precipitation / dissolution - Altered properties of fractures, faults, rock matrix - Alteration of minerals / volume changes -	*Fundamental Data Needs* No additional data needed for far field. See FEPs 2.2.09.01 and 2.2.09.05 and 2.2.01.01 for state of the art discussions. R&D necessary to support screening decision (potential for irreversible changes in clay	W56 Speciation Incl./Excl. W57 Kinetics of Speciation Excl. W59 Precipitation of Secondary Minerals Excl. W60 Kinetics of Precipitation and Dissolution Excl. N42 Chemical Weathering Excl.

Table A-1. (continued).

UFD FEP Number	Description	Associated Processes	State of the Art (UFD Roadmap)	Status & Crosswalk for WIPP
			properties due to thermal chemical reactions, dewatering of salt as thermal fields cause migration of water and vapor, development of a chemically altered zone).	
2.2.12.00	2.12. GAS SOURCES AND EFFECTS			
2.2.12.01	Gas Generation in Geosphere	- Degassing (clathrates, deep gases) - Microbial degradation of organics - Vaporization of water	***Not evaluated/ranked in UFD Roadmap***	N71 Microbes Incl./Excl. Incl. for colloids and gas generation; other impacts Excl. W44 Degradation of Organic Material Incl.
2.2.12.02	Effects of Gas on Flow Through the Geosphere **Priority 0.95 out of 8 (generic)**	- Altered gradients and/or flow pathways - Vapor/air flow - Two-phase flow - Gas bubbles - Natural Gas Intrusion from formations beneath repository (N32) [see also Buoyant Flow/Heat Pipes in 2.2.11.03]	*Fundamental Gaps in Method* *Fundamental Data Needs* Relevant research in European programs (GAST - NAGRA, FORGE - small scale modeling) and in Japan.	N32 Natural Gas Intrusion Excl. W25 Disruption Due to Gas Effects Incl. W42 Fluid Flow Due To Gas Production Incl.

Appendix B: CROSSWALK BETWEEN SALT RD&D CONSOLIDATED ISSUES AND UFD FEPS

In addition to the FEPs list in Appendix A, a number of other literature sources and previous salt research and testing were accounted for in the compilation of the candidate list of consolidated salt RD&D issues (Table 4-1). These sources have been discussed in Section 4. In this Appendix the final list of consolidated salt RD&D issues is mapped to the underlying FEPs listed in Appendix A.

Table B-1. Crosswalk of Salt RD&D Consolidated Issues (Table 4-1) to UFD FEPs Considered as Candidates for Salt RD&D (Table A-1)

Salt RD&D Technical Issue	UFD FEP Crosswalk
Wastes and Engineered Features (EBS) Feature/Process Issues	
1. Inventory and WP Loading	2.1.01.01 Waste Inventory - Radionuclides - Non-Radionuclides 2.1.01.03 Heterogeneity of Waste Inventory - Waste Package Scale - Repository Scale
2. Physical-chemical properties of crushed salt backfill at emplacement	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.08.01 Deviations from Design and Inadequate Quality Control 2.1.09.03 Chemical Characteristics of Water in Backfill
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.07.02 Drift Collapse - Drift deformation (EDZ) 2.1.07.03 Mechanical Effects of Backfill 2.1.07.04 Mechanical Impact on Backfill 2.1.07.05 Mechanical Impact on Waste Packages 2.1.07.06 Mechanical Impact on SNF Waste Form 2.1.07.07 Mechanical Impact on HLW Waste Form 2.1.07.08 Mechanical Impact on Other EBS Components - Seals - Liner/Rock Reinforcement Materials - Waste Package Support Materials 2.1.07.09 Mechanical Effects at EBS Component Interfaces 2.1.07.10 Mechanical Degradation of EBS 2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.11.03 Effects of Backfill on EBS Thermal Environment 2.1.11.08 Thermal-Mechanical Effects on Backfill 2.2.08.06 Flow Through EDZ - Salt 2.1.09.03 Chemical Characteristics of Water in Backfill

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.1.09.12 Chemical Effects of Drift Collapse
4. Changes in chemical characteristics of brine in the backfill and EBS	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.08.03 Flow in Backfill 2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.04 Chemical Characteristics of Water in Tunnels 2.1.09.05 Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels 2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.09.07 Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS - In Backfill - In Tunnels 2.1.09.12 Chemical Effects of Drift Collapse 2.1.11.13 Thermal Effects on Chemistry and Microbial Activity in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
5. Mechanical response of backfill	2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.07.03 Mechanical Effects of Backfill 2.1.07.04 Mechanical Impact on Backfill 2.1.07.05 Mechanical Impact on Waste Packages 2.1.07.06 Mechanical Impact on SNF Waste Form 2.1.07.07 Mechanical Impact on HLW Waste Form 2.1.07.08 Mechanical Impact on Other EBS Components - Seals - Liner/Rock Reinforcement Materials - Waste Package Support Materials 2.1.07.09 Mechanical Effects at EBS Component Interfaces 2.1.07.10 Mechanical Degradation of EBS 2.1.09.12 Chemical Effects of Drift Collapse 2.1.11.08 Thermal-Mechanical Effects on Backfill
6. Impact of mechanical loading on performance of the WP	1.1.08.01 Deviations from Design and Inadequate Quality Control 2.1.07.05 Mechanical Impact on Waste Packages 2.1.07.06 Mechanical Impact on SNF Waste Form 2.1.07.07 Mechanical Impact on HLW Waste Form 2.1.11.07 Thermal-Mechanical Effects on Waste Packages
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.08.01 Flow Through the EBS 2.1.08.03 Flow in Backfill 2.1.08.05 Flow Through Liner / Rock Reinforcement Materials in EBS 2.1.08.07 Condensation Forms in Repository - On Tunnel Roof/Walls - On EBS Components 2.1.08.08 Capillary Effects in EBS 2.1.08.09 Influx/Seepage Into the EBS 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.04 Chemical Characteristics of Water in Tunnels 2.1.09.05 Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.11.01 Heat Generation in EBS 2.1.11.10 Thermal Effects on Flow in EBS 2.1.11.11 Thermally-Driven Flow (Convection) in EBS 2.1.11.12 Thermally-Driven Buoyant Flow / Heat Pipes in EBS 2.1.12.02 Effects of Gas on Flow Through the EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.12.01 Gas Generation in Geosphere
8. Corrosion performance of the waste package	1.1.08.01 Deviations from Design and Inadequate Quality Control 2.1.03.02 HLW (Glass, Ceramic, Metal) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Cracking - Radionuclide Release 2.1.03.03 Stress Corrosion Cracking (SCC) of Waste Packages 2.1.03.04 Localized Corrosion of Waste Packages 2.1.03.05 Hydride Cracking of Waste Packages 2.1.03.06 Microbially Influenced Corrosion (MIC) of Waste Packages 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.05 Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
9. Mechanical and chemical degradation of the waste forms	2.1.02.01 SNF (Commercial, DOE) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release 2.1.02.02 HLW (Glass, Ceramic, Metal) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Cracking - Radionuclide Release 2.1.02.06 SNF Cladding Degradation and Failure 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.11.06 Thermal-Mechanical Effects on Waste Form and In-Package EBS Components 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
10. Brine flow through waste package	2.1.03.08 Evolution of Flow Pathways in Waste Packages 2.1.08.01 Flow Through the EBS 2.1.08.02 Flow In and Through Waste Packages 2.1.08.06 Alteration and Evolution of EBS Flow Pathways 2.1.08.08 Capillary Effects in EBS 2.1.11.10 Thermal Effects on Flow in EBS 2.1.11.11 Thermally-Driven Flow (Convection) in EBS 2.1.12.02 Effects of Gas on Flow Through the EBS
11. Changes in chemical characteristics of brine in the waste package	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.08.02 Flow In and Through Waste Packages 2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.04 Chemical Characteristics of Water in Tunnels 2.1.09.05 Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels 2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.09.07 Chemical Interaction of Water with Liner / Rock Reinforcement and

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	Cementitious Materials in EBS - In Backfill - In Tunnels 2.1.11.13 Thermal Effects on Chemistry and Microbial Activity in EBS 2.1.09.12 Chemical Effects of Drift Collapse 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
12. Radionuclide solubility in the waste package and EBS	2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.04 Chemical Characteristics of Water in Tunnels 2.1.09.05 Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels 2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.09.07 Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS - In Backfill - In Tunnels 2.1.09.13 Radionuclide Speciation and Solubility in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.11.14 Thermal Effects on Transport in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
13. Radionuclide transport in the waste package and EBS	2.1.03.08 Evolution of Flow Pathways in Waste Packages 2.1.08.01 Flow Through the EBS 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.51 Advection of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.52 Diffusion of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.53 Sorption of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.55 Formation of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.56 Stability of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.57 Advection of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.58 Diffusion of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.59 Sorption of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.61 Filtration of Colloids in EBS 2.1.09.62 Radionuclide Transport Through Liners and Seals 2.1.11.14 Thermal Effects on Transport in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues	
14. Stratigraphy and physical-chemical properties of host rock	2.2.02.01 Stratigraphy and Properties of Host Rock - Salt
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.1.07.02 Drift Collapse - Drift deformation (EDZ) 2.1.07.10 Mechanical Degradation of EBS 2.2.07.01 Mechanical Effects on Host Rock - Salt 2.2.08.04 Effects of Repository Excavation on Flow Through the Host Rock - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.07.02 Drift Collapse - Drift deformation (EDZ) 2.1.07.04 Mechanical Impact on Backfill 2.1.07.05 Mechanical Impact on Waste Packages 2.1.07.06 Mechanical Impact on SNF Waste Form 2.1.07.07 Mechanical Impact on HLW Waste Form 2.1.07.08 Mechanical Impact on Other EBS Components - Seals - Liner/Rock Reinforcement Materials - Waste Package Support Materials 2.1.07.09 Mechanical Effects at EBS Component Interfaces 2.1.07.10 Mechanical Degradation of EBS 2.2.07.01 Mechanical Effects on Host Rock - Salt
17. The formation and evolution of the EDZ	1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.07.10 Mechanical Degradation of EBS 2.2.01.01 Evolution of EDZ - Salt 2.2.07.01 Mechanical Effects on Host Rock - Salt 2.1.07.02 Drift Collapse - Drift deformation (EDZ) 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.11.01 Heat Generation in EBS 2.2.05.01 Fractures - Host Rock - Other Geologic Units - Salt 2.2.05.02 Faults - Host Rock - Other Geologic Units 2.2.05.03 Alteration and Evolution of Geosphere Flow Pathways - Host Rock - Other Geologic Units - Salt 2.2.08.01 Flow Through the Host Rock - Salt

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.2.08.04 Effects of Repository Excavation on Flow Through the Host Rock - Salt 2.2.08.05 Condensation Forms in Host Rock 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.01 Gas Generation in Geosphere 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt
19. Chemical characteristics of brine in the host rock	2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.11.01 Heat Generation in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.55 Sorption of Dissolved Radionuclides in Host Rock - Salt
20. Changes in chemical characteristics of brine in the host rock and EDZ	1.1.02.01 Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.09.01 Chemistry of Water Flowing into the Repository 2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.11.01 Heat Generation in EBS 2.2.08.05 Condensation Forms in Host Rock 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.09.55 Sorption of Dissolved Radionuclides in Host Rock - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
21. Radionuclide solubility in the host rock and EDZ	2.1.09.63 Radionuclide Release from the EBS - Dissolved - Colloidal - Gas Phase 2.2.01.01 Evolution of EDZ 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.09.05 Radionuclide Speciation and Solubility in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
22. Radionuclide transport in the host rock and EDZ	2.1.09.63 Radionuclide Release from the EBS - Dissolved - Colloidal - Gas Phase 2.2.05.01 Fractures - Host Rock - Other Geologic Units - Salt 2.2.08.05 Condensation Forms in Host Rock

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.2.08.06 Flow Through EDZ - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.09.05 Radionuclide Speciation and Solubility in Host Rock - Salt 2.2.09.53 Diffusion of Dissolved Radionuclides in Host Rock - Salt 2.2.09.55 Sorption of Dissolved Radionuclides in Host Rock - Salt 2.2.09.59 Colloidal Transport in Host Rock - Salt 2.2.09.61 Radionuclide Transport Through EDZ - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.01 Gas Generation in Geosphere 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt 2.2.14.01 Criticality in Far-Field
Repository System (EBS and Geosphere combined) Feature/Process Issues	
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.01.01 Waste Inventory - Radionuclides - Non-Radionuclides 2.1.01.03 Heterogeneity of Waste Inventory - Waste Package Scale - Repository Scale 2.1.11.01 Heat Generation in EBS 2.1.11.03 Effects of Backfill on EBS Thermal Environment 2.1.11.04 Effects of Drift Collapse on EBS Thermal Environment 2.1.11.05 Effects of Influx (Seepage) on Thermal Environment 2.2.08.05 Condensation Forms in Host Rock 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.01 Gas Generation in Geosphere 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt 2.2.14.01 Criticality in Far-Field
24. Buoyancy of the waste packages	2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	2.1.03.02 General Corrosion of Waste Packages 2.1.04.01 Evolution and Degradation of Backfill/buffer 2.1.08.01 Flow Through the EBS 2.1.08.03 Flow in Backfill 2.1.08.06 Alteration and Evolution of EBS Flow Pathways 2.1.08.07 Condensation Forms in Repository - On Tunnel Roof / Walls - On EBS Components 2.1.09.06 Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels 2.1.12.01 Gas Generation in EBS 2.2.08.06 Flow Through EDZ - Salt

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.01 Gas Generation in Geosphere 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.10.01 Microbial Activity in EBS - Natural - Anthropogenic 2.1.11.13 Thermal Effects on Chemistry and Microbial Activity in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.09.53 Diffusion of Dissolved Radionuclides in Host Rock - Salt 2.2.09.55 Sorption of Dissolved Radionuclides in Host Rock - Salt 2.2.09.59 Colloidal Transport in Host Rock - Salt 2.2.09.61 Radionuclide Transport Through EDZ - Salt 2.2.10.01 Microbial Activity in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.12.01 Gas Generation in Geosphere
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	2.1.09.02 Chemical Characteristics of Water in Waste Packages 2.1.09.03 Chemical Characteristics of Water in Backfill 2.1.09.55 Formation of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.56 Stability of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.57 Advection of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.58 Diffusion of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.59 Sorption of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel 2.1.09.61 Filtration of Colloids in EBS 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.09.55 Sorption of Dissolved Radionuclides in Host Rock - Salt 2.2.09.59 Colloidal Transport in Host Rock - Salt 2.2.09.61 Radionuclide Transport Through EDZ - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
28. Performance of seal system	1.1.08.01 Deviations from Design and Inadequate Quality Control 2.1.05.01 Degradation of Seals 2.1.08.04 Flow Through Seals 2.1.09.08 Chemical Interaction of Water with Other EBS Components - In Waste Packages - In Tunnels

Table B-1. (continued).

Salt RD&D Technical Issue	UFD FEP Crosswalk
	2.1.09.62 Radionuclide Transport Through Liners and Seals 2.1.11.09 Thermal-Mechanical Effects on Other EBS Components - Seals - Liner / Rock Reinforcement Materials - Waste Package Support Structure 2.2.08.01 Flow Through the Host Rock - Salt 2.2.08.04 Effects of Repository Excavation on Flow Through the Host Rock - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt
29. Performance of ground support	1.1.08.01 Deviations from Design and Inadequate Quality Control 2.1.06.01 Degradation of Liner / Rock Reinforcement Materials in EBS 2.1.08.05 Flow Through Liner / Rock Reinforcement Materials in EBS 2.1.09.07 Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS - In Backfill - In Tunnels 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt
30. Performance and effects of ventilation	1.1.08.01 Deviations from Design and Inadequate Quality Control 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.11.02 Thermally-Driven Flow (Convection) in Geosphere - Salt 2.2.11.03 Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Salt

Appendix C: SALT RESEARCH AND DEVELOPMENT STUDY PLAN—MARCH 23, 2012

This plan includes scope, budget, and deliverables for a generic salt research and development study plan. This plan was developed in response to the agreement on the technical objectives and science-based scope of work for the study of salt geologic media for disposal of DOE-owned and civilian high-level waste and used nuclear fuel.

William Boyle/NE (Tim Gunter) and Christine Gelles/EM agreed to convene a small team to complete a formal summary of the terms of the agreement reached. The summary was completed and conveyed to attendees on close of business Thursday, March 15th. The same small team was tasked to develop a Salt Research and Development (R&D) Study Plan that executes the terms specified in the Summary Agreement. The Study Plan (this document) has been completed by March 23, 2012, as agreed, and includes a description of each science-based scope of work (with time and cost estimates) for a defined research program.

The list of activities agreed upon includes:

1. Evaluate existing data.
2. Physical recovery plan.
3. Laboratory studies.
4. Develop and benchmark models.
5. International collaborations.

These studies can be undertaken in FY2012 and will constructively advance generic salt repository science. Justification and description are given for each activity, followed by scope, deliverables, and costs. Table 1 provides a summary of costs by activity. Table 2 provides a list of deliverables expected to result from the implementation of this plan.

Table 1 - Activity Titles and Costs

Activity	Description	SNL	LANL	LBNL	Other	Total
1	Existing Salt Data Compilation and Assessment	485	195		0	680
2	Test Planning For Re-Entry Into The North Experimental Area of WIPP	25	195		80	300
3	Thermal, Mechanical, Hydrologic, and Chemical Laboratory Studies Related to Salt	910	550		50	1510
4	Modeling Studies Related to Salt	1050	450	180	0	1680
5	International Collaboration	110	20		0	130
6	Salt Instrumentation Development And Test Methodologies	50	140		10	200
		2630	1550	180	140	
	Allocation for Salt Research and Development From NE-53					**4,500**

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Table 2 - Milestones

Milestone Number	Title	Date
1.1	Platform and organization structure for data management	7/30/2012
1.2	A bibliography produced by the database will summarize the existing data from WIPP and the Delaware Basin that has been captured in the database along with the results of the evaluation performed to date on the data	9/28/2012
1.3	A bibliography produced by the database will summarize the existing data from non-Delaware Basin salt sites and International Salt Programs that has been captured in the database along with the results of the evaluation performed to date on the data	9/28/2012
2.1	Test Plan for Forensic Analysis in the North Experimental Area of WIPP	9/27/2013
2.2	Re-entry Plan for Mining into the North Experimental Area of WIPP	9/27/2013
3.1a	Complete Test Plan revision based on external review and prioritized test matrix	6/1/2012
3.1b	Complete UFD Milestone M2 M2FT-12SN0806081 Coupled Thermal-Hydrological-Mechanical Processes in Salt QRL3	11/15/2012
3.2a	Test plan for determining thermal conductivity of granular salt as a function of porosity and temperature	7/9/2012
3.2b	Report on granular salt thermal conductivity as a function of porosity and temperature – contingent on 2013 funding	7/02/2013
3.3a	Report on results of shake-down testing of one sample at each temperature	9/28/2012
3.3b	Test Plan Completion for Thermomechanical Testing – contingent on 2013 funding	11/30/2012
3.3c	Final Report on Thermomechanical Testing– contingent on 2013 funding	7/02/2013
3.4.1a	Draft Report of literature search update	6/15/2012
3.4.1b	Final Report of literature survey	8/01/2012
3.4.2	Development of final test plan for FY2013 experiments	8/01/2012
3.5	Test Plan for Investigation of Material Interactions In Heated Salt	9/28/2012
3.6	Test Plan for Investigation of Thermodynamic Properties Of Brines, Minerals And Corrosion Products In High Temperature Systems	9/28/2012
3.7	Radionuclide Solubility Measurements	9/28/2012
3.8	Report on Assessment of the Utility of Neutron Measurements for the Characterization of Water in Salt	9/28/2012
4.1	Report on Safety Framework for Salt R&D Investigations	8/31/2012
4.2	Report on TSPA Model Development and Sensitivity Analysis of Processes Affecting Performance of a Salt Repository for Disposal of Heat-Generating Nuclear Waste	8/30/2012
4.3	Draft Report on Salt Repository Benchmarking Studies	9/28/2012
4.4a	Report on Model Development and Analysis of the Fate and Transport of Water in a Salt-Based Repository	9/28/2012
4.4b	Evaluation of EBS THM Coupled Processes in Salt	11/15/2012
5.1	U.S./German Workshop Presentations	10/10/2012
6.1	Summary Report on Salt Instrumentation Development	9/16/2013

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 1: EXISTING SALT DATA COMPILATION AND ASSESSMENT

Justification

Twenty-five plus years of data exists on the Salado formation in the Delaware Basin, other U.S. locations and throughout the international scientific community related to salt and its performance as a storage medium for nuclear waste. There is much still to be learned from this body of work especially when thermal effects are being considered. The material needs to be compiled and assessed for use in this context. This information includes:

- Geomechanical Properties of Salt
- Thermomechanical properties of salt
- Hydrological properties of salt
- Chemical Properties of Salt (brine and mineral chemistry)
- Material Interactions in Salt

Compilation of existing data in a format (for example in a database or online bibliography) that allows ready access to important historical research that has already been performed on salt both from U.S. and international programs is a high priority in FY12 because it supports all of the other activities in this proposal. A concise understanding of the tests performed during development of the Waste Isolation Pilot Plant (WIPP) provides information that supports Activity 2 (namely determining the location of re-entry and the type and location of forensic analyses that can be performed upon re-entry). Further, an assessment of existing data is needed, within the structure of the generic safety framework for salt disposal of heat-generating waste (being developed as part of Activity 4 of this proposal) for the purpose of establishing a recommended research program (part of which is addressed in Activity 3 as a laboratory program). Finally, modeling existing test information is an optimum starting point for benchmarking activities. Thus, this activity of compilation and assessment is paramount to the success of Activity 4.

Statement of Work

The focus of this activity will be to compile and assess the multiple data sources into a comprehensive salt testing database. This database and associated bibliography will make readily available these reports and data for supporting any future testing and safety framework activities related to a nuclear waste repository in salt. This activity consists of three subtasks.

1.1 Construction of the Chosen Platform.

The suggested platform is a database that organizes the reports/data in a manner that correlates them with the technical activities for a safety framework for heat-generating waste disposal in salt (a generic form of which will be developed as part of Activity 4). The database will be accessible from the web and provide project participants the ability to quickly collate existing information on the technical topic of interest. In addition, after initial database development users will be given the ability to enhance the information in the database to reflect the ongoing usage of the data and to modify aspects of the evaluation criteria that were initially performed at a higher level without input from the full assessment of the data in models and by Principal Investigator review. Placing this task first facilitates collaboration by laboratory participants.

Milestone: Platform and organization structure for data management, 7/30/12.

1.2 WIPP/Delaware Basin Data

The assessment of these data focuses on the nature of the testing that was performed at WIPP and in the Delaware Basin and to ascertain if the intrinsic properties of salt as it reacts to heat were determined or could be determined from the test data. This includes the intrinsic properties of brine and minerals as they react when heat is applied as well as any information on brine migration and material interactions with salt at elevated temperatures. The data will also be assessed following a specific procedure and associated checklist which establishes a set of uniform criteria for the evaluation process. The criteria will include aspects of quality assurance under which the data was collected (i.e., are test plans, notebooks, electronic data available), has the data been evaluated for precision, uncertainty or accuracy, is the data relevant to the higher heat regimes of DOE-owned and commercial high-level waste and used nuclear fuel in salt and other aspects related to the safety framework process.

Milestone: A bibliography produced by the database will summarize the existing data from WIPP and the Delaware Basin that has been captured in the database along with the results of the evaluation performed to date on the data, 09/28/2012.

1.3 Non-Delaware Basin and International Program Data

The assessment of these data focuses on the nature of the testing that was performed at non-Delaware Basin salt sites and from the International programs and to ascertain if the intrinsic properties of salt as it reacts to heat were determined or could be determined from the test data. This includes the intrinsic properties of brine and minerals as they react when heat is applied as well as any information on brine migration and material interactions with salt at elevated temperatures. The data will also be assessed following a specific procedure and associated checklist which establishes a set of uniform criteria for the evaluation process. The criteria will include aspects of quality assurance under which the data was collected (i.e., are test plans, notebooks, electronic data, available), has the data been evaluated for precision, uncertainty or accuracy, is the data relevant to the higher heat regimes of DOE-owned and commercial high-level waste and used nuclear fuel in salt and other aspects related to the safety framework process.

Milestone: A bibliography produced by the database will summarize the existing data from non-Delaware Basin salt sites and International Salt Programs that has been captured in the database along with the results of the evaluation performed to date on the data, 09/28/2012.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Activity 1 - Compilation and Assessment of Existing Data

Task	Description	SNL	LANL	Other	Budget
1.1	Construction of the Chosen Platform	110	20	0	130
1.2	WIPP/Delaware Basin Data	350	25	0	375
1.3	Non-Delaware Basin and International Program Data	25	150	0	175
	Totals	**485**	**195**	**0**	**680**

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 2: TEST PLANNING FOR RE-ENTRY INTO THE NORTH EXPERIMENTAL AREA OF WIPP

Justification

Heated room experiments were conducted in A and B rooms in the north experimental area. These tests were abruptly terminated, and at least some heaters and canisters were abandoned in place. Important information can be learned from examination of the reconsolidated salt attached to the heater, the nature of brine migration in the intact salt adjacent to the heater, and of possible corrosion on the heaters and canisters themselves that will benefit the knowledge of salt behavior under thermal conditions. Similar to Activity 1, this activity is a cost effective and expedient way to obtain thermally induced data without running a field test.

The purpose of this activity is to recover information from the abandoned test area at WIPP. Recovery of salt core could allow assessment of brine movement and interactions near the heaters and recovery of the heaters themselves would allow assessment of the physical and chemical conditions of closed emplacement holes and surrounding annular material. Reentry could also facilitate measurement of the related room closure and sampling and collection of mine-run salt that may have experienced reconsolidation as a consequence of room closure.

A physical recovery plan would, realistically, only involve preliminary planning associated with a generic plan developed for the Underground Research Laboratory (URL). The recovery plan would describe access to the north experimental area and establish potential forensic studies, which would include coring for microscopy and possible heater recovery for corrosion examination. It might be possible to ascertain the overall roof-to-floor closure and reconsolidation of the mine-run salt placed in the abandoned drifts.

Statement of Work

This activity provides the Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and WIPP Management and Operating (M&O) resources necessary to develop a plan to reenter and examine the north WIPP experimental area that was shut down when heater tests were abruptly terminated decades ago and to develop the appropriate scientific test plan to define the information needs and scientific objectives (e.g. sampling plan, coring plan, test equipment removal strategies). As the mining access will provide new drifts and the potential for alcoves, planning should consider using such areas as a potential "underground research lab" for domestic needs and international collaborations. Excavation for the WIPP URL (e.g. tunneling over from N-940) could allow reentry to the north experimental area and provide an opportunity for forensic reconnaissance of previously heated rooms.

Reentry will involve two primary tasks, one related to the planning by WIPP M&O personnel to perform the physical activities associated with the reentry into the north experimental area and a separate task associated with planning the testing to be performed upon gaining access to the area. These activities shall be coupled together as potential testing will dictate which areas will

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

be accessed and what types of access will be needed. The two primary tasks should encompass the following:

2.1 Develop Test Plan for Re-entry and Forensic Analysis

The Salt Disposal Investigations (SDI) test coordination office will develop a test plan that will determine the type, location and number of tests to perform in the North Experimental. Possible tests to consider when developing this plan include: measurement of saturation and porosity, measurement of pore pressures, collection of brines followed by chemical analysis, and sampling of solid materials to determine if alteration products were formed due to the applied heat. This plan needs to be outlined before developing the reentry plan so that reentry is designed to accommodate the planned tests. All test plans must be developed in accordance with the quality assurance (QA) procedures already in existence for WIPP.

Milestone: Test Plan for Forensic Analysis in the North Experimental Area of WIPP, 9/28/2013.

2.2 Develop Plan for Mining and Re-entry

WIPP M&O personnel will identify the process for planning a reentry into the north experimental area; this plan will be coordinated with the test planning described in Task 2.1 for the area accessed by WIPP M&O personnel.

Milestone: Re-entry Plan for Mining into the North Experimental Area of WIPP, 9/28/2013.

Activity 2 - Planning for Reentry into North Experimental Area

Task	Description	SNL	LANL	Other	Budget
2.1	Develop Test Plan for Re-entry Forensic Analysis	25	160		185
2.2	Develop Plan for Mining and Re-entry	0	35		35
2.2	Develop Plan for Mining and Re-entry (WIPP M&O Contribution)			80	80
	Totals	**25**	**195**	**80**	**300**

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 3: THERMAL, MECHANICAL, HYDROLOGIC, AND CHEMICAL LABORATORY STUDIES RELATED TO SALT

Justification

Laboratory studies allow generic salt properties (mechanical, thermal, hydrological, and chemical) to be measured in a controlled environment. The results of laboratory studies can be used to develop input parameters for models of material behavior and geochemical interactions as a function of temperature. There is a large body of laboratory data aimed at understanding the phenomenology of salt across a broad range of temperatures expected in a heat-generating waste disposal system. The laboratory studies described below in the scope of work are designed to add substantively to that body of knowledge and address any perceived gaps. These laboratory studies are also consistent with the aims of international salt repository research programs.

Statement of Work

The focus of this activity is to use laboratory studies to enhance the bases of disposal of heat-generating waste. Improved databases will be developed by experiment for thermomechanical behavior of granular salt, its thermal conductivity as a function of porosity and temperature, and to begin evaluation of the phenomenology of intact salt at high temperatures (Sections 3.1, 3.2, and 3.3). Other identified knowledge gaps or uncertainties in the available data for the mechanical, chemical, hydrologic and thermodynamic properties of salt at elevated temperatures will be explored as explained in latter subsections of Activity 3. These laboratory-based experiments will be aimed at reducing uncertainties that remain in the technical bases for a generic safety framework for disposal of heat-generating waste in salt.

3.1 Hot Granular Salt Consolidation, Constitutive Model and Micromechanics

This R&D amplifies ongoing Used Fuel Disposition (UFD) laboratory work on hot granular salt consolidation, its constitutive model, and micromechanics. The level of effort for FY12 was scaled in response to budget available. Additional funding will allow differential shear tests to enhance parameterization of the constitutive model. More microscopy R&D would provide further documentation of the mechanisms of consolidation. This work has been coordinated with international counterparts, including technical review of the test plan. A revision to the existing test plan will be made (Milestone 1) and will include a prioritized test matrix based on external review by international peers.

Milestones:

Complete Test Plan revision based on external review and prioritized test matrix, 06/01/2012.

Complete UFD Milestone M2 M2FT-12SN0806081 Coupled Thermal-Hydrological-Mechanical Processes in Salt, QRL3, 11/15/2012.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

3.2 Thermal Conductivity as a Function of Porosity and Temperature

This study investigates thermal conductivity as a function of porosity and temperature. A test plan for these investigations will be developed immediately (Milestone 1) and testing will begin in FY2012. Significant progress can be made on these laboratory studies, which provide essential input parameters for analyses of salt repository design or testing concepts for heat-generating waste. Salt testing expertise at RESPEC could add to SNL capabilities.

Thermal conductivity as a function of porosity and temperature will be accomplished by first drying WIPP mine-run salt at 100°C. A range of grain sizes will be used to fabricate specimens, currently envisioned to be shaped into billets 38-mm in diameter and thickness ranging 5 to 16 mm (after compaction). Specimens can be fabricated by die-compaction at room and/or elevated temperature to produce a range of porosity (~2% to ~40%) for thermal conductivity determinations. Testing involves measurement of thermal resistivity (1/conductivity) over a range of temperatures from 40° to 300°C using a guarded heat flow thermal conductivity device and an ASTM standard procedure. Calibration is made to quartz and Pyrex standards. Currently it is estimated that the functional relationship can be defined with approximately 30 tests ranging from nearly intact porosity of ~ 2% to unconsolidated porosity of ~40%. Triaxial samples resulting from the reconsolidation experiments described above will also be used, as available.

Milestones:

Test plan for determining thermal conductivity of granular salt as a function of porosity and temperature, 07/00/2012.

Report on Granular Salt Thermal Conductivity as a Function of Porosity and Temperature, 07/02/2013. Milestone completion of entire test matrix is contingent upon funding allocation in FY2013.

3.3 Laboratory Thermomechanical Testing

A specific request to conduct a suite of high-temperature laboratory tests on intact salt was made by DOE/NE. A suite of such testing was put forward as one of the primary efforts to be conducted before a high-temperature field test would be attempted. Salt core 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). A total of 9 tests (Table 3.3-1) 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. Extreme deformation is expected to cause the tests to be stopped, rather than specimen failure. The response is expected to resemble quasi-static compression rather than creep tests. We will need some sophisticated and durable facilities and instrumentation for this work.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Table 3.3-0-1. Uniaxial Compression Test Matrix

Test Number	Salt Type	Test Type	Temperature	Loading Condition
1,2,3	Intact	Uniaxial stress	200°C	Constant Stress/Strain Rate
4,5,6	Intact	Uniaxial stress	250°C	Constant Stress/Strain Rate
7,8,9	Intact	Uniaxial stress	300°C	Constant Stress/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. It is possible that some waste disposal concepts will involve temperatures greater than 200°C, so this high-temperature research is needed for the design and evaluation of such disposal concepts. An assessment of the need to run triaxial experiments at these temperatures will be made based on the results of these uniaxial tests. [Note: Triaxial will be orders of magnitude more difficult than uniaxial.]

Proposed effort in FY2012 involves shake-down testing that is needed to develop a suitable testing protocol and the test plan.

Milestone: Report on results of shake-down testing of one sample at each temperature, 09/28/2012.

Milestone FY2013 pending budget: Test plan completion for Thermomechanical Testing, 11/30/2012.

Final technical report July 2013 of the test matrix may depend on early success to develop test techniques, as well as the thermomechanical response of the scoping evaluations.

3.4 Brine Migration Experimental Studies

Development of a U.S. salt repository for heat-generating nuclear waste requires addressing significant possible effects caused by waste forms with high thermal output. It will be crucial to determine physical and chemical properties of: 1) brine migration and liberation in salt and 2) possible mineral phases (clay / sulfate) susceptible to dehydration and volume change (collapse) present in or near salt beds. The potential effects of thermally-driven brine migration (both inter- and intragranular) in a salt-based, heat-generating waste disposal system remain an open question. Some studies suggest that brine inclusions may migrate toward a heat source, while others have suggested that brine inclusions may move down the thermal gradient toward lower temperatures. Mineral dehydration and phase transformation experiments at elevated pressures and temperatures are equally significant in that potential water release and volume contractions may occur.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

3.4.1 Literature Survey and Analysis to Support Final Test Plan Development

The movement of brine in response to waste emplacement is an important factor in evaluating the near-field hydrochemical environment. Therefore a comprehensive review of thermally-driven brine migration will be conducted to reduce knowledge gaps and uncertainty in this area. Literature surveys will be conducted to identify relevant information on thermally-driven brine migration (both inter- and intragranular). Based on this survey, a set of laboratory experiments targeting the areas of uncertainty and/or knowledge gaps will be developed or added to the ongoing experimental setup already underway in the DOE-NE-53 UFD campaign. This work will proceed in parallel with the lab testing plan that has been justified in the UFD but received only limited funding, thus far in FY2012. If the literature search unveils additional parameter space or test conditions, the test plan will be revised accordingly. Compilation of experimental results can be compared to forensic data acquired as part of Activity 2.

Milestones:

Draft Report of Literature Search Update, 06/15/2012.

Final Report of literature survey, 08/01/2012.

3.4.2 Laboratory Upgrade and Experimental Test Plan Development

We would initiate an experimental test program to look at brine migration appropriate for generic salt repository pressure and temperature (P,T) conditions. It will be crucial to determine physical and chemical properties of: 1) brine migration in salt and 2) mineral phases (clay/sulfate) susceptible to dehydration and volume change (collapse) present in or near salt beds. The studies would focus primarily at mineral interfaces and span scales from microscopic (brine inclusions in salt grains) to sub-meter (marker beds).

The salt experiments will analyze how intragranular water migrates to grain boundaries and whether the water crosses the boundary or accumulates and flows along intergranular spaces. To perform some essential laboratory experiments, we propose to examine these rather extreme conditions 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.

Mineral dehydration studies at elevated P,T will evaluate at which values they decompose into water (liquid or vapor) and other denser minerals. This process will release water to the neighboring environments. It will also reduce the volumes of the minerals, thereby causing changes in host rock strength, porosity and permeability. These studies will be performed at both the micro and macro scales, in a manner similar to the salt experiments.
To accomplish these experiments, significant upgrades to the laboratory are required, including purchasing ancillary equipment, materials, and fabricating dedicated reaction vessels. The experimental apparatus must pass LANL electrical and pressure safety requirements and these requirements are both time and labor intensive. All experimental plans must be developed in accordance with the ES&H and QA procedures presently in existence in the DOE-NE-53 UFD campaign.

Milestone: Development of final test plan for FY2013 experiments, 08/01/2012.

3.4.3 Contract to RESPEC (50K-Sandia)

This is a contingency contract for the purpose of providing field core with predetermined damage imparted to the sample. Because the damage zone produces the brine in a bedded salt excavation, these brine liberation/migration experiments may have a need for specialty testing. Undeformed core with a QA pedigree exists in the Q Room access at WIPP and is available through Sandia. RESPEC's special testing capability and other expertise may be needed.

3.5 Develop Test Plan For Study of Material Interactions In Heated Salt

The interaction between brine, salt and emplacement materials in a heat-generating waste disposal system has important implications for repository performance. The corrosion of metals due to brine/salt interactions plays a primary role in defining the near-field chemical environment of a repository. Corrosion can control critical parameters such as redox conditions, pH, gas generation (i.e. H_2) and may even limit the importance of radiolysis. Corrosion products will also play an important role controlling the solubility of metals and actinides in fluids. Thus, an understanding of waste material behavior in such environments is critical to evaluating the safety of a salt based repository.

Literature surveys will be conducted to identify relevant information on brine/salt-materials interactions at a range of temperatures expected in a heat-generating waste disposal system. This review will focus on common materials used in waste disposal operations (e.g., waste packages, shielding, etc.). The surveys will be used to identify areas of uncertainty and/or knowledge gaps regarding this issue. Based on this analysis a set of laboratory experiments targeting the areas of uncertainty and/or knowledge gaps will be developed. The aim of the experiments will be to better understand the formation of corrosion products and the chemical environment created by corrosion.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Milestone: Test Plan for Investigation of Material Interactions in Heated Salt, 09/28/2012.

3.6 Develop Test Plan for Study of Thermodynamic Properties Of Brines, Minerals And Corrosion Products In High Temperature Systems

The thermodynamic properties of brines, salt and corrosion products in high temperature systems are fundamentally important to model development for disposal of heat-generating waste in salt because they affect solubilities of both corrosion products and source-term radionuclides. The thermodynamic properties of constituent salts, brines, and corrosion products are required for accurate modeling. Literature surveys will be conducted to identify relevant information on high-temperature thermodynamics of constituents important to disposal of heat-generating waste in salt. This includes thermodynamic properties of salt minerals including halite (NaCl), anhydrite ($CaSO_4$) and polyhalite ($K_2MgCa_2(SO_4)_4•2H_2O$). It also includes pressure, volume, temperature (PVT) properties, and heat capacity of brines, including pure NaCl solutions and its mixtures with other salts, as well as compositions in equilibrium with halite–polyhalite–anhydrite at elevated temperatures up to 200 ^oC and at saturated vapor pressures. The task includes evaluation of available Pitzer interaction parameters at elevated temperatures for major ions in brines, i.e., Na-K-Mg-Ca-Cl—SO_4—CO_3. At the same time, Pitzer interaction parameters at elevated temperatures involving chemical elements in waste packages and source-term radionuclides will be evaluated identify any data gaps. Evaluate and assemble available experimental data on corrosion products of waste packages in salt environments at elevated temperatures, if there are such data. Brine/salt-materials interactions will be examined at a range of temperatures expected in a heat-generating waste disposal system. The task will focus on common materials used in waste disposal operations (e.g., waste packages, shielding, etc.). The surveys will be used to identify areas of uncertainty and/or knowledge gaps. Based on this analysis test plan for laboratory experiments targeting the areas of uncertainty and/or knowledge gaps will be developed.

Milestone: Test Plan for Investigation of Thermodynamic Properties of Brines, Minerals And Corrosion Products In High Temperature Systems, 09/28/2012.

3.7 Radionuclide Solubility Measurements

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. A full test matrix for the radionuclide solubility experiments was provided in the SDI proposal. This proposed activity is to begin work on this overall program at temperatures up to 150C and chemical conditions typical of those expected in a salt repository.

Milestone: Radionuclide Solubility Measurements, 9/28/2012.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

3.8 Neutron Scattering Proof-of-Concept

This task will investigate the utility of conducting Small Angle Neutron Scattering (SANS) experiments at the Los Alamos Neutron Science Center (LANSCE) for the study of salt behavior. Neutron measurements on salt specimens will be conducted and assessed to determine the utility of this technique for probing the meso-scale pore structural variations due to water/moisture migration in salt. This study will be used to recommend whether similar measurements for salt and other media should be conducted in a larger, future experimental campaign.

Milestone: Report on Assessment of the Utility of Neutron Measurements for the Characterization of Water in Salt, 09/28/2012.

Activity 3 -Thermal, Mechanical, Hydrologic, And Chemical Laboratory Studies Related To Salt

Task	Description	SNL	LANL	Other	Budget
3.1	Hot Granular Salt Consolidation, Constitutive Model and Micromechanics	210	0	0	210
3.2	Thermal Conductivity as a Function of Porosity and Temperature	250	0	0	250
3.3	Laboratory Thermomechanical Testing	150	0	0	150
3.4	Brine Migration Experimental Studies	100	350	50	500
3.5	Develop Test Plan For Study of Material Interactions in Heated Salt	100	0	0	100
3.6	Develop Test Plan For Study of Thermodynamics of Brines, Minerals and Corrosion Products at High Temperatures	100	0	0	100
3.7	Radionuclide Solubility Measurements	0	100	0	100
3.8	Neutron Scattering Proof-of-Concept	0	100	0	100
	Totals	**910**	**550**	**50**	**1,510**

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 4: MODELING STUDIES RELATED TO SALT

Justification

This is an integration, evaluation, and modeling activity that serves multiple purposes, including being a tool to guide testing and modeling R&D activities via a risk-informed approach, a communication tool to inform stakeholders of Salt R&D results, and an evaluation tool to determine compliance with performance and project goals. This activity includes the following three elements:

- Safety Framework Development
- TSPA Model Development
- Coupled Thermal, Mechanical, and Hydrologic Model Development

The safety framework developed herein will be a primary communication tool for the Salt R&D Study and will contain the safety arguments that justify various testing and modeling activities. Post-closure safety assessment will be a key element of the safety framework, and the quantitative analyses that form the basis of the post-closure safety assessment are provided by the TSPA model. In particular, the TSPA model, in combination with THMC process model results, will provide the analytical basis for planning the activities in activities 1, 2, and 3, as well as THMC process model development efforts. Sensitivity and uncertainty analyses conducted with the evolving salt repository TSPA model and THMC models will determine, using a risk-informed approach, the degree of coupling needed between the TSPA model and THMC processes.

Statement of Work

4.1 Safety Framework Development

Develop a Safety Framework for disposal of heat-generating waste in salt. This is an integrated collection of evidence, analyses, and various qualitative and quantitative arguments used to demonstrate the safety of a salt repository for heat-generating waste. Its two major roles are as a management tool to guide the Salt R&D and as information tool to communicate with stakeholders. In particular, the safety framework developed in this work activity will provide the necessary umbrella structure for:

(1) Organizing and synthesizing existing and new salt repository science and salt repository design information.

(2) Identifying issues and/or R&D gaps pertaining to safe disposal of heat-generating nuclear waste.

(3) Planning and prioritizing the testing and modeling activities for investigating salt disposal, including those at the WIPP URL, using a risk-informed approach.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

(4) Transparently communicating information, safety understanding and confidence, and funding needs to Salt R&D stakeholders

The following major elements of the Safety Framework will be developed to the extent required to provide the necessary structure for organizing, synthesizing, and prioritizing existing and future Salt R&D investigations and analyses in the context of repository safety:

- *Statement of Purpose*. Describes the current stage or decision point within the program against which the current strength of the evidence in the safety framework is to be judged.
- *Safety Strategy*. The high-level approach for achieving safe disposal, which includes (a) an overall management strategy, (b) a siting and design strategy, and (c) an assessment strategy.
- *Site Characterization and Repository Design*. This includes a description of (a) the primary characteristics and features of the repository site, (b) the location and layout of the repository, (c) a description of the engineered barriers, and (d) a discussion of how the engineered and natural barriers (i.e., the multiple-barrier concept) will function synergistically.
- *Pre-Closure and Post-Closure Safety Evaluation*. This includes a quantitative safety assessment(s) of potential radiological consequences associated with a range of possible evolutions of the system over time, i.e. for a range of scenarios, both before and after repository closure.
- *Statement of Confidence and Synthesis of Evidence*. The statement of confidence is based on the synthesis of safety arguments and analyses, and it recognizes the existence of open issues and residual uncertainties. This element will be used to communicate and provide input to the other elements of the Salt R&D Investigations Study.

The first step in developing the salt repository safety framework will be to map (by reference) existing salt repository information into the safety framework elements described above. Subsequently, work will proceed to develop more detailed arguments for each of the safety framework elements noted above, by directly incorporating supporting evidence from various Salt R&D investigations.

In summary, the safety framework activity will primarily be used to integrate and prioritize other work activities, including laboratory and field testing, data mining, model development and analyses, and international interactions. It will incorporate existing information from previous salt repository performance assessments and associated analyses (see TSPA activity) to provide the basis for prioritization of these other activities.

Milestone: Report on Safety Framework for Salt R&D Investigations, 8/31/2012.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

4.2 Total System Performance Assessment (TSPA) Model Development

The activity will build a TSPA model to predict subsystem and total system performance of a deep geologic repository in salt for disposal of heat generating nuclear waste. This TSPA model will be comprised of a computational framework, four major model components: inventory and source-term, near-field, far-field, and biosphere, an uncertainty analysis module, and a post-processing module. Sensitivity and uncertainty analyses conducted with the evolving salt repository TSPA model and THMC models will determine, using a risk-informed approach, the degree of coupling needed between TSPA model components and THMC processes.

A key part of the safety framework is the post-closure *safety assessment*, which in past U.S. programs and regulations is generally referred to as the post-closure *performance assessment* (PA). The primary tool for conducting a post-closure safety assessment is the total system performance assessment (TSPA) model. The Salt Repository TSPA model, developed under this activity, will leverage existing TSPA modeling capability (e.g., from WIPP performance assessment models) and the model development work currently being conducted for UFD's Generic Disposal System Model (GDSM) and Advanced Performance Assessment Code (APAC) projects.

The existing and new knowledge base in Salt R&D associated with potentially relevant features, events, and processes (FEPs), laboratory testing, site characterization, and repository design will be used to inform the initial development of the TSPA model. In parallel, work will begin to incorporate advanced capabilities in the Salt Repository TSPA model, including the high performance computing framework capability being developed in the APAC project. An important step in the development of the Salt Repository TSPA Model will be the identification and evaluation of coupled processes important to overall system performance, and how the important coupled processes will be included in the TSPA model in a defensible way. An important aspect of this evaluation will be to conduct sensitivity and uncertainty analyses with the TSPA model, based on analyses from the underlying THMC process model(s), to determine those parameters and processes most important to the safety of a salt repository. These assessments will lead to specification of the methods and approach to be used for Salt Repository TSPA model development. It is envisioned that coupled processes near the heat-generating waste and in the disturbed rock zone will likely be included as boundary conditions to the TSPA model or incorporated as part of the source term. Information from the TSPA sensitivity and uncertainty analyses, as well as from studies with the THMC process model(s), will be integrated into the safety framework at various key decision points to inform, prioritize, and focus test design and data gathering activities.

Milestone: Report on TSPA Model Development and Sensitivity Analysis of Processes Affecting Performance of a Salt Repository for Disposal of Heat-Generating Nuclear Waste, 8/30/12.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

4.3 Generic Salt Repository Benchmarking

An international benchmarking collaboration with German partners has been arranged via a memorandum of understanding to compare current constitutive models and simulation procedures for calculations of the thermomechanical behavior and healing of rock salt.

In situ structures in the Asse mine have been selected for simulations in the new project. Parameter values for Asse-Speisesalz will be needed for this purpose. The goal of these studies is to evaluate the best models for thermomechanical-hydrologic (TMH) salt behavior that exist in the world and use this information to advance generic salt repository capabilities for US programs. Benchmark problems that are being carried-out by the German partners under the "Joint Project III on the Comparison of Constitutive Models" are: Comparison of current constitutive models and simulation procedures on the basis of model calculations of the thermomechanical behavior and healing of rock salt. These have been defined in international benchmarking collaboration with German partners that has been arranged via a memorandum of understanding to compare current constitutive models and simulation procedures for calculations of the thermomechanical behavior and healing of rock salt.

Partners will complete the isothermal "Bohrlochkonvergenz"(borehole convergence) benchmark test problem and compare with data from the corresponding test performed in 1979 at the Asse mine in Germany. This is a precursor problem that needs to be completed prior to starting the heated "Erhitzerversuche" (heater experiments) benchmark test problem and compare with data from the corresponding test performed in the 1983-84 timeframe at the Asse mine.

Milestone: Draft Report on Salt Repository Benchmarking Studies, 09/28/12.

4.4 Thermomechanical-Hydrological and Chemical (TMHC) Model Development

The main goal of this TMHC activity is to leverage existing computational models and tools to couple TM, TH, and C phenomena in salt under subsurface repository conditions, with the added focus on brine accessibility and moisture transport. Liquid brine stability will be assessed in a decoupled manner using thermodynamic modeling to predict chemical equilibria between solid salt and water vapor phases in the form of deliquescence calculations. The coupling between native salt deformation, damage accumulation that makes the brine accessible, and compaction/consolidation of granular salt and their cumulative effect on physical properties and fluid transport are key aspects of this work. The potential for adding simple model representations (e.g., in the form of simple functions) will be considered in light of recent work relevant to coupled processes in salt. This work will build upon existing work by using a mesh comprising intact and crushed salt and SIERRA code architecture (SNL).

The main modeling goals are:

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

4.4.1 Permeability and Porosity Evolution

Creep deformation of the intact salt tends to close the openings in salt. Room closure, in turn, compacts the granular salt and changes its permeability and porosity as compaction proceeds. Water vapor transport may promote moisture interactions with the granular salt, which is known to have strong influence on the reconsolidation rate and, hence, permeability and porosity. Existing permeability-porosity correlations will be evaluated through THM code simulations to identify knowledge and data gaps. Such data gaps can eventually be improved via laboratory testing. Approximations from the literature will be used for dilated rock salt. The mechanical model representations in ADAGIO (SNL) use the constitutive models for intact salt (Munson-Dawson) and granular salt compaction (Callahan). The above-mentioned phenomena represent stages of granular salt reconsolidation into the effective equivalent of intact salt. An important aspect of this work is the application of computational tools to characterize the transition from reconsolidating material to intact behavior during salt consolidation.

4.4.2 Multi-Phase Transport

The water source terms in salt repository will be a function of temperature, state of stress, and extent of the disturbed rock zone (DRZ). In addition, studies on the capillary properties of crushed salt as a function of brine saturation indicate the importance of this property on water transport as a function of compaction. This state of compacting granular salt can be envisioned to exist for some time period in the repository evolution. Therefore, multiphase transport in variably-saturated granular salt will be accounted for in the TMH model using existing capillary pressure data for crushed salt at various level of brine saturation.

To further advance our understanding of the nature of the water issue, and to provide a benchmark for the fully couple TMH model, a multi-scale model will be developed to track the fate and transport of native water present in salt. The model will be designed to provide source terms from small-scale processes leading to the liberation of water from salt, such as brine inclusion migration, grain-boundary water vaporization, mineral dehydration reactions, and will be capable of tracking the water movement in the liquid and vapor phases within intact and crushed salt for a given disposal configuration. Existing codes (the LANL FEHM computer code and the Lawrence Berkeley National Laboratory (LBNL) TOUGH-FLAC code) that handles, in a fully coupled fashion, the thermal-hydrologic-chemical behavior, will be modified to incorporate the water source terms listed above. Using a simplified description of the evolution of the system provided by the TM model, this transport model will then track the fate and transport of water in the system. Once the model is developed, it will be tested against relevant information related to water fate and transport in previous salt heater tests. It is anticipated that these comparisons will be qualitative, due to the nature of the data collected. Results of this analysis will also be compared to TMH calculations for a representative problem as part of the benchmarking effort for the TMH code and to evaluate the significance of TH and M coupling on water fate and transport.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

4.4.3 Brine Chemistry at Elevated Temperatures

The results of the data mining exercise should include geochemical evaluation of experimental data sets generated at elevated temperatures from various WIPP test programs. For example, acid brine generation from past heater test experiments. This effort will examine the thermodynamics of salt phase equilibria with updated data sets applicable to high temperatures. It will also explore modeling of gas phase equilibria in salt-bearing systems to better understand the generation of acid brines. Such effort could expand and refine existing thermodynamic databases for salt system at elevated temperatures and identify potential knowledge gaps in the evaluation of brine interactions at these conditions.

A review and analysis of the TM information in collaboration with German researchers has been initiated. A clear path for benchmarking has been developed and has received limited support in the DOE-NE-53 UFD Campaign. Benchmarking TM response will inform laboratory test planning, TM modeling, and any "field demonstration." A prioritized scope with deliverables is developed in a later section on modeling. The level of effort required to review and evaluate existing thermomechanical information is felt to be relatively smaller than the review and evaluation of brine and chemistry information. Abundant brine and chemistry testing and reporting work was done at WIPP and earlier at the Mississippi Potash (located in southeast New Mexico). Relatively little work has been done evaluating this information in the context of generic salt disposal applications. Brine availability in the disposal system may occur as a consequence of the TMH response of the salt due to excavation and emplacement of heat-generating waste. The question of how much brine would potentially be available can be quantified via TMH modeling. The potential effects of brine chemistry and its importance can be ascertained by review of the extensive testing done by M. Molecke (1983) and others and by modeling brine chemistry at elevated temperatures.

During verification and validation exercises, the thermomechanical processes including creation, evolution and mitigation of the disturbed rock zone will be modeled. In addition, 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 scale will be evaluated. These calculations lead to an assessment of the liberation processes and fate of the native brine.

Milestones:

Report on Model Development and Analysis of the Fate and Transport of Water in a Salt-Based Repository, 09/282012.

Evaluation of EBS THM Coupled Processes in Salt, 11/15/20122012.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Activity 4 - Modeling Studies Related To Salt

Task	Description	SNL	LANL	LBNL	Budget
4.1	Safety Framework Development	275			275
4.2	Total System Performance Assessment (TSPA) Model Development	275	25		300
4.3	Generic Salt Repository Benchmarking	155			155
4.4	Thermomechanical-Hydrological and Chemical (TMHC) Model Development	345	425	180	950
	Totals	**1,050**	**450**	**180**	**1,680**

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 5: INTERNATIONAL COLLABORATION

Justification

International collaborations with the German researchers will leverage their considerable expertise while enhancing our generic salt program credibility. Collaborations will have the goal of advancing the science and technology on key issues such as seal strategy, constitutive modeling, and granular salt consolidation. This scope includes workshops, publication, technical and logistical support, collaboration of state-of-the-art review papers and organizational activities. The Nuclear Energy Agency's Integration Group for the Safety Case (NEA IGSC) recently sanctioned a Salt Club for advancing salt repository options for member states and the USA. Initial meetings will set up the rules of engagement, deliverable goals, and a business model.

Scope includes active follow-up to the International Salt Mechanics VII conference, with the intent to hold the next such conference in the USA and participation in the European Commission's "Implementing Geological Disposal Technology Platform" (IGD-TP), which includes all repository media and a wide range of potential R&D. International collaboration builds upon collaboration to co-author state-of-the-art position papers.

Statement of Work

- Collaborate on a state-of-the-art paper on reconsolidation of granular salt. September 2012.
- Support review and concurrence on a catalogue of potentially relevant features, events, and processes (FEPs) for high-level waste disposal in salt, consistent with the conclusions of the 2nd US/German workshop participants. December 2102.
- Support a workshop on natural analogues in the safety case for salt. September 2012.
- Participate in the IGD-TP strategic initiative on seal systems for generic repositories.

This work can begin immediately, can be scaled to an appropriate budget, and would likely continue for the foreseeable period. Some budget expected to carry over to 2013.

Milestone: U.S./German Workshop Presentations, 10/10/2012.

Activity 5 – International Collaboration - $130K (20K LANL, 110K SNL)

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

ACTIVITY 6: SALT INSTRUMENTATION DEVELOPMENT AND TEST METHODOLOGIES

Justification

The instrumentation and data collection of any future thermal test in salt is expected to be a complex process. Gages need to be selected, designed, and tested that can accurately measure the anticipated range of responses in a salt test and withstand the anticipated harsh test environment for several years. An important test parameter associated with future planned thermal tests in salt is brine and vapor movement in the salt formation during the duration of the demonstration test. These measurements are generally not as straightforward as monitoring for temperature or ground movement. Additionally, the expected ground movements and brine conditions will make it imperative that measurement techniques account for these potentially adverse conditions. As such, new or more advanced techniques need to be developed and employed to measure, at a minimum, vapor and brine movement.

Additionally, geophysical techniques need to be developed and demonstrated prior to any planned deployment in a future salt study. Whereas geophysical measurement methods are established techniques, some may not be appropriate for this salt testing program due to such issues as minimum spatial resolution and limited sensitivity to contrasts between solid, fluid and vapor phases in the salt. For these reasons, there is uncertainty associated with applying these techniques to fluid and vapor migration in salt. Therefore, development and demonstration is required to address the resolution and sensitivity issues.

Statement of Work

This activity provides the resources necessary to develop the generic salt measurement and data collection techniques and to make usefully benefit of the unique skill sets and resources currently available from past WIPP studies, the Yucca Mountain Project, and from salt testing performed internationally. The instrumentation of any future thermal test in salt is expected to be a complex process and beginning the development of both classical measurement techniques and geophysics will greatly aid in the planning and eventual deployment of a salt field test and will help inform the planning efforts as to the feasibility of certain techniques. Underground deployment of instrumentation may be conducted in the construction and forensics of the WIPP compaction tests (e.g. instrumentation emplacement and survivability studies), bringing significant value in the planning and designing of any future thermal testing salt, including the data gathering techniques. This activity consists of three major tasks broken down by the type of system being developed:

Task 6.1: Salt Instrumentation Design
Task 6.2: Data Collection Design
Task 6.3: Hydrologic Geophysics Assessment

Milestone: Summary Report on Salt Instrumentation Development, 09/16/2013.

Appendix C (continued). Salt R&D Workshop Study Plan - March 23, 2012

Activity 6 - Salt Instrumentation Development And Test Methodologies

Task	Description	SNL	LANL	Other	Budget
6.1	Salt Instrumentation Design	25	25		50
	Salt Instrumentation Design (WIPP M&O Consultation)			10	10
6.2	Data Collection Design	25	90		115
6.3	Hydrologic Geophysics Assessment		25		25
	Totals	**50**	**140**	**10**	**200**

Appendix D: ATTENDANCE LIST

Below is the attendance list and breakout group assignments (see Appendix E) for the SNL-LANL jointly sponsored “Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt,” held March 6-7, 2013 in Albuquerque, NM, at the IPOC facility at Sandia National Laboratories.

Table D-1. Attendance List and Breakout Group Assignment

Name	Org	Email Address	Phone	Breakout Group Assignment
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Appendix E: WORKSHOP AGENDA

AGENDA

Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt
Albuquerque, NM
March 6 - 7, 2013

Organized by
Robert J. MacKinnon (SNL) and Bruce A. Robinson (LANL)

Location: Innovation Parkway Office Center (IPOC), Conference Room 2205, Sandia National Laboratories, Albuquerque, NM

Workshop Objective:

In March of 2012, DOE-NE and DOE-EM reached agreement on a set of technical objectives and a science-based scope of work relevant to the study of salt geologic media for disposal of DOE-managed high-level waste and civilian used nuclear fuel. Given the technical progress of this ongoing work, a workshop will be held to provide input to decision makers on RD&D activities that will have the greatest potential to contribute to the advancement of deep geologic disposal of nuclear waste in salt. This workshop will have two primary goals: (1) identify a comprehensive set of RD&D needs and approaches to addressing them, and (2) elicit input to a decision-making framework that will be used subsequent to the workshop to formulate a RD&D plan that will advance the science and engineering of deep geologic disposal of nuclear waste in salt. The range of RD&D activities to be considered include those in the areas of modeling and analysis, lab and field studies and demonstrations, instrumentation and characterization technologies, and confidence building.

Wednesday Morning Plenary, March 6

0830 – 0845	Welcome – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
0845 – 0900	DOE Perspectives – Prasad Nair (DOE-NE), Mark Senderling (DOE-EM) and Roger Nelson (DOE-EM)
0900 – 1000	Workshop Objective, Goals, Structure, and Approach – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1000 – 1015	Break
1015 – 1100	Continue - Workshop Objective, Goals, Background, and Structure – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1100 - 1200	Summary and Status of US Salt Repository Technical Basis - Christi Leigh (SNL), Don Reed (LANL), Jens Birkholzer (LBNL)

Wednesday Afternoon Breakouts, March 6

1200 – 1315 Lunch
1315 – 1345 Structure and Goals of Breakout Sessions – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1345 – 1415 Instructions to Breakout Groups – Dave Sevougian (SNL)
1415 – 1700 Breakout Group 1: Post-Closure Repository System (EBS post-closure processes within the excavation and NBS post-closure processes in the host salt formation) Chairs – David Sevougian (SNL), Don Reed (LANL); Rapporteur – Dan Levitt (LANL)
Breakout Group 2: Pre-Closure Repository System (design, demonstration, and pre-closure issues) Chairs – Frank Hansen (SNL), Ned Elkins (LANL); Rapporteur – Ernie Hardin (SNL)
MacKinnon (SNL) and Robinson (LANL) will act as roving participants to ensure Pre-Closure/Post-Closure Integration.

Breakout Groups will:

- Review RD&D strawman issue list
- Propose additional issues/remove issues as necessary
- Define specific tests/modeling needed to advance the state of the art to address Post-Closure System issues and Pre-Closure System issues
- Input to decision making framework

1700 – 1800 Reconvene and summarize breakout sessions – Breakout Chairmen
1800 – 1810 Look ahead to Thursday's activities – MacKinnon and Robinson

Thursday Morning Session on Field Testing at WIPP, March 7

0815 – 0900 Reconvene and Synthesis of Breakout Session results – Session Chairs and Rapporteurs
0900 – 0910 Introduction to Field-Testing Session –Bruce Robinson (LANL) and Bob MacKinnon (SNL)
0910 – 1145 Field-Testing Session
0910 – 0930 Heated Salt Testing History – Kris Kuhlman (SNL)
0930 – 1015 Underground Research at WIPP – Frank Hansen (SNL)
1015 – 1030 Break
1030 – 1115 Thermal Field Testing at WIPP – Doug Weaver (LANL)
1115 – 1145 Re-Entry into the North Experimental Area of WIPP – Doug Weaver (LANL) and Michael Schuhen (SNL)
1145 – 1300 Lunch

Thursday Afternoon Wrap Up, March 7

1300 – 1500 Resume Field-Testing Session

	Define specific tests/modeling/path forward Input to Decision Making Framework
1500 – 1515	Break
1515 – 1615	Plenary on workshop summary and future actions – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1615 – 1630	Concluding Remarks – Prasad Nair (DOE), Nancy Bushman (DOE), Roger Nelson (DOE)

Appendix F: SALT RD&D TEST PROPOSAL QUESTIONNAIRE

1.	**Name of Test:**
2.	**Principal Investigator(s):**
3.	**Test Objectives, Description, and Type (lab, field, etc.):**
4.	**R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):**
5.	**Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:** • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**
6.	**For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?**
7.	**Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):** • **Describe how the data will be collected**

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:
9. Define the pre-and post-test modeling/simulation needs for the activity, including: • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**
10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):
11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure: • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**
12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Appendix G: BREAKOUT GROUP REVISIONS TO ISSUE IMPORTANCE RATINGS

Tables G-1, G-2, and G-3 present the breakout group revisions to some of the issue importance ratings shown in Table 5-4. Table G-1 contains the Group 1 (postclosure) group revisions for the nominal evolution scenario, while Table G-2 contains the Group 1 (postclosure) group revisions for the human intrusion scenario, along with some assumptions regarding that scenario. Table G-3 contains the Group 2 (preclosure) group revisions for the nominal evolution scenario.

Table G-1. Breakout Group 1 (postclosure) Revisions to Pre-workshop Issue Importance Ratings for the Nominal Scenario (in **bold font**). [High "H" importance issues shaded in "light orange." See Tables 5-1 to 5-4 for an explanation of the pre-workshop rating methodology.]

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
Wastes and Engineered Features (EBS) Feature/Process Issues				
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)		
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)		- We must consider the clay content of the crushed salt backfill because clay can affect the mechanical properties of the salt backfill.
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability		
4. Changes in chemical characteristics of brine in the	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent		

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
backfill and EBS		gas generation (M) Indirectly related to limited and delayed releases (L)		
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)		
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability		
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation	**M (= I,P)**	- For the nominal scenario with a very low permeability intact host rock, brine migration will have little effect on containment. Gas/vapor migration would only affect a few meters of host rock around the emplacement drifts.
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository		
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases		
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases		
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	Indirectly related to limited and delayed releases		
12. Radionuclide solubility in the	L (= D,S)	Directly related to limited and delayed		

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
waste package and EBS		releases		
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases		
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues				
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design		
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone		
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion).	**M (= I,P)**	- For the nominal scenario with a very low permeability intact host rock, brine migration will have little effect on containment. Gas/vapor migration would only affect a few meters of host rock around the emplacement drifts.
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases		

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)		
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		
Repository System (EBS and Geosphere combined) Feature/Process Issues				
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constitutive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).		
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation		
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing		
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases		- Need to confirm/demonstrate that microbes are L for HLW and SNF (even though are considered H for TRU waste). Perhaps there is a need to do testing even if this one is an “L” (to confirm)
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases		
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository		- There has been testing done on this for WIPP and other repository programs

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions		
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing) Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides		
Modeling Issues				
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions		- This issue is an M only because of the word "efficient". Without this word, the rating should be H (Monte Carlo is not efficient). - Uncertainty analyses are extremely important for prioritizing R&D.
36. Efficient uncertainty	M (= I,P)	Indirect impact on demonstrating the		

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
quantification and sensitivity analysis methods		importance of primary safety functions		
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)		
***In-Situ* Testing/Design/Operations Issues**				
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of *in situ* stresses and rock movement (H) and brine and vapor/gas movement (M)		
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function		
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)	May not be possible in the time frame of an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function		
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		

Table G-1 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revisions to Issue Importance Ratings (Nominal Scenario)	Notes and Explanation of Breakout Group 1 Agreement and/or Revisions for the Importance Ratings
Confidence-Building Issues				
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety		
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes		
45. International peer review and collaboration	M	Adds credibility with the scientific community		
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42		
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs		
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency		

Table G-2. Breakout Group 1 (postclosure) Revisions to Pre-workshop Issue Importance Ratings for the Human Intrusion Scenario (in **bold**). [High "H" importance issues shaded in "light orange." See Tables 5-1 to 5-4 for an explanation of the pre-workshop rating methodology.]

[Note 1: The human intrusion scenario was defined to be the dose impact due to cuttings and other waste materials that reach the surface via the drilling borehole, but not dose due to releases to a "generic" aquifer because the "other geologic units" category in the UFD FEPs list (Sevougian et al. 2012, App. A) is considered to be outside of the scope of this workshop. Also, a pressurized brine pocket beneath the repository was specifically not included in this human intrusion scenario.]

[Note 2: The "limited or delayed releases" safety function was changed to a "primary" function for the human intrusion scenario, with ratings of "H," "M," and "L" for direct, indirect, and weak impacts, respectively, because the containment function is compromised for the human intrusion scenario.]

Salt RD&D Technical Issue	**Pre-workshop Issue Importance Rating (Nominal Scenario)[1]**	**Explanation of Pre-workshop Issue Importance Rating**	**Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario**	**Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings**
Wastes and Engineered Features (EBS) Feature/Process Issues				
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)		
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)		
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability		
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent gas generation (M)		

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
		Indirectly related to limited and delayed releases (L)		
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)		
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability		
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation	**M (= I,P)**	
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository		
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases	**H (= D,P)**	- Limited and delayed releases is the primary safety function in a human intrusion scenario
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases	**M (= I,P)**	- Only indirectly related to release of cuttings to the surface (perhaps directly related but this issue was determined by expert consensus to be less important than Issues 9, 11, and 12)
11. Changes in chemical characteristics of brine in the	L (= I,S)	Indirectly related to limited and delayed releases	**H (= D,P)**	- Limited and delayed releases is the primary safety function in a human intrusion scenario

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
waste package				
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	**H (= D,P)**	- Limited and delayed releases is the primary safety function in a human intrusion scenario
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	**M (= I,P)**	- Only indirectly related to release of cuttings to the surface (perhaps directly related but this issue was determined by expert consensus to be less important than Issues 9, 11, and 12)
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues				
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design		
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone		
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends.	**M (= I,P)**	

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
		Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion).		
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases		
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)		
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		
Repository System (EBS and Geosphere combined) Feature/Process Issues				
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constitutive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).		
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation		
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing		
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases		- Need to confirm/demonstrate that microbes are L for HLW and SNF (even though are considered H for TRU waste). Perhaps there is a need to do testing even if this one is an "L" (to

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
				confirm)
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases	**H (= D,P)**	- Could be combined with Issue 12 for the H.I. scenario. Wide disagreement on the importance of this issue for the H.I. scenario. Took a vote with a tally of 11 H, 5 M, and 2 L.
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository		
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions		
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing) Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides		
Modeling Issues				
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
34. Appropriate inclusion and scaling/representation of spatially and temporally	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
varying processes and features in process and TSPA models				
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions		- This issue is an M only because of the word “efficient”. Without this word, the rating should be H (Monte Carlo is not efficient). - Uncertainty analyses are extremely important for prioritizing R&D.
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions		
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)		
***In-Situ* Testing/Design/Operations Issues**				
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of *in situ* stresses and rock movement (H) and brine and vapor/gas movement (M)		
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function		
41. Demonstrate under	H (= D,P)	May not be possible in the time frame of		

Table G-2 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 1 Revision to Importance Ratings for Human Intrusion Scenario	Notes and Explanation of Breakout Group 1 Human Intrusion Importance Ratings
representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.		an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function		
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		
Confidence-Building Issues				
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety		
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes		
45. International peer review and collaboration	M	Adds credibility with the scientific community		
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42		
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs		
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency		

Table G-3. Breakout Group 2 (preclosure) Revisions to Pre-workshop Issue Importance Ratings for the Nominal Scenario (in **bold font**). [High "H" importance issues shaded in "light orange." See Tables 5-1 to 5-4 for an explanation of the pre-workshop rating methodology.]

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
Wastes and Engineered Features (EBS) Feature/Process Issues				
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)		- How about packaging of HLW? Well defined. But CSNF is not well defined. For CSNF case we need to know how much fuel is in each package.
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)	**H (= D,P)**	- Directly related to final state—not indirect. - Need to understand Issues 2 and 3 together. How can changes be high but initial conditions medium?
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability		- Assumed to encompass mechanical+hydrologic+chemical effects - Dependence on temperature is understood for some aspects, not others. Also rate dependence of changes is not completely understood. - Should include water effects, hydrologic properties, etc. - Overlaps with issue 15. - Property effects are most uncertain, and potentially most important, in the low porosity range, e.g., permeability as a function of porosity. (See results from recent US-German salt workshop: the questionnaire on crushed salt reconsolidation showed a diversity of opinions regarding its importance and level of knowledge) - Important in both preclosure and postclosure. Note that processes in evolution of the

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
				repository can be engineered to proceed faster or slower, and the repository development schedule can be adjusted accordingly, as appropriate. - Heat-generating waste disposal concepts should be different than non-thermal because of closure rates. See mechanical issues. Need to review the term "crushed" (use "granular" instead? "Run-of-mine"?)
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent gas generation (M) Indirectly related to limited and delayed releases (L)		- Agree that this is not high importance but we care about brine because it sets initial conditions for postclosure. Could preclosure heating change brine characteristics? - Early WIPP testing showed that brine could corrode some materials (e.g., SS) quickly—so this must be of at least M importance - Corrosion environment for EBS components in preclosure—this is indirect - Acid-gas effects are possible (recall YM contentions) which could occur early in repository evolution.
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)		- Linked strongly with issue 3. - "Event" important here is *in situ* reconsolidation - Full scale, *in situ* test would require too long of a time period - Shorter term lab testing will confirm models, which may be used to predict longer term behavior.
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability	**M (= I,P)**	- Preclosure design importance. - Retrievability is not an issue per se—reduce importance. - Rated L (= D,S) for retrievability because retrievability was changed to a secondary

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
				function. "Preclosure design" was added as primary function and this issue was rated as M (= I,P) for "preclosure design" - Modeling would be sufficient to understand WP degradation that could impact retrievability - Depends on regulations to some extent—new rules could bring back retrievability as important
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation		- Agree with high importance—directly produces changes in backfill properties - Reflux activity could seal up near-field backfill - Vapor transport = heat transport (enthalpy) - Refer to CCl4 dispersion in WIPP panels—this is an open system—at least until the DRZ heals
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository		
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases		
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases		
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	Indirectly related to limited and delayed releases		
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases		

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases		
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues				
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design	**M (=I,P)**	- Lowered importance because issues 15 and 16 cover the generic aspects
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		- Agree with importance - Clay seam behavior is important for mechanical and hydrologic behavior - Surprising that WIPP does not have better data on clay seam mechanical properties—this is why we do so much bolting in the roof. Didn't even have this type of data when we moved up to Clay Seam G. - Specific to bedded, not domal salt, and very relevant to siting a repository - Any brine migration process effect related to clay seams would be less important - Applies also under issues 14, 16 and 17.
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)		- EDZ effects are broken out in issue 17 - Thermal-mechanical aspects are (should be) covered in other issues - Overlaps strongly with issue 17.
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone		- Overlaps strongly with issue 16. - Addresses fracturing and sealing
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period		- See WIPP panel discussion for issue 18. - Separating the host rock and EDZ processes is difficult

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
		ends. Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion).		
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases		- Agree with importance
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)		- Agree with importance
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		- Agree with importance
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases		- Agree with importance
Repository System (EBS and Geosphere combined) Feature/Process Issues				
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constitutive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).		- EBS = WF, WP, backfill - Description is reversed (constitutive affects heat transfer) - No further testing proposed
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation		- Agree with low importance
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing	**H (= D,P)**	- Amenable to testing *in situ* - Current topic of international R&D - Gas generation could start during preclosure
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases		

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases		
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository		- Seals will not see temperature effects - Seal basis for WIPP can be applied - Seal longevity not in doubt even for >>10,000 years - No further R&D is needed.
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions		- No objection (or discussion)
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing) Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides		- No objection (or discussion)
Modeling Issues				
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		- Agree with importance—appropriate constitutive models are needed for design - US-German collaboration will provide useful information for mechanical models - Chemistry modeling is limited by Pitzer approach—may be limiting - Constitutive model testing is a fundamental part of *in situ* testing (e.g., a URL, SDDI, etc.)
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		- Agree with importance
33. Appropriate representation of coupled processes in TSPA	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of		- Agree with importance

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
model		performance of primary safety functions		
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		- Agree with importance - Beyond scope of R&D; need process models informed and incorporated or abstracted for PA.
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions		- Agree with importance - 3-D TM modeling will be needed to design a repository for heat-generating waste, especially a large one
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions		- Agree with importance
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		- Agree with importance - US-German collaboration
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)		- Agree with importance
***In-Situ* Testing/Design/Operations Issues**				
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of *in situ* stresses and rock movement (H) and brine and vapor/gas movement (M)		- Agree with importance - Instrumentation still a challenge for field testing, repository monitoring, etc.
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function		- Agree with importance

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
safety requirements.				
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)	May not be possible in the time frame of an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function		- Agree with importance - The post-test examination could be important - This is a full-scale implementation of the disposal concept - Should not be considered only in the context of the current SDI or SDDI proposals—to be taken up later; not a topic for R&D at this time.
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions		- Agree with importance - Would need an evolutionary program supported by lab data - What measurements to make? - We should take care not to oversell our capabilities in THMC predictions, or the importance of fully coupled models to repository safety - This is a specialized, sophisticated test specifically designed for model validation - Should not be considered only in the context of SDI or SDDI—to be taken up later; not a topic for R&D at this time.
Confidence-Building Issues				
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety		
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes	**M**	- International participants have supported analogs (not U.S.). For example, reconsolidation of crushed salt has analogs in mines (anthropogenic) - Reduced to "M" but could be upgraded to "H" if done correctly with more resources

Table G-3 (continued).

Salt RD&D Technical Issue	Pre-workshop Issue Importance Rating (Nominal Scenario)[1]	Explanation of Pre-workshop Issue Importance Rating	Breakout Group 2 Revisions to Issue Importance Ratings	Notes and Explanation of Breakout Group 2 Agreement and/or Revisions for the Importance Ratings
45. International peer review and collaboration	M	Adds credibility with the scientific community	Peer Review: **M** Collaboration: **H**	Split into two separate issues: peer review and international collaboration - Peer review does not have to be international and should be split off from intl. collaboration - Peer review is very good but collaboration is even more important because it saves our program lots of effort and gives credibility
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42		- Agree with importance
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs		- Agree with importance
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency		- Agree with importance

Appendix H: SALT RD&D TEST PROPOSALS

This appendix documents twenty-four testing/modeling proposals that represent RD&D activities thought to be beneficial by the test proposers (listed in each table) for resolving the salt RD&D issues in Table 7-1. The information in these proposals is based on the format of the Test Questionnaire presented in Appendix F (for all but two of the proposals). These detailed proposals have been considered carefully in Section 8 of this report with respect to the recommended future RD&D activities (FY14 and beyond). Whether and how much funding to allocate to each proposals is dependent on several considerations, including the importance ratings of the RD&D issues addressed by each proposal (see Items 4 and 5 in each questionnaire) and the current (or "state-of-the-art") knowledge level with respect to the given RD&D issue(s)—see Item 6 in each questionnaire. Section 7.3 (Table 7-3) provides a brief summary of the suite of proposed tests contained in this appendix, and Section 8 (Table 8-1) provides a recommended disposition for each proposal.

Table H-1. Clay Seam Shear Testing

1. Name of Test: Clay Seam Shear Testing

2. Principal Investigator(s) Frank Hansen (SNL)

3. Test Objectives, Description, and Type (lab, field, etc.):

- *In situ* tests in the new URL
- Laboratory tests
- International collaborations

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

Natural barriers (host rock and EDZ)—This testing has a first-order influence on H-rated issues regarding mechanical response of the host rock (Issues 15, 16 and 17 from Table 4-1).
It also bears on Issues 39 and 40 with respect to instrumentation development, and methods for *in situ* testing and characterization and *in situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.

15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)
17. The formation and evolution of the EDZ
39. Development of accurate instrumentation and methods for *in situ* testing and characterization
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

Confidence building and preclosure. See below.

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Our German colleagues would like to obtain shear strength and clay seam properties for benchmark modeling of WIPP Rooms B & D. There are several options to be considered. I put forward a few ideas here, but we should address the topic of shear strength testing in the near term. After you ponder the contents of this missive and give me advice, I will respond to the request from Germany.
The request from Germany:
Andreas Hample is the technical leader of the US/German Joint Project on modeling salt. Michael Bühler is the program leader for BMWi. Lupe Arguello is Sandia's Principal Investigator on the Joint Project. The Joint Project team is currently benchmarking the various codes and models against *in situ* salt tests conducted in Germany. At their recent Joint Project workshop on Feb. 19-20 in Hannover, Michael Bühler announced that the funding for the extension of the project has been approved by BMWi. This is very good news for salt repository science in the USA because it means the Joint Project teams will model WIPP Rooms B & D and by doing so will provide the best tools available for generic salt modeling. A new agreement (extension to the current Joint Project) is expected to be drawn up and officially start on October 1, 2013. Sandia will need to make arrangements for their participation in this benchmarking work.
The Joint Project team members have begun discussion of the details of the modeling of Rooms B & D at WIPP, which are specifically selected as simulation objects in the project extension. Lupe Arguello pointed out that the correct horizontal room convergence can only be calculated with appropriate assumptions about the shear behavior at the clay seams (sliding material interfaces). Therefore, the Joint Project team concluded that it might be very helpful and desirable to include appropriate shear tests in the large lab test series being conducted on WIPP salt by our German colleagues. They have indicated that this testing could be accomplished if we could

provide additional 12" diameter core samples with clay seams for shear tests at the IfG.

The modeling effort and laboratory testing represent important collaboration efforts and provide tremendous benefit to the US program. At the end of the joint project, the best salt models in the world will be poised for generic salt analyses. These tools will be vital for salt repository design and analyses. Any potential *in situ* testing/demonstrations would benefit because these calculation tools would provide the means to assess experiment response, which is necessary for establishing instrumentation needs, layout and data quality objectives. Structural response and operational trade-off studies would also use the best-available codes and models that the Joint Project will identify.

Sandia's previous treatment of clay seams:

With regard to the basis for the coefficient of friction used computationally for the clay seams—it is the value that was used by Munson in the historical calculations of the WIPP rooms (Int. J. Rock Mech. Min. Sci. Vol. 34, No. 2, pp. 237-247, 1997). However, the value itself comes from Munson's own admission (Munson et al., SAND88-2948, February 1989, pp. 39-40) that: Because the actual coefficient of friction cannot be determined at this time, the chosen value becomes a free parameter in the model. However, the value must be within reasonable limits. We feel that the value chosen is compatible with the observed underground shears. In short, it was a fitting parameter that was probably adjusted to match measured horizontal closure in Room D.

Others (such as RockSol) have calculated closures at WIPP and used something to represent the clay seam. Lupe and I suspect that other calculations used the same value for coefficient of friction in the clay seams, which has never been experimentally measured. The WIPP analysis and well as future testing in the URL is faced with a clear gap in information regarding the shear strength of the clay seams.

What should we do?

We could:

1. Provide samples for the German colleagues and allow them to run the shear tests.
2. Do nothing and accept that the historical assumptions are OK.
3. Obtain and test the clay seams in laboratories in the USA.
4. Conduct *in situ* experiments in the new URL.
5. Other suggestions?

Acquisition of cores orthogonally across a clay seam is challenging. Integrity of the samples acquired for this testing purpose is a little sketchy. Shipping across the ocean and assuring the integrity and representativeness of the clay interface seems difficult and problematic. Based on this alone, we should consider testing in the USA if needed. Sandia should propose laboratory and *in situ* testing utilizing the URL for sample acquisition and testing. *In situ* testing would need to be designed, but laboratory procedures (below) are readily available.

Laboratory Shear Testing (from Scott Broome):

Testing a natural clay seam within salt extracted from the WIPP underground in a laboratory environment may be approached in various ways. Three off-the-shelf technologies are:

1. Test using a direct shear apparatus. Sandia National Laboratories has access to small and large scale direct shear machines. The small scale machine can accept samples up to 4 in. by 4 in. and has a capacity of 2200 lbs. normal load. To achieve a lithostatic stress similar to the WIPP underground (~2000 psi), a sample surface area of 1.1 sq.in. or less must be used. The large scale machine can accept samples up to 11.3 in. by 11.3 in. and has a capacity of 18,200 lbs. normal load. A sample with 9.1 sq. in. or less must be used to achieve 2000 psi normal stress.
2. Test using an axial/torsion load frame. Sandia National Laboratories Geomechanics laboratory has an axial/torsion load frame capable of 220,000 lbs. normal load and 88,000 lb-in. or torque. These capabilities exceed lithostatic stress levels provided a samples with a surface area of 110 sq.in. or less is used.
3. Test using a triaxial shear configuration. Sandia National Laboratories Geomechanics laboratory has the capability to test a clay seam subjected to confining pressure and shear stress. The natural shear surface would be prepared such that it is along the length of a right circular cylinder at ~55 degrees to the horizontal. Various confining pressures would then be applied and axial load increased until shear displacement of the clay seam is observed.

All methods presented above provide determination of peak and residual shear strength. Sandia could readily prepare UFD Test Plans consistent with ASTM and other industry standards.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

See discussion above.
Also, the data will include a variety of direct shear or torsional evaluations of shear properties of clay seams.
In situ tests could capitalize on access to the URL space. The test concept could involve flat jack pressurization of an isolated area of the clay seam and imparting direct shear to a representative block of native material. These large-scale data would supplement the normal and shear information derived in more standard (ASTM and similar) tests in the laboratory.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

Laboratory tests are standard or near standard (direct shear, torsion, triaxial compression) with the attendant instrumentation. Field testing would involve pressure systems using flat jacks and in-plane and out-of-plane displacement measurements.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

The modeling effort and laboratory testing represent important collaboration efforts between US and German salt scientists. The types of modeling include finite element constitutive models for salt + clay seams. Very important for generic model development, constructability assessment and these parameters and tools will be vital for salt repository design and analyses.
These tests will provide validation opportunities and possibility to evaluate the state of the art.
Structural response and operational trade-off studies would also use the best-available codes and models that the Joint Project will identify.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Performance of backfill;
Seal system;
EDZ;
Features of the host rock (pristine host rock)

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Pre-emplacement and operations.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Provided above.

Table H-2. Single Heater Test

1.	**Name of Test:** Single Heater Test
2.	**Principal Investigator (s):** Frank Hansen (SNL), Carlos Jove-Colon (SNL)
3.	**Test Objectives, Description, and Type (lab, field, etc.):** • Generic *in situ* tests in the new URL • International collaborations • Modeling prediction and validation • Investigate potential for brine formation and migration at high temperatures and loading pressures. This needs to be investigated through *in situ* and laboratory experiments. • Local interactions at the metal/salt interface to investigate in-situ and laboratory-scale degradation and/or corrosion phenomena of metallic barrier and redox conditions. • Salt mineral equilibria at high temperatures for multiphase/multicomponent systems. This important to evaluate the controls on brine chemistry, particularly under high temperature evaporative conditions.
4.	**R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):** Natural barriers (host rock and EDZ)—This testing has a first-order influence on H-rated issue regarding mechanical response of the host rock (Issues 15, 16 and 17 from Table 4-1). It also bears on Issues 39 and 40 with respect to instrumentation development, and methods for *in situ* testing and characterization and *in situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements. These experiments are key to probing high temperature chemical conditions at barrier interfaces where there is a considerable knowledge gap in this saline system. 15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects 16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation) 17. The formation and evolution of the EDZ 39. Development of accurate instrumentation and methods for *in situ* testing and characterization 40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.
5.	**Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:** • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** Confidence building and preclosure. See below.
6.	**For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why are these data necessary?** Generic physics is a key consideration for testing in the URL at WIPP. Field work that is widely applicable would be of greater utility to all parties, because the nation has not made site selection decisions for heat-generating waste disposal since the Yucca Mountain site was retracted. Smaller, generic studies may well be favored to exact more broadly applicable results and require less time and money than proposed full-scale demonstrations. A standardized borehole heater test as shown below would be relatively low cost, performed at a small spatial scale in order to observe brine evolution trends in the shortest time possible. Modularity and limited size are emphasized so that tests can be run cost-effectively for many years if appropriate. These single-heater tests could be replicated in different (generic) salt formations using either vertical or horizontal orientation, applying different thermal and mechanical loading, and creating desired ranges of mass transport boundary conditions.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

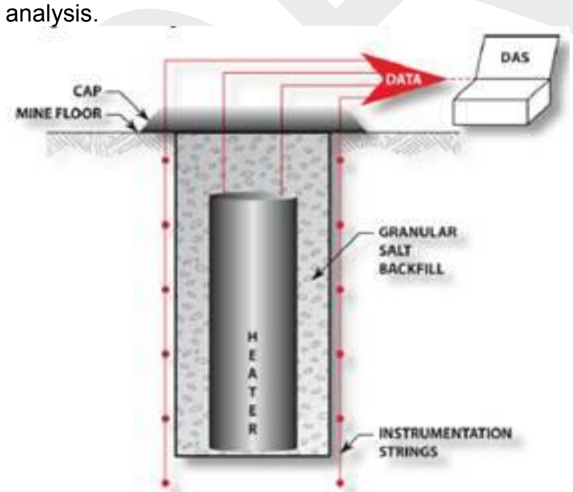
In situ tests could capitalize on access to the URL space.

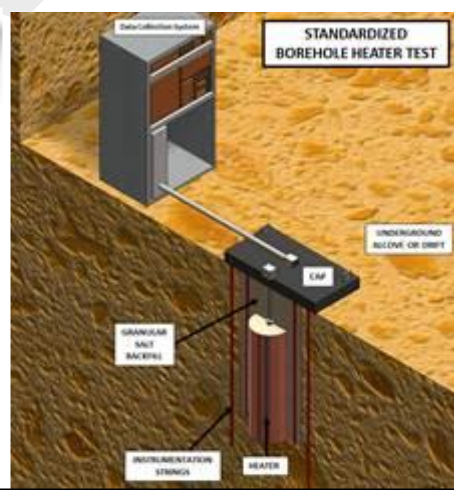
The basic configuration shown in the figures below would include temperature probes, gas and moisture collection, and isotopic analysis. Features that could be added to the test include real-time and/or post-test inspection of desiccated salts on the borehole wall, to distinguish relative amounts of Na, K, Mg and possibly Ca. Such multi-component nature of brine chemistry can evolve toward the formation of Mg-bearing salt mineral assemblage stable at high temperatures that are characteristic of acidic conditions. Existing models for brine migration under stress and temperature gradients could be validated or calibrated using controls on the sampled domain, heating conditions, and mechanical loading while investigating the chemistry of evolved brine. This type of generic experiment is important because moisture is required to corrode most prospective waste package materials for salt, especially the cheaper materials such as low-alloy steels. Corrosion rates are also sensitive to the brine cations. Hence, brine migration and composition are primary variables in the performance of waste packaging. Also, the amount of water (more specifically-hydrogen) present within and around a spent nuclear fuel package is a key factor in criticality evaluations. Moderator exclusion (i.e., no water accumulation in breached waste packages) is a simple and cost-effective strategy for preventing criticality, which is a consideration for direct disposal of dual-purpose canisters.

The amount of brine present in domal salt formations is far less than in bedded salts. Owing to the substantive difference between these two generic salt types, this single heater test might be deployed in the bedded salt at the WIPP URL and in a domal salt, perhaps with international collaboration. A test design could consider several variations, such as installation at different depths in the floor or wall or application of a loading sequence. A standardized single heater test could isolate certain phenomena of research interest in a smaller, more directed, and generic test configuration.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

As this is a proposal (and a good one), it is not a test plan. The instrumentation layout supporting the description above will be developed in the test plan(s). The schematics below indicate that deformation gauges such as Multi-Point Borehole Extensometers (MPBXs) would be used for in-plane deformation and Linear Variable Differential Transformer (LVDTs) might be employed for radial and out-of-plane displacements. Off-the-shelf temperature probes would be arrayed appropriately, depending upon the data quality objectives identified by modeling. Gas and moisture collection would support quantitative measurements and subsequent isotopic analysis.





9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

The modeling effort could take advantage of advances in coupled modeling supported by UFD, including collaboration efforts between US and German salt scientists. The types of modeling include finite element constitutive models for salt + damage + hydrological flow. These issues are central to evaluating code capability as well as re-examining quantity of the brine movement and nature of the vapor transport.

These tests will provide validation opportunities and possibility to evaluate the state of the art.
Structural response and operational trade-off studies would also use the best-available codes and models that the Joint Project will identify.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Waste package
Backfill
Coupled MT (H)
EDZ
Features of the host rock (pristine host rock)

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Preclosure and operations.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

To be developed, if needed, in the Test Plan.

Table H-3. Large-Scale Seal Test

1. **Name of Test:** Large Scale Seal Test

2. **Principal Investigator(s):** Frank Hansen (SNL)

3. **Test Objectives, Description, and Type (lab, field, etc.):**

   - *In situ* tests in the new URL
   - International collaborations
   - Modeling
   - Lab--ACI concrete testing

4. **R&D Issue(s) Addressed by Test (field tests should include one or more “H”-rated issues):**

   Natural barriers (host rock and EDZ)—This testing has a first-order influence on H-rated issue regarding mechanical response of the host rock (Issues 15, 16 and 17 from Table 4-1).
   It also bears on Issues 39-42 with respect to instrumentation development, and methods for *in situ* testing and characterization and *in situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.
   This concept also addresses evolution and mitigation of the EDZ.

   15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects
   16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)
   17. The formation and evolution of the EDZ
   39. Development of accurate instrumentation and methods for *in situ* testing and characterization
   40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.
   41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.
   42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions

5. **Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:**
   - **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

   Confidence building and preclosure safety. See below.

6. **For the proposed test describe the current “state of the art” knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?**

   Issues associated with panel or drift closure systems remain central to salt disposal. For further edification, the reader is referred to the proceedings of the US/German Workshops on Salt Repository Research, Design and Operation, which are posted on http://www.Sandia.gov/SALT/SALT_Home.html. Seal systems construction and functional demonstrations remain essential for ongoing salt repository research in Germany and may well be key considerations for heat-generating waste disposal in salt in the US. Long-term isolation often rests upon seal system design and demonstration. The license to open a repository is likely contingent upon demonstration of the ability to close it. Therefore, sealing systems components and their interaction with the native salt should be a high priority among construction demonstrations in the new space at WIPP.
   The justification for large-scale demonstration includes two essential elements: constructability and performance. Initially the emphasis would go toward construction demonstration, followed by measurements of performance. The issues of constructability will focus on evaluation of the ability to place large volumes of salt-based concrete underground. Inherent in the construction effort is development of procedures, safety standards, personnel

training, and quality control methods for future concrete emplacement within a salt repository or for placement of the Option D Panel closure, which remains the basis for the WIPP certification. Elements of performance will be monitored with installed instruments or measured through specific tests.

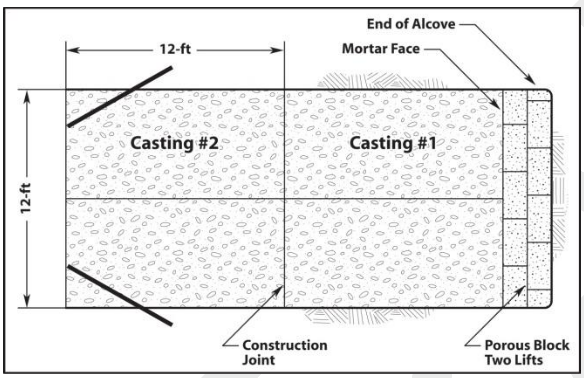
Performance testing would primarily examine permeability of the DRZ and construction techniques to mitigate it. In support of the WIPP repository sealing program, several potential seal components were tested as part of the Small-Scale Seal Performance Test (SSSPT) experiments. The SSSPT investigations provided preliminary information regarding construction and performance of potential repository seal elements. However, many construction features involved in placement of full-scale seals are directly dependent on size, shape, and age of the openings. Concrete placement may be demonstrated as shown in the figure below. After concrete placement and grouting, basic leak-off tests could be conducted, which involve pressurizing behind the concrete monolith and monitoring either the pressure decay or flow rate.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

See discussion above.

There is an entire series of parameters and measurements, starting with heat of hydration of the mass concrete. Standard American Concrete Institute concrete properties will be obtained.



Permeability testing in boreholes will measure the disturbed rock zone as it is created and mitigated. Effective permeability of the seal will be measured.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

Standard ACI Quality Control tests will be run at 7 and 28 days, or as appropriate. The Sandia permeability apparatus for borehole measurement will be used. Normal methods for pressure decay measurements will be used. See drawing.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

The modeling effort and field demonstration represent important collaboration efforts between US and German salt scientists. The types of modeling include finite element constitutive models for salt + EDZ damage and healing.

These validation demonstrations are very important for generic model development and constructability assessment. These parameters and tools will be vital for salt repository design and analyses.

These tests will provide validation opportunities and possibility to evaluate the state of the art.

Structural response and operational trade-off studies would also use the best-available codes and models that the Joint Project will identify.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Seal system;
EDZ;
Features of the host rock (pristine host rock)

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Pre-emplacement, operations.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Provided above.

Table H-4. Salt Defense Disposal Investigations (SDDI) Thermal Test

1. Name of Test:

Salt Defense Disposal Investigations (SDDI) Thermal Test

2. Principal Investigator(s):

Doug Weaver (LANL); Ned Elkins (LANL); Bruce Robinson (LANL);
Frank Hansen (SNL)

3. Test Objectives, Description, and Type (lab, field, etc.):

- Demonstrate a proof-of-principle concept for in-drift disposal in salt.
- Investigate, in a specific emplacement concept, the response of the salt to heat, in particular the evolution of the small but non-negligible quantities of water within the salt as the heat diffuses into the surrounding geologic medium (water budget).
- Develop full-scale response for dry, run-of-mine salt.
- Develop a validated coupled process model for disposal of heat-generating wastes in salt.
- Evaluate the environmental conditions post facto.

4. R&D Issue(s) Addressed by Test (field tests should include one or more “H”-rated issues):

3. Measure changes in physical-chemical properties of crushed salt backfill after waste emplacement (H)
4. Measure changes in chemical characteristics of brine in the backfill and EBS (M)
5. Measure mechanical response of salt backfill (H)
7. Measure brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation (H)
15. Measure changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects (H)
16. Measure mechanical response of host rock due to excavation (e.g. roof collapse, creep, drift deformation) (H)
17. Measure the formation and evolution of the EDZ (H)
18. Measure brine and vapor movement through the host rock and EDZ, including evaporation and condensation (H)
20. Measure changes in chemical characteristics of brine in the host rock and EDZ (M)
23. Measure the thermal response of EBS and Geosphere (H)
26. Measure microbial activity in the EBS and host rock (L)
40. Perform an *in situ* demonstration and verification of repository design, with respect to its impact on the ost rock and the ability to comply with preclosure and postclosure safety requirements. (H)
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation. (H)
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions. (H)

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Confidence-Building
2. Preclosure and Design
3. Postclosure Safety

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

- Direct placement of HLW canisters in open drifts on disposal room floors, rather than in boreholes, offers the possibility of vastly more efficient and flexible disposal operations.
- The concept of disposing waste packages on the floor of a disposal room and covering them with crushed salt has not been tested at WIPP or in bedded salt, and therefore the behavior of the system under these conditions must be thoroughly investigated.
- Testing of this specific disposal concept may have benefit to future emplacement of TRU wastes at WIPP.
- By conducting the demonstration test in a configuration that mimics the disposal of defense HLW packages, we will establish the early-time evolution of the system for conditions in which packages are placed on the floor, and covered with run-of-mine salt.
- Such an operationally focused test, conducted under current QA requirements and processes, will be invaluable as a proof of principle experiment that establishes, through direct observation rather than only models, the efficacy of this disposal concept for a repository in bedded salt.
- Most of the test configurations of early thermal experiments were based on the premise of waste emplacement in vertical boreholes or conducted in domal salt.
- For the tests conducted at WIPP, the evolution of the water contained in the salt was not the primary focus of those past field tests, so measurement systems were not optimized to study the phenomenon of water movement.
- It is hypothesized that temperature-driven water movement for the in-drift emplacement configuration could be significantly different than that for the borehole configuration.
- A key focus of future testing will be to develop and deploy instruments that track brine and water vapor movement, which was not adequately considered in past field tests, and has never been measured in this configuration.
- For the in-drift emplacement design, the hypothesis is that significant quantities of water would be expelled from the disposal horizon during the first few decades after waste emplacement, leading to a lesser amount of water contacting waste packages.
- This thermal testing program will consider both pre and post-closure hydrologic conditions, partly because in the post-closure condition, either accidental or purposeful intrusion into the emplacement horizon will require in-depth understanding or the evolution, status, and potential ES&H affects associated with that intrusion.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

The instrumentation of the SDDI thermal test is expected to be a complex process involving several steps. First, gages will be selected that can accurately measure the anticipated range of responses in the test and withstand the anticipated harsh test environment for several years. In order to ensure test accuracy, the gages will be calibrated before use and will be installed within a surveyed coordinate system specific to the test drift. Gages will be monitored by a data acquisition system and data placed in a database to facilitate data reduction and analysis. The gages, as feasible, will be maintained on a regular schedule to ensure long-term success for the experiments (Munson et al. 1997; DOE OCRWM 1998). These testing activities (including gage calibration) will be performed according to established SDDI quality assurance procedures. Past salt testing experience has proven that with redundant instrumentation, robust gage design, pre and post-test gage calibration, and gage maintenance where feasible, will lead to successful application of sensors despite a harsh environment application (Droste 2003).

An important test parameter associated with this experimental work is brine and vapor movement in the salt formation during the duration of the demonstration test. These measurements are generally not as straightforward as monitoring for temperature or ground movement. Additionally, the ground movements and brine conditions expected to be observed during this demonstration test will make it imperative that measurement techniques account for these potentially adverse conditions. 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.

Geophysical techniques (in addition to the more traditional instrumentation listed on the following pages) are expected to be developed, demonstrated, and potentially deployed to monitor salt drift properties important to the test. A period of one-year duration at the beginning of the time-line is set aside to develop and demonstrate these geophysical measurement techniques, including the more conventional monitoring instrumentation that will measure salt drift properties. All of the geophysical measurement methods are proven, but some are site or application-specific. They are well established techniques, but some may not be appropriate for this salt testing program due to such issues as minimum spatial resolution and limited sensitivity to contrasts between solid, fluid and vapor phases in the salt. For these reasons, there is uncertainty associated with applying these techniques to fluid and vapor migration in salt. Therefore, the planned demonstration period at the beginning of this test program will be used to develop advancements that address the resolution and sensitivity issues.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

The following section discusses instrumentation anticipated to be candidates for the SDDI field demonstration test as well as some of the geophysical techniques being considered. This is not a comprehensive list and several different types of instruments may be available for each need. Each measurement technique will be thoroughly investigated during the instrumentation development period as a function of detailed test planning. Lessons learned from past testing completed at WIPP, the Yucca Mountain Project, and salt testing performed internationally will be considered.

<u>Temperature Measurements</u>
- Thermocouples/Resistance Temperature Detectors
- Fiber Optic Temperature Array

<u>Mechanical Measurements</u>
- Multi-Point and Single-Point Borehole Extensometers
- Room Closure Gages
- Active Time-Lapse *In Situ* Seismic Wave Transmission Measurements and Monitoring
- Pressure Cells
- Passive Seismic Event Monitoring

Hydrologic Measurements
- Time Domain Reflectometers
- Heat Dissipation Probes
- Electrical Resistivity Tomography
- Ground Penetrative Radar
- Active Neutron Probe
- Gas Sampling Ports
- Brine Sampling Ports

<u>Miscellaneous Measurements</u>
- Thermal Flux Meters
- Power Meters
- Air Velocity Gages
- Gas/Air Pressure Transducers
- Air Humidity Sensors/Chilled Mirror Hygrometers
- Real-Tim Remote Video

9. Define the pre-and post-test modeling/simulation needs for the activity, including:
- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

The directed SDDI research will inform, confirm, 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 proposed *in situ* field tests and will continue to provide bases for performance assessments in the future. Next generation coupled thermal-mechanical-hydrologic 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. 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. It is critical to validate these TMHC models so that it they be used with confidence to represent the coupled processes in a repository PA analysis.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

SDDI involves the integrated testing of simulated waste packages (canister heaters), covered by salt backfill in a in a configuration that mimics the disposal of defense HLW packages (in drift emplacement).

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

- New test results, augmented by extensive geomechanics experience and data at the WIPP site, should enable us to make confident predictions of the long-term evolution of the repository environment in the period up to and after repository closure.
- This SDDI thermal test would set the foundation for additional higher heat field studies relevant to the disposal of civilian used nuclear fuel (e.g. SDI), should the nation decide to consider a repository for civilian waste in bedded salt.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Experiments to evaluate consolidation of hot, dry, run-of-mine salt, will evaluate a stress/temperature/porosity function that will be used to model elements of the SDDI proposed field demonstrations. An assessment of thermal conductivity as a function of porosity will properly account for the transient evolution of the disposal area: as the mine-run salt consolidates, thermal conductivity increases. Therefore, the thermomechanical laboratory tests on granular salt produce information that is directly applicable to salt disposal of heat generating waste.

Understanding the mobilization of native brine is essential to establish the evolution of the underground setting of this disposal concept. Migration of small amounts of water present 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 processes. 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. 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 DHLW waste 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.

Table H-5. Water Migration Tracer Test During the Proposed SDDI Experiment

1. Name of Test: Water migration tracer test during the proposed SDDI experiment

2. Principal Investigator(s):

Philip Stauffer, Florie Caporuscio, Paul Reimus LANL
Ernest Hardin SNL

3. Test Objectives, Description, and Type (lab, field, etc.): Field Test with Lab Analysis

The first goal of this tracer test is to better understand the movement of water as it migrates through and away from the run-of-mine backfill during the proposed 2-year SDDI experiment. We hypothesize (based on recent simulation results) that significant water transport occurs during waste heating through both liquid and vapor phase migration, and that such migration can be tracked through the introduction of stable isotope tracers (Deuterium and O-18) added to the run-of-mine backfill. Simulation results suggest that water will migrate away from the heaters, especially when and where boiling occurs, creating a dry zone around the heaters and a wetter region where water vapor condenses. Redistribution of water will be seen through the redistribution of tracer. Sampling ports located within the backfill will allow extraction of small volumes of gas to determine changes in concentration with time. We also expect that some fraction of the stable isotopes introduced into the backfill will migrate in the vapor phase into the air of the experimental drift and eventually out of the drift through the damaged rock zone and/or through the bulkheads. Sampling in both the drift air and outside the bulkheads (including possibly from within DRZ fractures) will allow us to measure how fast such migration occurs. Additional samples will be taken from the DRZ both laterally and vertically to gain insight into migration. Finally, post experiment analysis of the backfill should allow a mass balance on what fraction of the initial water remains within the backfill.

A second goal of this tracer test is to understand the turn-over rate for air in the experimental drift. A second set of tracers with variable water/air partitioning coefficients (e.g. SF_6, CF_4, which have minimal partitioning to water, and CH_2F_2, which has much greater partitioning to water) will be introduced into the experimental drift in short pulses (within the backfill and/or into the drift air), allowing simultaneous estimates of air turn-over rate, moisture evolution, and water tracers along pathways for gas movement. Samples for pulse breakthrough observation will be taken from the drift air and from points outside the bulkheads such as in discrete DRZ fractures that are found to be conductive during pre-experiment testing. Tracer flushing from the drift air will give us an estimate of drift air turn-over rates, while differential breakthrough in the backfill or flow features such as discrete fractures in the DRZ will support estimates of integrated moisture evolution along flow paths, due to differences in partitioning coefficients.

Numerical modeling will be used to further refine and prioritize the test goals to increase the likelihood of success of the tracer experiment. Simulations will be used to test a range of scenarios including high vs. low drift air turn-over, high vs. low DRZ permeability, and differences between the two proposed experimental drifts (hot vs. warm). Various schemes for differentiating and interpreting observations of traced isotopic water, moisture from background ventilation, and connate water will be addressed at this stage.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

6. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation
32. Appropriate representation of coupled processes in process models
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models
37. Verification and validation
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Preclosure safety
2. Confidence-building

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

To date, most of the work on brine migration in salt repositories has focused on water moving from the DRZ into drifts or boreholes (e.g., Kuhlman and Malama, 2013). In the proposed SDDI experiment, the presence of a large volume of run-of-mine backfill creates a new environment for water/vapor transport in relation to the waste packages. To show that we understand how this new configuration behaves, we need data from the SDDI experiment on water migration through the backfill in both the vapor and liquid phases. Through the proposed tracer test we also will get some of the first measurements of vapor migration in the DRZ.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

Small-volume gas samples will be taken from within the backfill and the drift air during the 2 year SDDI test by use of small diameter sampling tubes (anti-corrosion stainless steel or titanium). Additional samples will be taken outside the bulkheads during the 2 years of testing. Post-test water samples will be extracted from samples of the backfill, for mass balance analysis. Post-test samples from the DRZ will be taken from walls, floor, and roof.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

Isotope samples will be measured on a Picarro analyzer (http://www.picarro.com/) allowing for very small sample volumes (so as not to perturb the test) and highly accurate measurements to be made at the site. Model validation will require temperature measurements (such as distributed temperature sensing fiber optic cable for high spatial resolution with minimal system perturbation) and moisture monitoring as proposed in other tests plans (e.g., Dan Levitt, Table H-9).

Similar trace gas samplers would be used for the second component of the experiment (SF_6, CH_2F_2, CF_4)

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

Pre-test modeling will be performed to further refine and prioritize the test goals to increase the likelihood of success of the tracer experiment. For example, simulations can be used to test a range of scenarios including high vs. low drift air turn-over, high vs. low DRZ permeability, and differences between the two proposed experimental drifts (hot vs. warm).

Modeling during testing will be done to parameterize transport processes and refine ongoing pulse tracer testing.

Post-test modeling will include transport into the DRZ and comparison to isotope migration observed in the post-test data.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Backfill, EDZ, drift air, boundary conditions on air outside of the bulkheads.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Data gathered applies mainly to the test period of 2 years. Some applicability to longer times through understanding of turn-over rates for drift air and implications for drying of the backfill. Validation of predictive models will support repository predictions on the order of hundreds to thousands of years.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Pre-test modeling to refine and test the experimental plan. This phase will evaluate and confirm the impact of gas sampling and tracer injection in the backfill and drift air during testing. Samples taken outside the bulkheads are not expected to impact the test operations.

Pre-test lab work to verify current modeling assumptions and results (e.g., Caporuscio lab test plan).

Pre-test lab work to establish limits and constraints of Picarro stable isotope measurements under expected field conditions. Pre-test lab work to measure/verify partitioning of tracers to saturated brines as a function of temperature, which are likely different than published values for much more dilute aqueous solutions. Also, screen for any gas-phase partitioning to the salt itself. May also want to evaluate/verify fractionation of isotope tracers as a result of boiling/condensation processes, which may have never been done for saturated brines and might be different than for more dilute solutions.

Data gathering on current in-situ isotopic values of drift air/brine.

Table H-6. Salt Decrepitation Effects

1. Name of Test: Salt Decrepitation Effects

2. Principal Investigator(s): Kris Kuhlman (SNL)

3. Test Objectives, Description, and Type (lab, field, etc.):

Objectives: Understand decrepitation effects on salt structural, hydrological, and thermal properties.
Description: A combination of salt cores and salt backfill will be heated to the decrepitation point (250-300 degrees C) in a triaxial apparatus, allowing for variable confining pressures. Temperature, stress, strain, acoustic emissions, and gas permeability will be measured before/after testing, during heating, and after decrepitation. Many tests have experienced decrepitation, but the effect it has on the thermal/hydraulic/mechanical properties of salt has not been quantified. Based upon the testing results, we will work to improve the representation of this coupled behavior in THM models (thermal effects on brine, which mechanically change the rock)
Type: Laboratory test initially, with components of the test eventually done at borehole/field scale

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement
7. Brine and vapor movement in backfill and emplacement drift
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological and chemical effects.
32. Appropriate representation of coupled processes in process models

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:
- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

This would apply mostly to pre-closure safety, but would potentially effect early post-closure and confidence building (at least related to disposal of the hottest waste).

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Salt decrepitation is not well quantified. Much of the existing "knowledge" is based upon limited testing under less-than-controlled conditions. The effects it has on the coupled THM system, its representation in constitutive models, and our ability to predict its effects are almost non-existent.

Current upper thermal limits for design of salt repositories, is based upon a very conservative value of 200 degrees C, which was chosen to avoid decrepitation (which was quite poorly understood when this was proposed in the 1960s as part of Project Salt Vault).

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):
- **Describe how the data will be collected**

- The triaxial apparatus used to confine the sample, will be used to impose specified axial and confining pressures on the core or crushed salt sample.
- Microphones will be used to measure acoustic emissions through time during heating.
- Nitrogen permeability tests will be conducted across the sample before, during, and after heating
- The samples will be loads and unloaded to estimate Young's modulus and Poisson's ratio; sonic velocity measurements could also be taken to estimate dynamic Young's modulus and Poisson's ratio.
- Directional train of intact samples and volumetric strain of crushed salt samples will be measured during testing.
- Temperature will be measured at several locations on the sample, to determine if a thermal gradient exists across the sample during heating – which would cause brine inclusions to migrate before decrepitation.
- Brine loss rate will be estimated by passing dry nitrogen gas through/around the sample and passing the exposed gas through desiccant canisters which are weighed periodically.

8.	**Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:** see #7.
9.	**Define the pre-and post-test modeling/simulation needs for the activity, including:** • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)** The thermal and mechanical evolution of the samples during applied heating will be predicted before testing, using standard geomechanical models with available constitutive models. Existing mathematical models for brine migration will be implemented to predict the brine loss rate from the sample. The deviation of the observed thermal/mechanical/hydrologic properties due to decrepitation (if any are observed) would be the point of the test. If these changes are measureable, new constitutive models will be developed to implement and include these effects.
10.	**List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):** host rock, backfill, and potentially seal systems (e.g., drift seals which use crushed salt and would be near the waste)
11.	**Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:** • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** mostly pre-emplacement and early post-closure (high temperatures are needed for decrepitation)
12.	**For field tests define additional lab tests or other separate activities/data needed to support this test:** N/A

Table H-7. Development of an Integrated Geophysical Imaging System for Field-Scale Monitoring of Brine Migration and Mechanical Alteration in Salt Repositories

1. Name of Test:
Development of an Integrated Geophysical Imaging System for Field-Scale Monitoring of Brine Migration and Mechanical Alteration in Salt Repositories

2. Principal Investigator(s):

T.M. Daley, Y. Wu, J. Birkholzer, & J.B. Ajo-Franklin (Lawrence Berkeley National Laboratory)

3. Test Objectives, Description, and Type (lab, field, etc.):

The goal of the proposed test program is to investigate the geophysical signature of both brine migration and mechanical-chemical alteration in salt repository environments with a focus on borehole imaging technology for field-scale heater tests. Prior tests in a variety of subsurface contexts have shown the utility of both electrical resistance tomography (ERT) and continuous active source seismic monitoring (CASSM) in capturing fluid migration fronts and mechanical-chemical changes. We propose to undertake a suite of core to mesoscale laboratory experiments to examine the joint electrical/seismic signatures of brine migration in both granular and cored salt as well as similar measurements investigating the response of salt during compaction or tensile failure. All experiments will be conducted over a range of pressure and temperature conditions, and will be supported by structural imaging methods (e.g. x-ray, SEM, & thin-section petrography). The goal will be to isolate unique geophysical signatures present during both evolution of the EDZ and each phase of brine migration ranging from the evolution of isolated fluid inclusions to a connected, percolating, brine-filled fracture network. Following laboratory experiments, we will undertake the design of a field-scale electrical/seismic imaging system to isolate these responses during a possible heater test (e.g., SDDI or SDI). The field system will integrate a combination of semi-permanent piezoelectric seismic sources developed at LBNL with heat-tolerant geophones packages for CASSM and acoustic emission monitoring, along with an integrated electrode array for ERT monitoring. Particular attention will be paid to electrode coupling and response for ERT monitoring of conductive fluids. The system geometry will be evaluated through a forward modeling exercise and if possible, will be deployed in-situ for baseline testing. We will also test joint-inversion algorithms tailored to combining seismic & ERT results to the results of any synthetic experiments. At the end of this test program, a field-ready joint geophysical imaging system will be ready for utilization in a salt heater or any other *in situ* test program in a salt repository.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation (rated "high")
17. The formation and evolution of the EDZ (rated "high")
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation (rated "high")

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Preclosure safety
2. Postclosure safety
3. Confidence-building

Brine migration and associated micro-damage/fracturing is a critical issue for making the safety case for salt repositories with defense high-level waste (EM responsibility) or civilian used nuclear fuel (NE responsibility), as it may potentially result in degradation of the waste containment system and alteration of salt rheological properties. Characterization and evolution of the EDZ is also a crucial task and mediates a range of interactions with the native formation.

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

A limited number of previous tests have examined either the seismic or electrical response of salt samples during brine infiltration and salt deformation. Few have jointly measured both properties to allow characterization of the combined signature during both stages of micro & macro fracturing (e.g. EDZ evolution and tunnel failure) as well as brine transport from single crack occupation to percolating networks. Field utilization of combined borehole seismic/ERT imaging techniques are also relatively unusual; the state-of-the-art in terms of geological carbon storage is the combined cross-well seismic/ERT deployment conducted by LBNL in a deep sandstone formation at the SECARB Cranfield site (e.g. Doetsch et.al. 2013). Similarly, LBNL has recently partnered to deploy seismic/ERT instruments to monitor *in situ* heating of oil-shale. To our knowledge, no repository heater test has combined the two techniques although isothermal ERT tests have recently been conducted in salt as part of the ADDIGAS project (Jockwer & Wieczorek, 2008). Our tests will fill a significant data gap that exists examining joint geophysical attributes in the context of salt storage with particular focus on elevated temperature response.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

We propose measurement of seismic response (P-wave & S-wave velocity + attenuation) as well as electrical response (DC resisitivity + IP) of core-to-mesoscale salt samples both while intact and 1) during extension & compression (pre-failure), 2) during failure and crack network evolution and 3) during brine invasion and transport induced by temperature gradients. These experiments will be collected during short (days/weeks) laboratory tests to provide the petrophysical data necessary to interpret and invert field geophysical monitoring tests. The focus will be on inverting the joint dataset for (a) crack density during porosity evolution and (b) brine saturation during the transport phase.

As mentioned previously, the accompanying field seismic measurement system will be based on combining a small-scale multi-source piezoelectric source array developed previously (see Ajo-Franklin et.al. 2013) with an array of heat-resistant geophones to allow real-time seismic tomography around a future heater system test. The electrical measurement system will consist of a co-located borehole electrode array suitable for ERT and IP measurements with the same spatial extent as the seismic measurements. After pre-processing and tomographic inversion, the combined system will yield seismic properties (P-wave & S-wave velocity + attenuation) and electrical properties (resistivity & frequency-dependent amplitude and phase) as a function of both space and time with temporal resolution ranging from minutes (for seismic) to hours (for ERT).

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

1) The laboratory measurements will be conducted in the Environmental and Applied Geophysics Laboratory (EAGL) at Lawrence Berkeley National Laboratory. A previously developed temperature controlled resonance bar measurement system will be utilized for seismic measurements (see Nakagawa 2013). This system will be upgraded to incorporate a 4 electrode IP system to allow simultaneous measurement of electrical properties during experimental manipulations.

2) Development and fabrication of the field measurement system will be conducted at the Geophysical Measurement Facility (GMF) at Lawrence Berkeley National Laboratory. The seismic source array will be fabricated from high-temperature piezoceramic elements and should function effectively to 200 C. Geophone elements will be commercial high-temperature miniature models (e.g. I/O SM45) which will function to a similar temperature threshold. The electrical measurement system will consist of a custom solid metal electrode array with a compatible design for co-deployment. Both systems will be tested to insure performance in the high-temperature corrosive environments likely present in environments within a salt repository.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

While no modeling will be explicitly required for the early stages of our experimental work, we anticipate that coupled hydrological/thermal/mechanical modeling would be quite useful in generating test property distributions for geometry design of the field geophysical monitoring system. We aim to build an active collaboration with one of the modeling groups and leverage pre-field test modeling studies to design the field geophysical system.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

The laboratory experiments will involve measurements on both pristine host rock and granular material although some samples extracted from the EDZ could also be utilized. The field scale monitoring could include seal system, backfill, EDZ and pristine host rock.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The data provided by laboratory and field testing will be useful through the pre-emplacement, preclosure and postclosure periods.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

As described above, the proposed field tests would be supported by initial lab scale tests on salt cores.

Table H-8. Geophysical and Acoustical Monitoring of Fluid Migration and Fracture Evolution for WIPP Salt Thermal Tests

1. Name of Test: Geophysical and acoustical monitoring of fluid migration and fracture evolution for WIPP salt thermal tests

2. Principal Investigator(s): Peter Roberts (LANL)

3. Test Objectives, Description, and Type (lab, field, etc.):

Geophysical techniques are needed to be developed and/or demonstrated to assess their ability to monitor salt drift properties important to the SDDI thermal test, in particular, the movement of brine and water vapor. This activity is needed prior to the finalization of detailed test planning and the start of procurement activities for the SDDI test. All of the geophysical measurement methods are proven, but some are site or application-specific. They are well established techniques, but some may not be appropriate for this salt testing program due to such issues as DRZ influence, minimum spatial resolution and limited sensitivity to contrasts between solid, fluid and vapor phases in the salt. For these reasons, there is uncertainty associated with applying these techniques to fluid and vapor migration in salt. Therefore, the planned demonstration period at the beginning of this test program will be used to develop advancements that address the resolution and sensitivity issues. The objective is to assess and implement the following methods for monitoring fluids and fracture evolution in salt:

1) Active seismic combined transmission and reflection tomography
2) Active seismic reflection imaging and direct imaging of faults
3) Active seismic doublets for measuring sub-percent velocity changes
4) Passive seismic monitoring of microseismic signals and ambient noise
5) Nonlinear acoustics measurements of moisture content and micro-cracks
6) Electrical Resistivity Tomography (ERT)
7) Combined seismic and ERT
8) Statistical analysis of acoustic/seismic forward and backward scattering signals
9) Estimation of acoustic/seismic attenuation, including attenuation tomography
10) Laboratory resistivity measurements of core samples to understand brine and vapor movement

Type: Initial lab sensitivity experiments. Then implement field tests at WIPP during thermal tests.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

<u>"H"-rated R&D issues addressed:</u> 3, 7, 14, 15, 16, 17, 18, 39, 46

<u>Relevant Functions/Type/Importance:</u>
Primary: The suite of measurement techniques above address aspects of the repository that isolate the waste and the EBS from external events or changes, and therefore help maintain the integrity and longevity of the barriers.
Primary: The suite of measurement techniques above address aspects of the repository that prevent fluid contact with the waste.

<u>Relevant Impacts:</u>
Directly related to the final state of the backfill permeability (containment function of the backfill) as well as the surrounding material.
Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)
Directly related to brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety: high-sensitivity monitoring of fluids and fractures for early detection of leakage
2. Preclosure safety: monitoring excavated zones for early signs of deformation/collapse

6.	**For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?** Data from new LANL methods should provide sensitivity to migration of fluids and vapor, and formation and evolution of cracks in salt beyond what current state-of-the-art geophysical techniques can offer. These methods have been tested in other Earth and engineered materials but not in salt. They are applicable over a wide range of scales, can be used for standoff measurements at distance from the heat sources, and can provide near real-time (4D) monitoring of changes occurring in the walls surrounding the backfilled area. We view the LANL approaches and methods as complementary enhancements to tasks proposed by other Labs and we will identify possible joint-Lab efforts.
7.	**Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):** • **Describe how the data will be collected** -Acoustic and seismic transmission and reflection waveform data -Microseismic signals generated by fracture growth and salt movement -Nonlinear acoustics data using Time-Reversed Nonlinear Elastic Wave Spectroscopy (TR-NEWS) -Electrical signals Data will be collected using instrumentation described in Box 8.
8.	**Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:** Acoustic transducers, seismometers and electrodes will be used for sensors. These will be placed in holes drilled into the drift walls to depths sufficient to penetrate past the EDZ. Appropriate digitizing instrumentation will collect the data. Geophysicists at LANL will process and analyze the data, but again, we view these tests as an excellent opportunity for collaborations with other Lab efforts.
9.	**Define the pre-and post-test modeling/simulation needs for the activity, including:** • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)** N/A
10.	**List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):** Primary targets: EDZ and pristine host rock Secondary targets: Waste package and backfill
11.	**Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:** • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** Data gathered will apply to the entire life of the repository including pre-emplacement.
12.	**For field tests define additional lab tests or other separate activities/data needed to support this test:** Lab tests on representative samples of WIPP salt, clay and fluid will be performed to determine the sensitivity of each method to the key parameters to be measured during the thermal test. These tests will provide proof-of-concept data as well as guidance for how the field tests will be designed and performed.

Table H-9. *In Situ* and Laboratory Testing of Moisture Monitoring Methods

1. Name of Test: *In situ* and laboratory testing of moisture monitoring methods.

2. Principal Investigator(s): Dan Levitt (LANL)

3. Test Objectives, Description, and Type (lab, field, etc.):

Reliable techniques are needed to measure and monitor changes in moisture status of the backfilled salt. While there are numerous such techniques for measurements in soil or rock, there is very information on the success of such techniques in salt. The ability to detect very small changes in the moisture content of the backfill provides valuable information on the migration of brine fluid and vapor due to evaporation and condensation. Measurements on small (~cm) scale to larger (~m) scale could provide such information.

This activity will test the applicability in salt of several "tried and true" moisture monitoring techniques in soil and rock. Activities include:

1) Laboratory testing of the response of a neutron probe to run of mill salt at various water contents; lab test conducted in large drum (e.g. 55-gallon drum) to provide ~m-scale measurements
2) Calibration of a neutron probe to run of mill salt at various water contents
3) Laboratory testing of time-domain reflectometry (TDR) probes to provide ~cm-scale measurements of changes in water content of run of mill salt
4) Laboratory testing of heat dissipation probes (HDP) to provide ~cm-scale measurements of water potential of run of mill salt
5) Laboratory testing of the water content – water potential relationship of backfilled salt using hanging water columns; also determine the saturated hydraulic conductivity (Ksat) of typical run of mill salt
6) Laboratory testing of other potential techniques (e.g. resistance blocks)
7) Field testing of the feasibility of using a neutron probe, pulled through a 2-inch diameter access tube emplaced horizontally in backfilled salt
8) Field testing of the feasibility of using TDR or HDP sensors emplaced in backfilled salt; including sensor (and datalogger) longevity in a salt environment

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

"H" –rated issues include: 7, 18, 31, 39, and 46

Relevant Functions/Type/Importance:
Primary: The suite of measurement tests above address aspects of the repository that isolate the waste and the EBS from external events or changes, and therefore help maintain the integrity and longevity of the barriers.
Primary: The suite of measurement tests above address aspects of the repository that prevent fluid contact with the waste.

Relevant Impacts:
Directly related to brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
Directly related to the final state of the backfill permeability (containment function of the backfill) as well as the surrounding material.
Directly related to backfill permeability (i.e., to containment)

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Preclosure safety: monitoring of changes in moisture status of backfilled salt; provides information on evaporation and condensation
2. Confidence Building in model simulations

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Data from these methods should provide cm- to m-scale measurements of moisture status indicating migration of fluids and vapor. These methods have been tested in other Earth and engineered materials but not in salt. The methods using sensors can be used for standoff measurements at distance from the heat sources, and can provide near real-time (4D) monitoring of changes occurring in the backfilled area.

We view the LANL approaches and methods as complementary enhancements to tasks proposed by other Labs and we will identify possible joint-Lab efforts.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

Water content of backfilled salt; see Box 8
Water potential of backfilled salt; see Box 8
Hydraulic properties of backfilled salt; see Box 3.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

For an *in situ* layout, access tubes will be emplaced horizontally in salt backfill and manually logged by pushing/pulling a neutron probe through the access tube. Measurements will be made at frequent spatial intervals (e.g. every 15 cm) by taking a long (e.g. 64-second) measurement at each interval. These manual measurements will be taken weekly

TDR and/or HDP sensors will be emplaced in backfilled salt at various depths and distances from a waste package (or heat source), with sensor cables bundled into a protective enclosure with a datalogger and power supply. Sensors will be read and recorded on a frequent time interval such as every 12 hours.

For laboratory layout, bench-tops are required to test sensors and large drums (e.g. 55-gallon) are required for testing the neutron probe in salt

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

N/A

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Primary targets: Salt backfill
Secondary targets: EDZ and pristine host rock

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Data gathered will apply to the pre-emplacement and preclosure time periods, although data collection with sensors could also continue in the postclosure period.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Lab tests on representative samples of run of mill salt will be performed to determine the sensitivity of each method to the key parameters to be measured during the thermal test. These tests will provide proof-of-concept data as well as guidance for how the field tests will be designed and performed.

Table H-10. Thermo-Hydro-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay on Permeability and Brine Migration in Salt at High Temperatures and Pressures

1. **Name of Test:** Thermo-Hydro-Mechanical-Chemical Experiments to Study the Effect of Creep and Clay on Permeability and Brine Migration in Salt at High Temperatures and Pressures

2. **Principal Investigator(s):** Tim Kneafsey and Seiji Nakagawa (LBNL)

3. **Test Objectives, Description, and Type (lab, field, etc.):**

   We propose complex THMC laboratory experiments to measure the coupled thermal-hydro-mechanical processes in the near-field EDZ, at conditions representative of a repository for heat-producing defense *and* civilian waste. We will measure the evolution of permeability and mechanical properties of salt (containing clay) influenced by high temperature, different stress conditions, and different levels of pressure of the intruding fluid as would be experienced by salt in the EDZ, and we will examine the fate of water/brine in this system. Because these processes are dependent on the presence, abundance, and distribution of clay, samples with and without clay will be tested. Post-closure fracture healing and fluid migration in the host rock will also be examined to quantify the effect of pressure solution under repository conditions on permeability.

   Core-scale laboratory experiments will be conducted on natural, repository-relevant salt cores subjected to realistic stresses and temperatures. Initially, the cores will be examined for clay content and distribution via X-ray computed tomography (CT) scans, and the mineral composition of the clay will be determined via XRD. Geophysical properties including electrical conductivity, spatially distributed electrical resistance for tomographic reconstruction (Electrical Resistivity Tomography), and the seismic velocities will be measured. Subsequently, the cores will be subjected to mechanical loading (simulating excavation damage) and thermal loading, which will introduce distributed microcracks, shear fractures (micro faults) resulting from their linkage, and open, tensile fractures. The induced micro-damage and the fractures will be examined again via CT imaging and geophysical measurements. If measurable, changes in the gas permeability due to the damage will also be measured. In the third phase of the experiment, the damaged cores will be subjected to elevated temperature and pressure for an extended duration up to 2-3 months. CT imaging, gas permeability, and geophysical measurements will be conducted periodically to monitor the changes in the cores. These experiments will be conducted on salt cores with different clay contents and distribution so that their impact on the evolution of the damage zone can be investigated. The tests will also be conducted under both ventilated and non-ventilated conditions (to represent changes in natural and engineered moisture boundary conditions) to examine their impact on the water/brine migration and the evolution (healing) of the damage. Finally, detailed post-test sample examination will be conducted using geophysical measurements, and X-ray CT imaging, and destructive sample characterizations, to determine the distribution and migration of brine in the sample. Experiments will use custom core-scale cells and novel micro-triaxial test cells (the latter can be placed into the micro computed tomography Advanced Light Source Beamline 8.3.2 to monitor real-time micro-damage healing and sealing processes).

   In addition to the experiments on cores containing multiple distributed cracks and fractures, we also propose to conduct experiments on a single crack/fracture in a salt sample so that the process of damage healing can be examined and quantified more precisely. The main focus of this experiment is on the role of pressure solution at the contacting asperities, and its influence on the permeability reduction over time. A single fracture in a cylindrical core (induced via Brazilian loading) will be subjected to a confining stress and elevated temperatures. Prior to testing, the fracture faces will be characterized using profilometry, and the sample will be carefully reassembled with a slight mismatch to create an initial permeability, and scanned using X-ray computed tomography (CT) to provide a second indication of the fracture aperture distribution. The sample will be placed in a jacket in a pressure vessel, a confining stress will be applied and then the sample will be heated. Gas permeability will be monitored over time as the sample creeps. Separate samples will be treated as above but saturated brine will be passed through the fracture and permeability monitored over time. Upon completion of the test, the fracture surfaces will again be characterized to examine where changes occurred and what was the cause of the changes. If complete healing has occurred, this will be indicated by permeability measurements and by CT. Impact of clay on the healing will also be examined by using a fracture containing a thin coating of clay.

Measurements on large cores will be complemented by static and dynamic micro-tomographic imaging experiments on smaller samples to examine the spatial characteristics of the fracture healing processes.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

a. Natural Barriers 15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects
b. Natural Barriers 17. The formation and evolution of the EDZ
c. Natural Barriers 18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation
d. Modeling Issues 33. Appropriate representation of coupled processes in TSPA model

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:
List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)

1. Postclosure safety
2. Preclosure safety
3. Confidence building

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Not many studies have been performed examining the THMC hydrologic properties of salt at high temperature and with mesoscale (core scale) migration of fluid. In this study, we will quantify the THMC properties of salt and clay-bearing salt under conditions applicable to a "hot" repository over a range of temperatures (50^{o}C to 200^{o}C, relevant to both defense and civilian waste). The addition of thermal processes, which affect brine migration and water vapor formation and transport, may change the behavior of the stressed salt.

Dilatancy within the EDZ drives immobile brine into the induced microcracks and fractures (shear zones). If connected cracks and fractures are pervasive so that a large pressure gradient exists in the system, heat from the waste will produce vapor which will be transported away from the drift and condense where the temperature of the rock is lower. This process will occur together with the migration of trapped brine within individual salt crystals and at the grain boundaries under a thermal gradient. The dominant deformation (creep) mechanism of salt under the repository-relevant conditions is pressure solution and precipitation (e.g. Schleder and Urai, 2005; Spiers et al., 1990) which is accelerated under high temperature and transport of supersaturated solution. During the heating period, the EDZ will experience competing effects of accelerated healing of the damage from the increased temperature and a deceleration from the loss of brine. In contrast, away from the drift tunnel where temperature increase is small, condensed water will partially dissolve the salt, and also accelerate pressure dissolution leading to healing the damage. This complex thermal-hydrological-mechanical-chemical coupling requires core-scale laboratory measurements correlating the evolution of damage characteristics in EDZ to the resulting mechanical and hydrological properties, which will provide input to numerical THMC models for predicting long-term performance of the natural barriers.

In many waste repositories in salt, the host rock commonly contains distributed clay particles and seams. These provide points of stress concentration in the host rock, which can control how the damage (microcracks and fractures) develops during drift excavation and by thermal loading. Connected fractures in the damage zone can serve as fast paths for brine intrusion, but also as a conduit for migration of water vapor away from the drift. During the heating phase of the post closure period, clay can also add water to the system, through physical-chemical reactions under elevated temperature and pressure. When subjected to high temperature and stress with water (brine) availability, fractures in the damage zone close gradually, primarily due to precipitation of salt from the brine and pressure dissolution of contacting asperities within the fractures. Clays also play an important role in the latter, because their presence at the asperity contacts creates a fast path for diffusive transport of the dissolved salt, resulting in much faster closure of the fractures (e.g. Renard et al, 2001). Correlating the clay content and distribution in salt to its short and long-term coupled thermal-hydrological-mechanical behavior will lead to accurate predictions of the EDZ properties and their evolution during the post-closure period. Such attempts have not been previously made.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

The experiments will be conducted on natural salt cores with different degrees of clay content and distribution. Data collected will include properties from the initial sample characterization including clay mineralogy, abundance, distribution, and moisture content, and for fracture tests: fracture aperture distribution and permeability prior to test, intermittent permeability during the test, final fracture aperture distribution. Additionally:

Phase I (Intact samples):
X-ray CT images (nominal resolution~0.5mm but fractures as thin as ~0.1mm can be imaged) of initial clay inclusions in salt
Baseline electrical conductivity (provides proxy information to the brine permeability) and seismic velocities
Baseline gas permeability measurements (if applicable)
Electrical resistance measurements for tomography (to indicate water migration)

Phase II (Damaged samples):
X-ray CT images of induced damage including dilatancy and fractures correlated with clay inclusions
Electrical conductivity and seismic velocities
Gas permeability measurements
Electrical resistance measurements for tomography

Phase III (Healed samples. Measurements conducted periodically up to 2-3 months)
X-ray CT images of healed damage correlated with clay inclusions
Electrical conductivity and seismic velocities
Gas permeability measurements
Electrical resistance measurements for tomography
Moisture quantification for open systems

Describe how the data will be collected:
Methods include typical gravimetric techniques, CT, X-ray diffraction, ultrasonic transducers, and conductivity bridges. Optical profilometry will be used for fracture characterization, as well as X-ray CT. Permeability will be computed from flow rate and pressure differential. Very low permeability may be measured using transient methods (pressure decay permeametry).

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

- A customized core holder capable of applying elevated temperature and pressure will be built and used.
- GE Lightspeed 16 medical CT scanner will be used to investigate core-scale structural heterogeneity (fractures, clay particles, seams)
- Ultrasonic measurement equipment will be used to investigate the mechanical property changes in the core
- Electrical conductivity measurement equipment will be used to examine the electrical permeability of the core
- Permeability will be measured in the standard way using a differential pressure transducer (e.g Rosemount 1151 or 3051) connected to both sides of a core with pumps on both sides.
- Optical profilometry will be performed using a Nanovea PS50 Profilometer.

Ancillary equipment for providing and controlling temperature and pressure and for acquiring data.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:
Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)

Pre- and post-test modeling would be recommended to model the coupled processes and to interpret experimental results.

	List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.): This test applies primarily to the EDZ where damage is likely to occur and where brine mobilization and migration processes are expected, and to the pristine host rock to a lesser extent as some thermal damage may occur.
11.	**Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure: e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** Data gathered applies to pre-emplacement (for planning phase, site selection and drift construction), preclosure, and postclosure periods. Because of the limitation of the duration of the experiment, extrapolating the observed behavior of salt samples in the laboratory will require further research including modeling activities.
12.	**For field tests define additional lab tests or other separate activities/data needed to support this test:** N/A.

Table H-11. Long-Term Steel Corrosion Analyses from Room A1/B Re-entry

LONG-TERM STEEL CORROSION ANALYSES FROM A1/B RE-ENTRY

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Summary
We propose to calibrate a multi-decadal model for steel corrosion in salt from heater fragments retrieved during the room A1/B re-entry. Corroded steel from 4 heaters left in Rooms A1 and B in the mid-1980s will be retrieved and analyzed to establish the rate and mechanism of long-term corrosion. Samples will be taken from heaters and canisters that were back-filled with salt and/or bentonite, but whose peak test temperature varied. Corrosion products will be characterized to quantify controls over long-term corrosion. Corrosion results from the Room A1/B heaters should provide multi-decadal data points for models of steel corrosion, hydrogen generation and Fe^{+2} production (under anoxic conditions). Also, geochemical tests of the steel-salt interface will be done to assess the nature and extent of acid-generation by Mg-containing WIPP brines.

Testing
Retrieval of metal samples will be done in collaboration with the hydrological testing of near-heater salt cores being proposed (PI: K. Kuhlman). Specifically, we propose to collect corroded metal samples after the adjacent salt cores have been removed. The hydrological testing thrust proposes to collect cores adjacent to: 1. A 4-kW guard heater in Room B; 2. An unheated canister in Room B, and; 3. A 470 W heater in Room A1. We propose to retrieve metal samples from each of these heaters and canister, and also propose collecting additional corroded samples from an unheated canister in Room A1. Where possible, and if the budget allows, repeated sampling of each target will be pursued. Initially heaters/canisters with crushed salt backfills will be targeted. The 4-kW heaters reached 200 - 230^{o}C; the 470-kW heaters reached 70 - 80^{o}C. Heaters were run for 3-5 years. The unheated targets will have corroded under ambient temperatures of ~ 27^{o}C. The chosen targets should therefore record the effect of temperature on steel corrosion over a broad range. Note though that while the unheated targets can be assumed to have corroded at the same temperature for the duration, the heated targets will have seen two temperatures, the high temperatures of the heating test and the subsequent corrosion under ambient conditions. Our hypothesis is that the ambient corrosion rate can be subtracted out of the heater data to resolve high temperature corrosion rates. Later analyses of bentonite-backfilled steels will examine the effect of the bentonite on baseline corrosion.

Corrosion Analysis
Corrosion rates will be estimated by corrosion product mass buildup. Visual and/or optical microscopic measurement of corrosion product thickness will be used along with XRD characterization of corrosion products to estimate the number of moles of iron oxidized per cm^2 of steel. Corrosion products are likely to be magnetite (Fe_3O_4), limonite (FeOOH), and akaganeite (FeO(OH,Cl)) among others (Krumhansl et al., 1991). SEM/EDS with semi-quantitative analysis will also be done to better constrain alteration phase chemistry. Because of

the potential reactivity of reduced Fe phases (for example "green rust"), parallel samples will be taken, sealed in an inert N_2 atmosphere, and their surface mineralogy compared over time with steel samples exposed to the atmosphere. If a difference is observed, subsequent tests will emphasize preventing oxygen access to samples. If sufficient fluid is present at or near the metal corrosion product interface, it will be sampled and analyzed for major elements as well as Fe.

Our initial hypothesis is that the estimated corrosion product mass from the heater tests can be described by the following mass balance:

Corrosion Product Mass (mol/cm^2) = $Time_{heated}$*$Rate_{Hi\text{-}T}$ + $Time_{ambient}$*$Rate_{27oC}$

Where $Time_{heated}$ is the number of years the heater ran; $Rate_{Hi\text{-}T}$ is corrosion rate (mol/cm^{2}year) at the average temperature of heating; $Time_{ambient}$ is the number of years the heater stayed at ambient temperature, and; $Rate_{27oC}$ is the corrosion rate at 27^{o}C. Again, $Rate_{27oC}$, will be determined from the unheated steels.

This approach should provide bulk corrosion rates at 27, 70 - 80, and 200 - 230^{o}C. These rates will then be used with the Arrhenius relationship to determine the operational activation energy of steel corrosion and provide a temperature-dependent predictor of steel corrosion. Note that it will be important to verify any change in corrosion product identity as a function of temperature as it might suggest different corrosion mechanisms.

Rates and mechanisms will be compared against the baseline corrosion test results done on steel coupons (PI: G. Roselle) and from corrosion analyses of canisters that were previously removed.

Acid Generation Analysis

Previous work (Krumhansl et al., 1991) documented the production of fluids with acid pHs (pH 0.7) by heaters in Room B and the potential generation of acids by heating remains a source of concern. Magnesium salts, such as carnallite ($KMgCl_3{:}6H_2O$) in the WIPP are thought to thermally decompose to produce hydrocholoric acid gas, HCl(g), in small quantities:

$$KMgCl_3{:}6H_2O \rightarrow Mg(OH)_2 + KCl + 4H_2O + 2HCl(g)$$

An effort parallel to the corrosion product analysis described above will be a limited effort to detect signatures of HCl generation. Specifically, small samples (< 0.1 g) of the salt adjacent to the corrosion product rind from each of the heaters will be separated, then washed with ~ 3 ml of distilled, deionized water and the pH measured. Our hypothesis is that pHs lower than pH 2 are likely indicators of appreciable acid generation.

References

Krumhansl, J. L., C. L. Stein, G. D. Jarrell, K. M. Kimball (1991) Summary of WIPP room B heater test brine and backfill material data. SAND90-0626.

Table H-12. Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography

1.	**Name of Test:** Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography
2.	**Principal Investigator(s):** Hongwu Xu (LANL), Jonathan Ajo-Franklin (LBNL)
3.	**Test Objectives, Description, and Type (lab, field, etc.):** The goal of the proposed test program is to investigate the coupling between brine migration and salt microstructure and deformation at relevant temperature and pressure conditions. Both ex-situ and in-situ experiments will be conducted. The ex-situ measurements will be done on samples from laboratory brine studies at different stages of the runs (start, end and in-between). For in-situ measurements, environmental cells with controls of temperature, pressure and their gradients will be designed and fabricated. All the three types of water in salt – brine inclusion, grain boundary water, and water bounded with secondary minerals (e.g., clay) – will be investigated. The use of both dynamic neutron and X-ray tomographic imaging will yield complimentary results, as neutron can probe larger, bench-scale samples while X-ray can generally provide higher spatial and temporal resolution.
4.	**R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):** *7.* Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation (rated "high") 18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation (rated "high")
5.	**Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:** • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** 1. Preclosure safety 2. Postclosure safety 3. Confidence-building Brine migration is a critical issue for making the safety case for salt repositories containing high-level waste, as it may potentially result in degradation of the waste system and alteration of salt rheological properties.
6.	**For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?** Previous laboratory studies on brine migration in salt were mostly conducted on thin-section specimens using high-temperature transmitted-light microscopy. Recent development in neutron and synchrotron X-ray imaging techniques enables collection of high-quality 3D data on bulk salt samples (ranging from several mm to several dm in size) that are more representative of geologic materials. In particular, the neutron/synchrotron beamline setups allow incorporation of various environmental cells (which we will design in this project) with controls of not only temperature but pore pressure and stress state as well. The proposed experiments will yield unprecedented data that can serve as input parameters for modeling studies and will support the planned heater tests in the field.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

We propose to characterize the liberation/migration of three types of water (brine inclusion, grain boundary fluid and secondary mineral water) in salt and the effects on salt microstructure and deformation behavior using neutron and synchrotron X-ray tomography. This work includes four parts: 1) Image pristine and crushed (for backfill) salt samples; 2) Image specimens from laboratory brine migration studies (e.g., those done by Caporuscio et al.); 3) Design and fabricate environmental cells (temperature, pressure and/or their gradients); and 4) Perform in-situ time-resolved measurements using the developed cells, focusing on imaging brine migration and alterations in salt microstructure during compression. Systematic measurements will yield new data on brine migration as a function of temperature/temperature gradient, pressure/pressure gradient, and the type of water, and will thus shed lights on the mechanisms of interactions among brine migration, salt microstructure and salt deformation behavior.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

1) Neutron imaging facility at the Los Alamos Neutron Science Center, LANL; 2) Synchrotron X-ray imaging facility (Beamline 8.3.2) at the Advanced Light Source, LBNL; 3) Newly developed environmental cells at both facilities.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

No modeling studies are required for the proposed experiments. To the contrary, the experiments will provide important input parameters and validation datasets for pore- and engineering-scale modeling/simulation of the coupled brine migration and salt deformation processes.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Host rock (including halite and coexisting, hydrous minerals such as clay); backfill; EDZ; waste package

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The obtained data may be applied to all the processes (both preclosure and postclosure). Brine migration depends on many factors/parameters (temperature, pressure, stress, and their gradients) that vary with the thermal load of waste package, the distance from the waste and that from the EDZ. It is also dependent on the type of the salt (host rock vs. crushed salt) and the kind of water (brine inclusion, grain boundary fluid and secondary mineral water). Series of experiments will be conducted to address various scenarios.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-13. Validation of Constitutive Models and Parameterization of Unsaturated Brine Flow in Intact and Crushed Salt

1.	**Name of Test:** Validation of constitutive models and parameterization of unsaturated brine flow in intact and crushed salt
2.	**Principal Investigator(s):** Kris Kuhlman (SNL); Bwalya Malama (SNL)
3.	**Test Objectives, Description, and Type (lab, field, etc.):** **Objectives:** (1) To test validity and (2) determine parameters of constitutive models for multi-phase/multi-component brine flow in intact and crushed salt, under different thermal, compaction, and confining stress (mechanical) conditions. **Description:** No data exist to parameterize "unsaturated" (multi- phase/component immiscible flow of brine and vapor/air) flow of brine in salt. Numerical simulation models require constitutive models and the associated input parameters, specifically, the (1) moisture retention curve (i.e. capillary pressure versus saturation relation) and (2) variation of brine/air permeability as a function of saturation. We propose laboratory tests to provide salt-specific data, taking into account thermal and mechanical loading, to validate the use of traditional moisture retention curve and unsaturated permeability models (e.g., the models of Brooks & Corey, and van Genuchten). Additionally, power-law based porosity-permeability relationships (e.g., Kozeny-Karman), and aperture-permeability relationships (e.g., the cubic law), under variably saturated conditions, need to be evaluated. **Type:** Laboratory scale test
4.	**R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):** 7. Brine and vapor movement in backfill and emplacement drift 32. Appropriate representation of coupled processes in process models
5.	**Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:** • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** (1) Confidence-building for constitutive models and the input parameters used in brine-air-vapor flow modeling, (2) Pre-closure safety, and (3) Early post-closure.
6.	**For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?** Numerical modeling of multi-phase/multi-component brine movement in salt depends on constitutive relations to express capillary pressure and relative gas and brine permeability as functions of saturation. Presently, the Brook-Corey-Burdine and van Genuchten-Mualem models are assumed to be valid and parameters borrowed from soils and petroleum literature are used in computations. Their validity for intact or crushed salt has never been tested experimentally. Additionally, the salt-specific input parameters needed for these constitutive models have never been measured (only a few field measurements of air entry pressure in salt and anhydrite have been made). Models also typically depend on traditional relationships between porosity and permeability, and these are often the foundation for constitutive models relating rock stress/strain to permeability (e.g., Kozeny-Karman). These empirical relationships were developed for water flow through silica sands, and have not been validated or parameterized for brine flow in either intact or crushed salt. The proposed tests would provide data to justify use of current models and parameterize them, or show deficiency of the models for salt to encourage development of more appropriate models (e.g., it has been shown in granite rocks, the often-used cubic law breaks down for very small apertures – similar to those in low-permeability salt). Further, the effects that thermal and mechanical loading have on these relationships is largely unknown.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

- For determination of salt-specific moisture retention curves the data collected will be capillary pressure versus brine saturation
- For permeability, capillary pressure differentials and brine flow rates
- Some parameters to be determined are air-entry pressures for intact and crushed salt, residual moisture content, and Brooks-Corey (λ) and van Genuchten parameters (α, n).
- Hysteresis, capillary pressure ranges & sample sizes needed for characterization.
- Gas permeability tests will be conducted at different brine saturation levels. Brine saturation can be controlled through adjusting confining pressure on partially saturated salt cores.
- Total brine content will be estimated by thermogravimentric analysis
- Relative amounts of free (intergranular) and trapped (intragranular and intracrystalline) brine will be estimated using existing SNL nuclear magnetic resonance laboratory capabilities
- Samples from several locations and salt types would be tested to understand the variability of these parameters with amount of anhydrite/clay impurity or between bedded and domal salt.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

(a) For moisture retention curves the instrumentation to be used include (1) Tempe pressure cells for low capillary pressure range (0 to -0.1 MPa), and (2) a Dewpoint potentiometer by Decagon Devices for the intermediate-to-high capillary pressure range (-0.1 to -10 MPa).
(b) Tensiometers will be used to measure capillary pressures. Off-the-shelf instrumentation such as the HYPROP distributed by Decagon Devices will also be used to measure brine flow rates and capillary pressures for determining unsaturated permeability.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

Data collected from the tests will be used to validate existing constitutive models and to parameterize these models. The constitutive models and their parameters are inputs to the multi-phase/multi-component brine flow numerical codes used in PA and for simulating coupled hydro-thermo-mechanical processes.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Host rock, backfill, and panel closure systems (e.g., Run-of-mine salt). Tests on host rock will be on intact and crushed salt.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The data applies to the first 200 years, mostly pre-emplacement, preclosure, and early post-closure (once the salt is completely healed and the system is back to complete saturation, at late-time beyond 200 years, these processes will be less important)

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-14. Stability of Polyhalite in the Salado Formation

1. Name of Test: Stability of Polyhalite in the Salado Formation

2. Principal Investigator(s): Florie Caporuscio (LANL)

3. Test Objectives, Description, and Type (lab, field, etc.):

Laboratory investigation to understand the stability of polyhalite at elevated temperatures and pressures. The polyhalite bed just below the emplacement drift is actually a mixed mineral layer (anhydrite 70%, polyhalite 30%). Thus structural water in the minerals may be liberated due to increased temperatures. Experiments would involve hydrothermal Dickson cells to recreate repository P,T conditions, XRD and SEM analyses, geochemical analyses and calorimetry determinations to identify the stability of polyhalite and evolution of water at elevated temperatures.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

#4 - Changes in chemical characteristics of brine in the backfill and EBS
#7 - Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
#14 - Stratigraphy and physical-chemical properties of host rock
#18 - Brine and vapor movement through the host rock and EDZ, including evaporation and condensation

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety
2. Confidence-building

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

The polyhalite beds below the emplacement drift were misidentified in terms of mineralogy. Stability of polyhalite in the Salado Formation is largely unknown. Thermodynamic data for polyhalite is scarce and conflicting while none is available for WIPP specific polyhalite.

The stability of polyhalite at increased temperatures is important to understand, since dehydration of this mineral would liberate 6 weight percent water. This amount of water could have significant effects on backfill stability, potential corrosion of canisters, and general brine migration.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

Experimental – T, P – every minute, per length of experiment (6 weeks)
XRD mineral ID- JCPDS files
Mineral stability- XRD- elevated T, variable humidity- 25°C intervals, from 25 - 300°C. Humidity 25-95%
EMP analyses – major elements +/- 0.01 wt%, trace elements +/- 0.005 wt %
SEM - textural and petrogenic images, EDX chemistry spectra
Differential Scanning Calorimetry (DSC) and Thermogravimetry (TG) – dehydration temperatures, enthalpies and associated weight losses
High-temperature Drop-Solution Calorimetry – formation enthalpy (H) measurements and phase stability determination

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

All instrumentation at LANL GGRL building (except the high-temperature drop-solution calorimeter, which is in TA-35):

- Dickson pressure vessels- Creates high P,T conditions for gold reaction vessels
- EMP- chemical analyses at 10 micron beam scale
- SEM – 5 – 100 micron scale imaging and chemical spectra
- XRD- mineral identification and lattice parameters at STP conditions.
- XRD temperature cell – mineral identification at variable temperatures and relative humidities.
- DSC/TG - dehydration temperatures, enthalpies and associated weight losses
- High-T drop solution calorimeter – determination of the enthalpies of formation

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

All experimental data will be fed to 1) constitutive, 2)process, and then 3) coupled process (FEHM) models

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Determination of polyhalite stability and water release by dehydration (which may occur in backfill, drifts and pristine host rock) will affect both chemistry and physical characteristics of the system features listed.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

This data set, at temperatures from 25-300°C and 150 bar and subsequent quench, will have applicability from preclosure to long term post closure (10,000 years), depending on individual experiment designs.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-15. Stability of Hydrous Phases (Corrensite, Bassanite) in the Salado Formation

1. **Name of Test:** Stability of Hydrous phases (corrensite, bassanite) in the Salado Formation – Applicable for SDDI waste emplacement studies

2. **Principal Investigator(s):** Florie Caporuscio (LANL)

3. **Test Objectives, Description, and Type (lab, field, etc.):**

   Laboratory investigation to understand the stability of corrensite, smectite, and bassanite at <100°C temperatures and repository pressures. Corrensite, smectite (clays), and bassanite (a metastable sulfate) are water rich minerals found in the Salado formation. Thus structural water in the minerals may be liberated at temperatures between 40 and 95°C. Experiments would involve XRD environmental cells, SEM and TEM analyses along with geochemical analyses to identify the stability of corrensite and bassanite and evolution of water at <100°C temperatures. XRD Environmental cell experiments will be run at 5°C intervals and stepped humidity values to collect a very precise T/ RH stability field for the 3 mineral phases.

4. **R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):**

   #4 - Changes in chemical characteristics of brine in the backfill and EBS
   #7 - Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
   #14 - Stratigraphy and physical-chemical properties of host rock
   #18 - Brine and vapor movement through the host rock and EDZ, including evaporation and condensation

5. **Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:**
   - **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

   1. Confidence-building
   2. Postclosure safety

6. **For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?**

   Stability of corrensite, smectite, and bassanite at <100°C temperatures and repository pressures are largely unknown. Thermodynamic data for corrensite and bassanite are scarce and conflicting, while none is available for WIPP specific chemistries.

   The stability of corrensite, smectite, and bassanite at <100°C is important to understand, since dehydration of these minerals would liberate a total of > 7 weight percent water. This amount of water could have significant effects on backfill stability, potential corrosion of canisters, and general brine migration.

7. **Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):**
   - **Describe how the data will be collected**

   XRD mineral ID- JCPDS files (pre experiment)
   Mineral stability- XRD cell - elevated T, variable humidity- 5°C intervals, from 25 - 100°C. Humidity 25-95%. XRD Environmental cell experiments will be run at 5°C intervals and stepped humidity values to collect a very precise T/ RH stability field for the 3 mineral phases.
   EMP analyses – major elements +/- 0.01 wt%, trace elements +/- 0.005 wt %
   SEM - textural and petrogenic images, EDX chemistry spectra
   TEM – Determine crystal structure and crystal chemistry of reaction minerals
   High-temperature Drop-Solution Calorimetry – formation enthalpy (H) measurements and phase stability determination

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

- EMP- chemical analyses at 10 micron beam scale
- SEM – 5 – 100 micron scale imaging and chemical spectra
- XRD- mineral identification and lattice parameters at STP conditions.
- XRD temperature cell – mineral identification at variable temperatures and relative humidities.
- High-T drop solution calorimeter – determination of the enthalpies of formation

9. Define the pre-and post-test modeling/simulation needs for the activity, including:
- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

All experimental data will be fed to 1) constitutive, 2) process, and then 3) coupled process (FEHM) models

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Determination of corrensite, smectite, and bassanite at <100°C temperatures and water release by dehydration (which may occur in backfill, drifts and pristine host rock) will affect both chemistry and physical characteristics of the system features listed.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:
- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

This data set, at temperatures from 25-100°C and low pressure will have applicability from preclosure to long term postclosure (10,000 years), depending on individual mineral dehydration temperatures.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-16. Use of Ultra-Low Field (ULF) Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)) to Map and Quantify Brine Content in an Undisturbed Salt Core

1. Name of Test: Use of ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)) to map and quantify brine content in an undisturbed salt core**.**

2. Principal Investigator(s): Florie Caporuscio (LANL)

3. Test Objectives, Description, and Type (lab, field, etc.):

The objective of the test described here is to use a non-destructive method (ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)) to map and quantify brine content in an undisturbed salt core. This technique is portable, inexpensive and can be adjusted to any size core sample. The technique relays on a pulsed pre-polarization method, followed by detection via optimized pick-up coils in a low magnetic field. This laboratory technique can be utilized to detect variations in water transport trough a salt core including variations induced by a temperature gradient.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

#7 - Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
#18 - Brine and vapor movement through the host rock and EDZ, including evaporation and condensation

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety
2. Confidence-building

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Studies on brine migration in intact salt subjected to temperature gradients predict that brine transport will be affected by the nature of the brine inclusion, the temperature gradient, the physical properties of the salt, and the mineralogical compositions of the salt. However, many uncertainties remain on the rate of brine migration, brine behavior at grain boundaries, and the behavior of water associated with secondary minerals. Quantitative data on brine migration in an intact heterogeneous salt are not available. The data available in the literature were performed on small scale samples and often under represent the complexity and heterogeneity of real salt samples. We propose to use ultra-low field (ULF) nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) to monitor in real time brine movement in an intact undisturbed salt core. This will add to our understanding of brine migration in salt and especially the contribution from water associated to secondary minerals.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

- Brine distribution and water content
- Changes in brine distribution as a function of temperature gradients and time
- Petrographic analysis of salt core specimens post heating

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

- Custom built ultra-low field nuclear magnetic resonance ((ULF- NMR)
- Temperature controllers and a custom built heating stage
- Optical microscopy

9. Define the pre-and post-test modeling/simulation needs for the activity, including: • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)** The data generated will bridge an important data gap that exist between brine migration in a single crystal and associated modeling and large scale modeling of brine migration in salt.
10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.): The testing described here will benefit understanding brine migration in the pristine salt, the backfill salt and EDZ.
11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure: • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** The data generated will benefit understanding brine migration under a temperature gradient and is relevant to both pre-closure conditions and to long term post closure.
12. For field tests define additional lab tests or other separate activities/data needed to support this test: N/A

Table H-17. Elevated-Temperature Measurements of Plutonium(III) and Neodymium(III) Solubility in Low to Moderate Ionic Strength Aqueous Solutions

1. **Name of Test:** Elevated-Temperature Measurements of Plutonium (III) and Neodymium(III) Solubility in Low to Moderate Ionic Strength Aqueous Solutions.
2. Principal Investigator(s): Jonathan Icenhower and David Shuh (LBNL); Donald Reed (LANL)
3. Test Objectives, Description, and Type (lab, field, etc.): The objective of these experiments is to generate solubility data for Pu(III) over a temperature (50 to 200°C) and ionic strength range (0 to 0.010 m NaCl, $MgCl_2$) pertinent to disposal of heat-emanating radioactive waste in a salt repository. Experiments will be carried out in a titanium Parr reactor at 50, 100, 150 and 200°C.This temperature range not only covers the likely repository temperature interval expected from disposal of both defense high-level waste (EM responsibility) and civilian used nuclear fuel (NE responsibility), but also provides a way to retrieve the thermodynamic data needed for modeling the fate and transport of Pu(III) in the repository. Experiments will be conducted from both undersaturation and supersaturation directions. The initial experiments will be conducted using the non-radioactive analog element Nd(III) before moving on to Pu(III).
4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues): Issue 12: *Radionuclide solubility in the waste package and EBS*: Rated "High" for postclosure.
5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case: • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** 1. Postclosure safety. 2. Confidence-building. 3. Preclosure safety
6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary? These data are necessary for understanding and predicting the fate and transport of Pu(III) in the waste package and EBS. No previous data on Pu(III) solubility exists above 25°C. Plutonium will likely be manifested as Pu(III) because the presence of anaerobic bacteria and the concentration of aqueous Fe(II) will prevent higher Pu oxidation states. Although some Pu(IV) is possible, the higher relative solubility of Pu(III) (~100×) for the conditions expected in the repository makes this valence state the most important one to study. Previous data have not been generated because experiments at higher temperature and pressure are difficult to perform. Note also that the solubility of Pu cannot be extrapolated accurately to higher temperatures and pressures because the existing thermodynamic database lacks the necessary parameters. For example, previous work has shown that experimentally-derived solubility data for Hf(IV) did not match values extrapolated from geochemical codes. Accordingly, experimentally-determined data are vital.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):
- **Describe how the data will be collected**

Solubility data will be determined by measuring the Nd(III) or Pu(III) concentration in the reactor by ICP-MS methods. Concentrations in the ppt and ppq range are possible, which is more than 1,000-fold better than solubility studies carried out in the 1990's. Measuring the solute concentrations over time will ensure that equilibrium has been obtained (constant concentration over a time interval). Several methods for treating solids can be used. In the case of neodymium, we can start out with crystals of anhydrous Nd_2O_3, which are unstable in aqueous solution. These will be loaded along with the solution into the reactor. These crystals can be partially dissolved at a higher temperature (e.g., 300°C) and then the system will be cooled to the temperature of interest. New material, $Nd(OH)_3$, will precipitate on the undissolved Nd_2O_3, effectively isolating Nd_2O_3 from solution and further reaction. A low concentration of a contrasting agent, such as Gd(III) can also be added to the solution and Gd(III) will be present in the newly precipitated $Nd(OH)_3$. After terminating the experiment the solid material will be set in epoxy resin and polished to expose the core of Nd_2O_3 and the rim of $Nd(OH)_3$. We will image the material using a Scanning Electron Microscope (SEM) equipped with an Energy Dispersive Spectrometer (EDS) or by using micro X-ray Fluorescence (μXRF) at the Advanced Light Source. The presence of sharp crystallographic boundaries and the detection of Gd(III) in the overgrowths will unambiguously show that the solids grew under equilibrium conditions. Another way to conduct the experiments is to precipitate $Nd(OH)_3$ crystals using standard methods (identity checked by X-ray diffraction) at room temperature. We will then load the reactor with the $Nd(OH)_3$ crystals and solution and run the experiment at temperature. The crystals will dissolve until the solution reaches saturation (so-called "undersaturation" direction). In this case, the only indication of equilibrium will be constant aqueous Nd(III) concentration over a time interval. In the last type of experiment we will use a solution that is already supersaturated in $Nd(OH)_3$ and allow it to reside at the temperature of interest until the aqueous Nd(III) concentration becomes constant over time (so-called "supersaturation" direction). Although these last two types of experiments are less rigorous, they are the standard methods and are much simpler. We plan to employ all of these methods for both Nd(III) and Pu(III), as time and funding warrants, and will provide guidance on best practices for future studies on other radionuclides.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

As described above, the instruments include the Parr reactor, ICP-MS, SEM, XRD and a beamline at the Advanced Light Source. All of these capabilities are available for our use at LBNL.

9. Define the pre-and post-test modeling/simulation needs for the activity, including:
- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

No modeling activities are anticipated in this investigation.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Although these experiments are relevant to waste package studies, we will begin without the complications of the presence of corrosion products from canisters or spent fuel and their analogs.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:
- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The most applicable time period will be well into the postclosure period, when enough time has elapsed for the potential breech of steel canisters containing radioactive waste. We acknowledge that by this time the disposal system will have cooled significantly from its peak temperature, but can still be significantly above 25°C (50 – 100°C). Certain early-failure or human intrusion scenarios might make necessary solubility assessments at even higher temperature, close to peak temperature. We also reiterate that making measurements over a wide temperature interval is necessary to extract robust thermodynamic data.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-18. Laboratory Study on the Long-term Porosity and Permeability Reduction in Salt Backfill Under Elevated Temperature Conditions

1. **Name of Test:** Laboratory Study on the Long-term Porosity and Permeability Reduction in Salt Backfill Under Elevated Temperature Conditions

2. **Principal Investigator(s):** Tim Kneafsey and Seiji Nakagawa, LBNL

3. **Test Objectives, Description, and Type (lab, field, etc.):**

We propose to investigate the compaction of granular (mine-run) salt backfill under small to moderate stress and elevated temperature conditions (up to ~200°C). The primary objectives of this study are to (1) evaluate the rate of compaction and permeability reduction of the backfill at elevated temperatures with strong temperature gradients, (2) examine the impact of fluid content and boundary conditions (open vs closed system for heat and moisture transport), and (3) investigate the impact of clay content on the rate of porosity/permeability reductions. Laboratory experiments will be performed on packs of granular repository salt within a temperature-controlled pressure vessel for an extended period of time up to 1-2 months. Reduction of the porosity will be determined periodically via x-ray CT imaging of the remaining pore space in the packs, and the permeability of the pack will be measured via air permeability tests. Seismic velocity of the packs will be also measured so that the changes in the grain contacts can be quantified. Multiple electrodes will be placed in the sample allowing assessment of local electrical conductivity (inverse of resistivity) to aid in monitoring brine migration. The experimental boundary conditions will include both uniform heating of the sample and application of a thermal gradient so that the effect of water migration within the sample can be investigated. Experiments will be conducted with closed and open boundaries to ensure that the impact of moisture losses into open tunnel sections is well understood. The experiment will also investigate the impact of clay in the salt pack, which is expected to accelerate the rate of compaction resulting from the pressure dissolution of the grains.

4. **R&D Issue(s) Addressed by Test (field tests should include one or more “H”-rated issues):**

a. EBS Issue 3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement.
b. EBS Issue 7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
c. Modeling Issue 33. Appropriate representation of coupled processes in TSPA model

5. **Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:**

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety
2. Preclosure safety
3. Confidence-building

The compaction and permeability evolution of salt backfill at realistic repository conditions is a critical issue for making the safety case of a salt repository for both defense high-level waste and used nuclear fuel.

6. **For the proposed test describe the current “state of the art” knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?**

Studies on the behavior of backfill materials have been mostly conducted at ambient conditions. A recent experimental campaign by Olivella et a. (TIPM, 2011) examined porosity changes in salt resulting from the application of a thermal gradient (temperatures up to 85°C). The samples used have been relatively wet (S=40%). In our tests, we will investigate porosity/permeability changes over a wider range of conditions, representative of a moderate to strongly heated repository with temperatures up to 200°C, the impact of clay inclusions, and vented and unvented moisture conditions.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

  - Moisture removed from the system will be sorbed and analyzed gravimetrically. These measurements will be made as needed, likely more frequently early in the tests.
  - Porosity will be quantified using X-ray computed tomography. To the extent possible, moisture movement corrections will be applied from post-test gravimetric analyses. The X-ray CT measurements will be made regularly, at reasonable intervals.
  - Seismic velocities will be measured either using a Split-Hopkinson Resonance Bar apparatus, or ultrasonically. These measurements will be made frequently (daily to weekly depending on the rate of change).
  - Gas permeability will be measured by applying a known airflow through the sample and measuring the differential pressure generated. These measurements will be made intermittently over the course of a test.
  - Porosity will be quantified using X-ray computed tomography. The X-ray CT measurements will be made regularly, at reasonable intervals guided by permeability and seismic velocity measurements.
  - Moisture migration will be measured using electrical conductivity across multiple pairs of electrodes (simple electrical resistance tomography) and from post-test gravimetric analyses.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

- A customized core holder capable of applying elevated temperature and pressure will be built and used.
- A medical X-ray CT scanner will be used to investigate core-scale structural heterogeneity (fractures, clay particles, seams)
- Ultrasonic measurement equipment will be used to investigate the mechanical property changes in the core (mounted in endcaps)
- Electrical conductivity measurement equipment will be used to examine the electrical conductivity of the core (endcaps and distributed electrodes)
- Ancillary equipment for providing and controlling temperature and pressure and for acquiring data

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

No modeling required for the activity.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Backfill is the major feature involved. Backfill is granular mine-run salt. Different salt types may be tested (including hydrous minerals such as clay). Test conditions will be realistic representations of emplacement conditions.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The obtained data may be applied to all the processes (both preclosure and postclosure).

12. For field tests define additional lab tests or other separate activities/data needed to support this test:
N/A

Table H-19. Mechanistic Modeling of Brine and Vapor Movement

1. Name of Test:
Mechanistic modeling of brine and vapor movement

2. Principal Investigator(s): Qinjun Kang (LANL)

3. Test Objectives, Description, and Type (lab, field, etc.):

Brine processes (e.g., migration towards the heat source, water-vapor phase transition) may significantly change the salt microstructure and rheological properties, and hence affect repository performance. The objectives of this test are to provide a systematic study of the effect of various factors on the behavior of brine inclusions (e.g., temperature gradient, size and shape of the brine inclusion, salt self-sealing/healing at the grain boundaries and fractures), and to help interpret experimental results, guide the design of new experiments, and provide constitutive relationships for engineering-scale simulations.

4. R&D Issue(s) Addressed by Test (field tests should include one or more “H”-rated issues):

#7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
#18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation
#31. Appropriate constitutive models (e.g., Darcy flow; effective stress)

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety
2. Confidence-building

Movement of water and vapor can lead to degradation of the waste system or to a significant alteration of the rheological properties of the salt. Without a quantitative understanding of the controlling processes that lead to the migration of water toward the waste disposal package, we will not be able to rule out the possibility of large quantities of corrosive water coming in contact with the waste package, leading to a breach of the package and escape of radionuclides into the repository environment. Also a fundamental understanding of the changes in salt rheological properties resulting from brine and water movement is essential to demonstrating understanding of the evolution of the processes of crushed salt reconsolidation and healing of the EDZ.

6. For the proposed test describe the current “state of the art” knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

To date, the problem of water and vapor movement has been tackled only with simplified analytical models that leave out important physics and chemistry – the full problem has been viewed as being intractable. The proposed test, with its preliminary results, is showing the way toward a full accounting of all of the important physical/chemical processes, enabling a far more realistic treatment of this phenomenon than has been possible in the past.
In addition, flow and transport of gas molecules in nanopores are strongly affected by non-continuum effects, which cause the conventional continuum model based on the Darcy equation to fail. The proposed test will account for the slip effect at the vapor-solid interface in nanoscale pores, and will provide new constitutive models for engineering-scale modeling.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

Constitutive models for permeability-porosity, stress-strain, etc. will be derived directly from the pore-scale modeling.

8.	**Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:** N/A – theoretical and modeling study only
9.	**Define the pre-and post-test modeling/simulation needs for the activity, including:** • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)** Constitutive models for water release from crushed and EDZ salt would be developed based on the underpinning theory and models developed.
10.	**List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):** Backfill; EDZ.
11.	**Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:** • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** Pre-closure and early post-closure – from time of emplacement until the crushed salt and EDZ system seals itself (0 to ~1000 y)
12.	**For field tests define additional lab tests or other separate activities/data needed to support this test:** N/A

Table H-20. THM Optimization of Preclosure Repository Design

1. Name of Topic: THM Optimization of Preclosure Repository Design
2. Principal Investigator(s): Jonny Rutqvist and Laura Blanco-Martin (Lawrence Berkeley National Laboratory) Phil Stauffer and Florie Caporuscio (Los Alamos National Laboratory)
3. Test Objectives, Description, and Type (lab, field, etc.): The objective of this study is to develop and compare preclosure moisture design and operation strategies to optimize the system for preclosure and postclosure THM behavior. Brine mobilization and migration is of concern in a salt repository for heat-emanating waste such as defense high-level waste and civilian used nuclear fuel. This proposal plans to investigate possibilities of engineering solutions to manipulate (reduce) the moisture conditions in the near-field salt. Such solutions may include optimized ventilation designs, brine drainage options, engineered seals, or the addition of hygroscopic minerals to the backfill. For example, ventilation during waste emplacement and early operation will reduce the relative humidity, thereby drying out moisture from the backfill and the surrounding rock. Drying is also expected to impact the mechanical behavior of the excavation since the convergence rate, crushed salt compaction rate, and self-sealing of the disturbed zone depends on the moisture content. Evaluation of different options will be conducted using coupled processes modeling for studying the benefit and potential consequences of engineering designs.
4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues): The proposed research addresses a wide range of "H"-rated issued listed under different categories below: *Wastes and Engineered Features (EBS) Feature/Process Issues:* 3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement 5. Mechanical response of backfill 7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation *Natural Barriers (Host Rock and EDZ) Feature/Process Issues:* 15. Changes in physical-chemical, properties of host rock due to excavation, thermal, hydrological, and chemical effects 16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation) 17. The formation and evolution of the EDZ 18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation *Repository System (EBS and NBS combined) Feature/Process Issues:* 23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere) 28. Performance of seal system *Confidence-Building Issues:* 43. Develop generic safety case
5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case: • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** 1. Postclosure safety: for prediction of long-term sealing behavior including brine migration. 2 Preclosure safety: for design and optimization of the pre-closure engineering measures such as ventilation. 3. Confidence-building: application of model to long-term predictions with uncertainty analysis.

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Significant brine inflow into open excavations has been observed during various heater experiments, especially in bedded salt. Modeling also shows that over time moisture will migrate from the surrounding rock into the granular salt backfill where it can accumulate and trapped by the converging tunnel. The potential for using ventilation, drainage, and seals for removing moisture during the preclosure period has not been investigated. This could provide clear strategies for optimizing the postclosure behavior of the system in terms of moisture evolution within the repository tunnel and how the moisture evolution might impact the long-term mechanical evolution, including large strain convergence and self-sealing.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

THM simulation results for generic repository cases over thousands of years, including how preclosure ventilation and other moisture manipulation options may impact brine and vapor movement and how in turn impacts the performance of the system, including convergence, disturbed zone evolution, and self-sealing.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

N/A

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

This proposal involves coupled processes model with advanced constitutive model for the evolution of stress, strain, potential damage, and long term healing and sealing.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Includes near field repository features, including waste overpack, granular salt backfill, host rock with disturbed zone, and seals (plugs).

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The model simulations are focused on preclosure and early postclosure, but consequences for the long-term postclosure behavior will also be investigated.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

Task can be started using available literature data and sensitivity studies, in particular related to brine and vapor transport in salt host rock and backfill and how convergence, creep, healing depends on moisture content and temperature. Any new laboratory data on water retention properties, brine movements and creep under different moisture contents would be appreciated.

Table H-21. Benchmarking Simulations for THM Behavior of Rock Salt

1. Name of Topic: Benchmarking Simulations for THM Behavior of Rock Salt
2. Principal Investigator(s): Jonny Rutqvist and Jens Birkholzer (LBNL) Phil Stauffer and Bruce Robinson (LANL) Carlos Jove-Colon, Kristopher Kuhlman, and Ernest Hardin (SNL)
3. Test Objectives, Description, and Type (lab, field, etc.): The goal of this study is to have different modeling teams with their different THM codes simulate a series of THM rock salt modeling problems in a benchmarking exercise. The objective is to compare advanced models and methodologies, evaluate importance of individual modeling choices (i.e., conceptual models, weak or link coupling, complexity), demonstrate validity of assumptions and approaches, and increase confidence in results. While complementing ongoing TM benchmarking studies, this proposal places focus specifically on the brine mobilization and migration processes and their two-way coupling to temperature changes and mechanical deformation. A first stage in this new benchmarking effort would be to identify, select, and define modeling test cases envisioned within a multi-step approach: (1) conduct model-to-model comparison for THM processes in a generic simplified repository setting, (2) perform model-to-model and model-to-data comparisons for a selected THM laboratory/field experiment (e.g., Kuhlmann and Malama, 2013), (3) move into a final benchmarking phase in which different modeling groups will conduct comparative model simulations for the planned SDDI experiment. This will provide valuable monitoring data on THM processes with focus on brine migration and vapor phase transport. It is recognized that brine mobilization and migration is also controlled by chemical processes, in particular at elevated temperatures, and that inclusion of "C" will be a valuable addition to the benchmarking exercise. The proposal therefore comprises a designated task of developing and executing a test plan for inclusion of chemistry in the benchmarking simulations, either integrated as part of the THM test cases or as a separate "chemical" benchmark on predictions of brine chemistry at various conditions. Note that the study would be open to all interested US and international modeling groups, e.g., from Germany.
4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues): 7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation 15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects 16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation) 17. The formation and evolution of the EDZ 18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation
5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case: • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** 1. Postclosure safety 2 Preclosure safety 3. Confidence-building

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

Model benchmarking exercises help refine implementation and increase confidence in complex predictive studies. DECOVALEX is an example of an ongoing international model comparison project, but it has not involved rock salt. German researchers have conducted model comparisons since 2004, with emphasis on constitutive models for thermo-mechanical behavior in salt. In a US-German collaboration, several of these groups are currently engaged with Sandia National Laboratories to conduct thermo-mechanical benchmark simulations for WIPP related modeling problems (Rooms B and D). In the mid-1990s, the Swedish INTRAVAL project has included attempts to match observed isothermal brine inflow to small-diameter boreholes at WIPP (SAND97-0788). Another model comparison has also been conducted using data from the large-diameter isothermal WIPP brine inflow experiment (SAND96-0561). What has been missing to date is a benchmarking exercise that would specifically address the complexities of adding "H" (and "C") to the thermo-mechanical problems, placing emphasis on the mobilization and migration of brine.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

The main result from the benchmarking study will be an understanding of the similarities and differences in THM (and C) model predictions for several test problems, an evaluation of the reasons for differences between individual models as well as between models and data, and an overall assessment of prediction uncertainty.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

N/A

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

N/A

10. List system features involved in test(e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

May include granular salt backfill and host rock with disturbed zone.

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

Will depend on exact nature and definition of benchmarking test cases.

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-22. THM Model of Salt Rock Microstructural Damage and Healing

1.	**Name of Test:** THM Model of Salt Rock Microstructural Damage and Healing
2.	**Principal Investigator(s):** Daisuke Asahina and Jim Houseworth (Lawrence Berkeley National Laboratory)
3.	**Test Objectives, Description, and Type (lab, field, etc.):** The objective is to develop detailed modeling capabilities for mechanistic microstructure modeling of coupled processes in salt, including visco-plastic creep and micro-fracture damage evolution under shear stress at elevated temperatures conditions and impact on brine mobilization and migration. When salt is placed under conditions of sufficient shear stress, rock damage occurs as a result of grain-boundary opening referred to as dilatancy. Rock permeability increases dramatically as microfractures along grain boundaries become globally connected. The model representation of thermal, hydrological, mechanical, and micro-damage processes is done at the microstructural scale where salt grains are represented by Voronoi polyhedral cells for mechanical and fracture damage, as well as for thermal conduction. Heterogeneous conditions in which clays or other hydrous porous minerals occupy a portion of the salt formation are incorporated as discrete features. Thermal-hydrological processes within salt grains may be included in the model to examine the potential mobilization of intragranular fluid inclusions. THM processes in the microstructure model will be solved with the existing TOUGH2-RSBN model developed at LBNL, which computes mechanics and fracture damage using a Rigid-Body-Spring-Network method. The impact of dilatancy and damage on flow and transport is represented directly in the TOUGH2 model through the introduction of fracture cells along grain boundaries as damage occurs. Thermal-hydrological processes are treated in the microfracture network. The ultimate goal is to predict, at a fundamental level, permeability damage in salt rock in terms of a discrete microfracture network that evolves in response to coupled THM processes, and to provide better constitutive relationships of THM parameters for larger-scale continuum models.
4.	**R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):** 15. Changes in physical-chemical, properties of host rock due to excavation, thermal, hydrological, and chemical effects (rated "high") 17. The formation and evolution of the EDZ (rated "high") 18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation (rated "high") 31. Appropriate constitutive models (e.g., Darcy flow; effective stress) (rated "high") 34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models (rated "high")
5.	**Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:** • **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)** 1. Preclosure safety 2. Postclosure safety 3. Confidence-building Permeability damage in the EDZ of salt rock is a critical issue for making the safety case of a salt repository for defense high-level waste *and* used nuclear fuel, as it may potentially enhance brine migration, associated degradation of the waste system, and radionuclide transport away from the waste emplacement zones.

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

The current state of the art treats permeability evolution in the EDZ of a salt rock as constitutive (often empirical) relationships between effective confining stress and dilatant volume strain. However these relationships have only been tested for relatively simple conditions of rock stress and have not been fully extended to include effects of thermal processes or inhomogeneities in the salt rock. A more detailed micro-structural modeling approach is necessary as more and more complexity is added into a temporally-evolving system responding to multiple coupled processes. This is also looking forward to future model development which would include chemical coupled processes that play an important role in healing processes in salt.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):

- **Describe how the data will be collected**

A relatively narrow region representing the near-field of an emplacement drift in rock salt will be modeled in detail to investigate the generation of dilatant rock damage. The model will be conducted to investigate a range of conditions representative of a post-closure repository setting, including the effects of waste heat. The mechanical constitutive model will include variable saturation and temperature effects and will include visco-elastic creep processes. Thermal-hydrological effects including vaporization/condensation and two-phase relative permeability are to be modeled. The modeling results will show the temporal and spatial development of a microfracture-damaged rock as well as the behavior of brine and vapor flow processes in the EDZ.

8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout:

N/A

9. Define the pre-and post-test modeling/simulation needs for the activity, including:

- **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)**

Because this is a modeling proposal, it seems appropriate here to discuss experimental work that would enhance the value of the modeling product. Laboratory experiments are needed to measure the changes in permeability and porosity undergoing dilatant fracturing in a salt sample. These factors should be investigated as affected by temperature, stress conditions and pore pressure in the intruding fluid. Current work at LANL visualizes via optical methods brine migration processes at appropriate scale to be used for model comparison. Also, results from imaging brine migration and alterations in salt microstructure via tomographic methods as described in the test proposal questionnaire "Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography" (Table H-12) by Hongwu Xu (LANL), Jonathan Ajo-Franklin (LBL) could be compared with computed salt damage and fluid flow from the TOUGH-RBSN simulator.

10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):

Host rock (including halite and coexisting, hydrous minerals such as clay); EDZ

11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure:

- **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.**

The data obtained from this work may be applied to all the processes (both preclosure and postclosure). Conditions in the EDZ depend on many factors/parameters (temperature, pressure, stress, and their gradients) that vary with the thermal load of waste package, the distance from the waste, etc. It is also dependent on the type of the salt (homogeneous halite as found in diapiric salt bodies or more heterogeneous salt rock as found in bedded salt bodies).

12. For field tests define additional lab tests or other separate activities/data needed to support this test:

N/A

Table H-23. Brine Migration in Salt: Review and Constitutive Model Development

1. Name of Test: Brine Migration in Salt: Review and Constitutive Model Development

2. Principal Investigator(s): Jim Houseworth, Jonny Rutqvist, Hui-Hai Liu, Jens Birkholzer (LBNL)

3. Test Objectives, Description, and Type (lab, field, etc.):

In pure salt rock, brine may be present in intergranular films between salt grains and may occur as fluid inclusions within the salt grains (Kulman and Malama, 2013). Often, salt is found in combination with other evaporites and clays. A number of these minerals can have intergranular water and water bound as part of the mineral structure (e.g., gypsum). In the case of smectite and vermiculite clays, water also occurs within the interlayers of the aluminosilicate sheets. For disposal of heat-emanating waste (e.g., used nuclear fuel, high-level waste), there is concern about temperature-driven brine mobilization and migration affecting performance. For example, the observation that brine in fluid inclusions can migrate toward a heat source was a major focus of the initial investigations of brine migration in salt rock relative to disposal of heat-generating high-level nuclear waste. However, brine migration is subject to a number of different driving forces in addition to temperature. The objective of this proposal is (1) to review existing formulations for the various mechanisms that cause brine migration in salt rock and (2) to develop improved constitutive models based on recent and ongoing research that can be used for implementation into THMC simulators.

The development of constitutive models for brine migration will require an understanding of the behavior of brine migration through interconnected intergranular pore spaces, migration of brine in isolated fluid inclusions, interactions between these two configurations of brine, impacts of mechanical deformation and temperature gradient, and the ways in which clays and other constituents of salt rock contribute to brine migration. Brine movement through interconnected intergranular brine films may be described in terms of traditional Darcy-flow mechanisms associated with flow through porous media, where pressure and gravitational potentials drive fluid flow. However, the possibility of non-Darcy flow through the intergranular pore spaces also needs to be considered because of salt's extremely low permeability. Non-Darcy flow has been reported in low-permeability clay rock and recent investigations have found that flow behavior in nanotubes exhibits non-Darcy behavior (Liu and Birkholzer, 2012). This suggests that flow through the extremely narrow intergranular pore spaces in salt rock may also be subject to a non-Darcy flow mechanism. However, little information is available on this subject. It may be possible to improve on constitutive models for flow through salt rock utilizing constitutive models derived for non-Darcy flow through nanotubes (e.g., Ma et al., 2010; Farrow et al., 2011). This could be done with the proposed model of microstructural flow behavior in salt rock (THM Model of Salt Rock Microstructural Changes Including Discrete Microfracture Formation and Healing) in which flow through intergranular pore spaces are to be modeled explicitly (i.e., a network of nanotubes). Additional factors that drive brine flow include the Soret effect, where brine flux is driven by the temperature gradient, as well as osmotic couplings caused by chemical potential gradients. Finally, inter and intra-granular brine may also be found in association with a non-condensable gas phase and may require consideration of two-phase flow.

The distinctive characteristic of salt rock is the relative ease at which the rock can dissolve into aqueous solution as compared with many other rock types and can affect significantly brine migration. Salt dissolution is subject to various thermodynamic conditions that can affect the solubility. Salt solubility increases with temperature such that temperature gradients result in disequilibrium in salt concentrations within the aqueous phase. Therefore, a fluid inclusion will have higher equilibrium salt concentrations at the high-temperature side of the inclusion as compared with the low-temperature side. This sets up a concentration gradient that drives salt diffusion from high to low temperatures, and results in dissolution of salt at the high-temperature end of the inclusion and precipitation of salt at the low-temperature end. This dissolution-diffusion-precipitation process leads to thermal migration of isolated fluid inclusions that has been well-documented (Roedder and Chou, 1982). However, temperature is not the only thermodynamic condition that alters solubility; pressure and chemical potential also play a role and can also lead to analogous migration behavior (Urai et al, 2008). The migration of aqueous phase essentially "through" salt rock by dissolution-diffusion-precipitation affects not only fluid inclusions but also grain-boundary brine as well. When fluid inclusions and grain boundaries migrate they can also collide, leading to interactions between these different brine configurations in salt rock. Complex relationships have been observed regarding the ability of such collisions to result in, for example, incorporation of the fluid inclusion brine into the grain-boundary brine, or alternatively that the fluid inclusion passes through the grain boundary essentially unaffected (Schenk and Urai, 2005). This information needs to be reviewed and analyzed to develop constitutive relationships that account for these processes in a continuum scale that is more relevant to models for performance assessment. Laboratory studies visualizing temperature-driven brine migration are currently conducted within the UFD campaign and will be interpreted for the purpose of model development.

4. R&D Issue(s) Addressed by Test (field tests should include one or more "H"-rated issues):

18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation (rated "high")
31. Appropriate constitutive models (e.g., Darcy flow; effective stress) (rated "high")
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models (rated "high")

5. Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:

- **List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)**

1. Postclosure safety
2. Confidence-building

Brine migration is a critical issue for making the safety case of a salt repository for high-level waste because it plays a key role concerning the amount of brine that interacts with the waste and is available for radionuclide transport.

6. For the proposed test describe the current "state of the art" knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?

While past studies have made some important observations for brine migration and some simple mathematical relationships have been developed (e.g., Kuhlman and Malama, 2013), the current state of the art knowledge is limited. Several more recent observations have not been integrated into a comprehensive constitutive model or even a comprehensive understanding of the interaction between different factors that affect brine migration, and even the relatively simple mathematical relationships developed in the past have not yet been fully incorporated into modern coupled-processes simulators.

Brine migration research for nuclear waste disposal focused primarily on fluid inclusion migration caused by thermal gradients (Roedder and Chou, 1982). In this case, fluid inclusions migrate and "collide" with stationary grain boundaries where small inclusions are either stopped at the grain boundary while larger inclusions release fluid into the grain boundary. On the other hand, some more recent work on grain-boundary migration under natural conditions has focused on migration caused by pressure-solution, dislocation energy density, and grain-boundary surface curvature. In this case, grain boundaries are migrating whereas fluid inclusions are stationary. Grain-boundary collisions with fluid inclusions have shown a variety of behaviors including (1) incorporating inclusion fluid into grain boundary; (2) causing a temporary bulge in the grain boundary that is subsequently cut off and left behind as a fluid inclusion; (3) passes through the grain boundary unaffected. These different modes of interaction were observed to depend on the rate of grain-boundary migration, thickness of the grain boundary, and size and shape of the inclusion (Schenk and Urai, 2005). After grain-boundary migration ceases, there is also a tendency of grain-boundary water to break up into isolated inclusions (Desbois et al, 2010). It is also interesting to note that while fluid inclusion migration speed under a temperature gradient increases with inclusion size up to 1 cubic millimeter in volume (Roedder and Belkin, 1980), grain-boundary migration speed driven by pressure or dislocation density gradients peaks at a thickness between 10 and 100 nm (Urai et al., 1986). Very little information seems to be available linking the thermally-driven fluid inclusion migration process with the pressure-dislocation-driven grain-boundary migration process and the different forms of grain-boundary interactions with fluid inclusions.

There also appears to be very little information regarding issues such as non-Darcy flow through salt intergranular boundaries or how salt formations with more complex mineralogy, including clays and hydrous evaporites, may affect brine migration.

7. Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy): • **Describe how the data will be collected** Data to support this will be taken from the existing literature and from supplemental experimental investigations described in Section 8. The data collected will be applicable to convective flow processes within intergranular pore spaces according to Darcy or non-Darcy processes caused by pressure, gravitational, thermal, or chemical gradients, dissolution-diffusion-precipitation-type brine migration processes including thermal-driven, pressure-solution-driven, and dislocation-density driven migration processes, and interactions between isolated fluid inclusions and grain boundary fluids.
8. Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout: N/A
9. Define the pre-and post-test modeling/simulation needs for the activity, including: • **Description and type of model addressed by test (constitutive; process; coupled process; N/A if testing for constructability)** This is a model development proposal; however, it will utilize data and information available in the literature and from ongoing or planned UFD campaign experimental work. As mentioned above, laboratory studies visualizing temperature-driven brine migration are currently conducted within the UFD campaign. Valuable data may also be generated under the proposal “Imaging Brine Migration in Salt Using Neutron and Synchrotron X-ray Tomography”. Together, the experiments are expected to yield new data on brine migration as a function of temperature/ temperature gradient, pressure/pressure gradient, and the type of water, which can be used in the development of constitutive models that describe interactions among brine migration, salt microstructure and salt deformation behavior.
10. List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.): Host rock (including halite and coexisting, hydrous minerals such as clay); EDZ
11. Time period of applicability for data gathered: pre-emplacement; preclosure; postclosure: • **e.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.** The constitutive models will be applicable to both near-field and far-field host rock and would be applicable to brine migration caused by repository-induced and natural effects. Because of the wide variety of driving forces for brine migration, the model will need to address processes over a wide range of time scales. Data to support this will be taken from the existing literature and from supplemental experimental investigations described in Section 8.
12. For field tests define additional lab tests or other separate activities/data needed to support this test: N/A

References for Test H-23

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Table H-24. Validation Experiments Using a Geocentrifuge to Examine Canister Movement in a Salt Repository

Validation Experiments Using a Geocentrifuge to Examine Canister Movement in a Salt Repository

Drs. Earl D. Mattson, and Mitchell A. Plummer, Idaho National Laboratory
Proposed FY14 budget: $350K

Salt deposits are currently used for permanent entombment of low level nuclear waste (LLW) and the advantages of that approach are now being considered for disposal of high-level nuclear waste (HLW) and Used Fuel Disposition (UFD). One important question that must be answered is how the heat evolved from HLW/UFD waste canisters may affect the properties of the surrounding salt and how that interaction may cause migration of the waste canisters within the host formation. While this question has been addressed in several numerical simulation studies, experimental studies, to complement and test those models, have yet to be conducted. Accordingly, we propose a series of laboratory experiments to investigate the potential transport of waste canisters in rock salt using heated physical models on a large-scale centrifuge platform.

Numerical simulations of heated canister movement in a salt deposit have had mixed conclusions. Dawson and Tillerson (1978) indicate that a heated canister in a salt deposit would initially sink due to negative buoyancy, then rise as a convection cell develops around it, and eventually sink again as the heat flux decays and the convection cell dies. Their results predict that the total displacement would be less than a canister's length (DOE, 2012). These results were questioned in the 2010 U.S/German Workshop held in Mississippi, where they suggested that the potential for movement of the canisters may need to be addressed in HLW disposal in salt performance assessments or in supporting models (Hansen and Leigh, 2011). More recently, SNL (Clayton, 2013) has suggested that the salt viscosities used by Dawson and Tillerson were too conservative and SNL's newest modeling results suggest nearly no movement of a waste canister.


INL's 2-m centrifuge

To provide a physical test of the heated canister movement problem, we propose an experimental test that takes advantage of geocentrifute testing to scale the buoyancy effects associated with waste packages in low-viscosity salt. Centrifuge testing is an experimental technique that is often used to study geotechnical problems because it provides a means of scaling models to a size appropriate to the laboratory while maintaining the force distributions of the larger scale problem. It is most often used to study the strength and capacity of foundations, settlement of embankments, stability of slopes and the rock around subsurface tunnels. To set up a model with the appropriate stress scaling, we will size the heated canister to 1/*N*th that of the full-scale HLW canister and subject the experiment to a centrifugal acceleration of *N*. *N* represents the centrifugal acceleration compared to earth gravity.

Scaled models studying heated canister potential movement in salt deposits can be conducted on the INL's 2-meter centrifuge. This centrifuge has an experimental platform dimension of 0.5 by 0.7 meters and is capable of applying up to 130 g of acceleration on an experimental package (Smith, et al., 2001). Preliminary analysis indicates that large rock salt blocks (~30 cm on a side) could be used in these tests. The tests would generally entail placing cylindrical cartridge heaters in scaled cylindrical rods to represent the HLW/UFD canisters. These scaled waste packages will be placed in the middle of a rock salt block through a pilot hole. A known acceleration would be applied to the experiment and the heater would be activated at a known power level. Temperature would be monitored through a series of thermocouples and the location of the heater package and the expected salt convection cell would be monitored through high speed electrical resistive tomography (Versteeg et al., 2005). Alternatively, the test could be also temporarily stopped and x-rayed at INL's x-ray tomographic facility.

Preliminary experiments will be conducted to verify centrifuge scaling laws, following suggested relationships specified by the TC2 Technical Committee (ISSMGE-TC2, 2007). To verify defensible interpretation of the experimental results, we will follow the "modeling of models" approach (i.e., conducting similar tests but at different accelerations) for buoyancy transport, convection cell development, and heat conduction phenomena. If the TC2 scaling laws apply, time for the simulated heater package movement will scale as N^2 (*N* times the velocity for buoyancy transport and 1/*N* the travel length). Therefore, an experiment conducted for one day at 25gs would represent 625 days of transport in the field. Subsequent tests will investigate canister movement under a number of field relevant scenarios.

For experimental design, that requires consideration of non-uniform acceleration effects on transport processes within the geocentrifuge experiments, we will use a combination of two Multiphysics simulation packages, COMSOL's Multiphysics and INL's Multiphysics Object Oriented Simulation Environment (MOOSE). Experimental results will be compared to existing geomechanical simulations (e.g., SNL and Dawson and Tillerson) to ensure these models have included of the relevant processes that could affect canister transport.

Results from these scaled experiments should improve the understanding of coupled thermal-mechanical-hydrologic-chemical processes in the near-field of relevant disposal model environments, and lead towards the development of improved models to represent these processes or a validation that the relevant processes already exist in the current models.

Appendix I: LITHOLOGY, MINERALOGY AND WATER CONTENT OF BEDDED SALT DEPOSITS: IS THE SALADO FORMATION REPRESENTATIVE?

Frank Perry
Earth and Environmental Sciences Division, Los Alamos National Laboratory
LANL Report LA-UR-13-22414

DOE has outlined plans to conduct a thermal test in bedded salt at the WIPP facility to understand the behavior of water (brine) in a repository system at heat loads representative of high-level waste and spent nuclear fuel of defense origin (DOE, 2012). It is therefore pertinent to ask whether a test conducted at WIPP would be representative of other bedded salt deposits in the U.S. <u>Conclusion:</u> major bedded salt deposits form in shallow cyclic marine environments and therefore share similarities in lithologic sequences, accessory minerals and water content. Comparisons of bedded salt deposits considered in this study leave no reason to believe that the results of a thermal test at WIPP would not be applicable to other major bedded salt deposits in the U.S.

Bedded evaporite sequences include the most voluminous salt bodies on the Earth. Bedded salts of the greatest thickness and extent (and greatest volume) in the U.S. occur within four major sedimentary basins or basin groupings: 1) the Permian-age salts of the “Permian Basin” (including the Delaware, Midland, Palo Duro and Anadarko Basins); 2) the Devonian through Jurassic-age salts of the Williston Basin; 3) the Jurassic-age salts (bedded and domal) of the Gulf Coast Basin; and 4) the Silurian-age salts of the Michigan and Appalachian Basins (Figure I-1). Bedded salts in the Gulf Coast and Williston Basins lie primarily at depths of >2 kilometers (except for some portions along basin edges) and have not been considered in detail as host rock for HLW repositories. The “Permian Basin” (including the Palo Duro and Anadarko Basins, as well as adjoining ramp areas), is the largest region within the U.S. where bedded salt occurs within a few hundred meters of the surface (Figure I-1).

It is widely agreed that major bedded evaporate deposits (areal extent > 10,000 km^2) originate in restricted, shallow-marine environments that, while differing in detail, typically produce a cyclic sequence of primary evaporates related to marine transgressions and regressions at continental margins (Presley, 1987; Lowenstein, 1988; Schrieber and El Tabakh, 2000; Sarg, 2001). The typical lithologies within these sequences include carbonates (reflecting less restrictive marine conditions), sulfates, and Na, K and Mg chlorides, each reflecting an increasing degree of salinity (Schrieber and El Tabakh, 2000). Interbedded siliciclastic mudstones represent nearby arid terrestrial sources and the influx of continental clay and silt into mud and salt flats that are periodically flooded and desiccated (Presley, 1987). Clay and silt layers may form as primary layers introduced from nearby terrestrial sources, or may as residual lag deposits following halite dissolution from a fresh influx of seawater into salt flats (Hovorka, 1998).

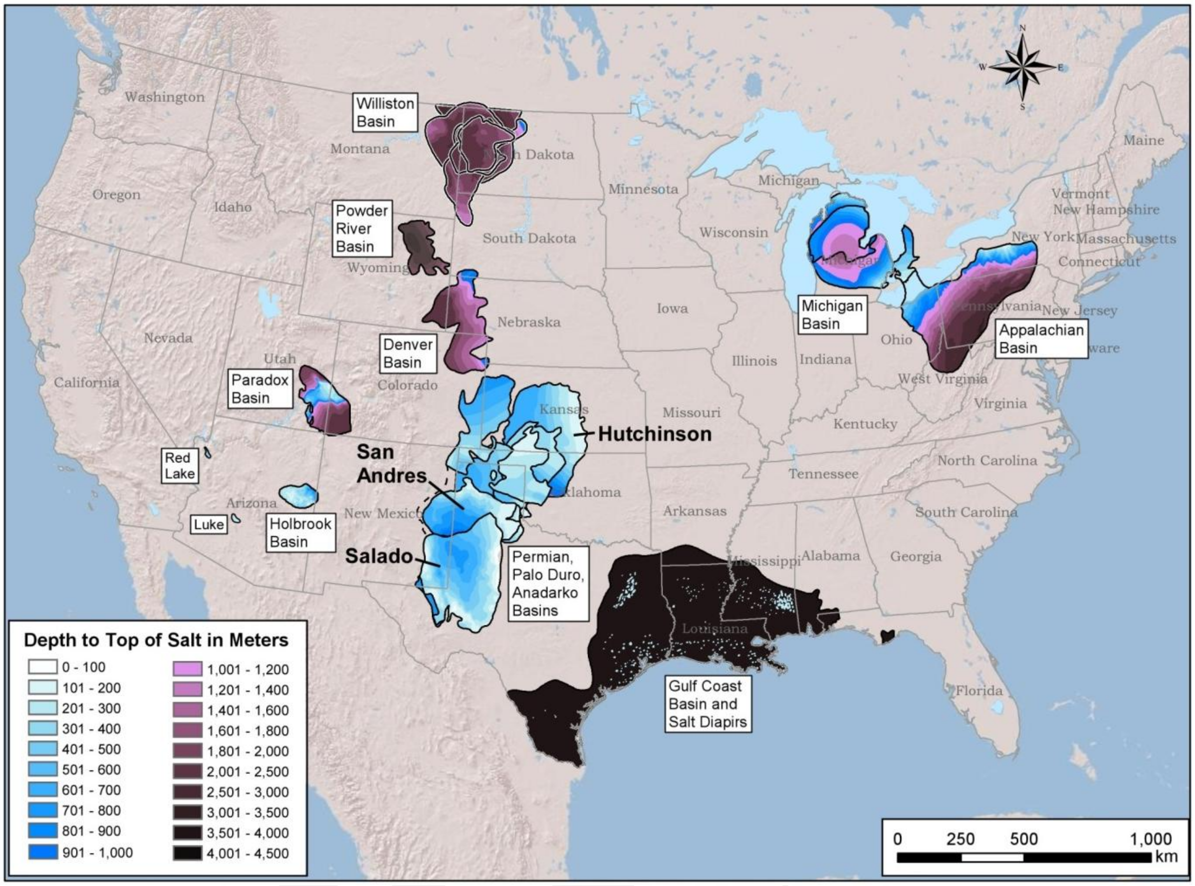

Figure I-1. Major salt formations in the U.S. showing depth to top of salt (Perry et al., 2012).

Diagenetic process following deposition and burial of bedded evaporites include dehydration of gypsum under pressure and recrystallization of halite into masses of larger interlocking grains (Schrieber and El Tabakh, 2000). Recrystallization processes often lead to migration and possible concentration of accessory minerals such as clay along crystal margins within the salt mass (Hovorka, 1998), as well as migration and coalescence of primary brine inclusions to form larger secondary inclusions within salt crystals (Roedder, 1984). Episodes of early dissolution and recrystallization is a normal process in bedded salt deposits and has an important role in determining the final distribution of both accessory minerals and brine inclusions.

Comparative Data for Bedded Salts

Water mobilization and migration in a salt repository in the presence of heat emitted from radioactive decay of the waste are phenomena that are incompletely understood. This fact motivates the need for conducting both laboratory-scale and *in situ* thermal testing. With respect to field testing, a legitimate question arises as to whether a test performed at one bedded salt site will yield data that is representative of behavior at another site. Because of the importance of the water fate and transport issue, two characteristics are considered here as most important to the behavior of the near-field environment within a nuclear waste repository in bedded salt: 1) water content of the near-field system, and 2) the concentration and distribution non-halite constituents within the system, both as impurities within the salt and as interlayered stratigraphic horizons within the salt formation. Given that many of these minerals are hydrous (clay, polyhalite), their concentration is related to the overall water content of the salt system.

Detailed data for the mineralogy and water content of bedded salt is available from only a few studies related to disposal of radioactive waste in salt. The Salado, San Andres and Hutchinson salts are major bedded salt formations within the Permian Basin (Figure I-1). They have been the subject of studies for radioactive waste disposal because they are of large lateral extent, occur in relatively unpopulated regions and lie within several hundred meters of the Earth's surface (Figure I-1). A relatively large amount of data is available for these bedded salts (particularly the Salado and San Andres) compared to others within the U.S. allowing comparison to the Salado in terms of lithologic characteristics, mineralogy and water content.

Mineralogy of Bedded Salt

Salt horizons within bedded salt deposits never occur as pure halite. They typically include both hydrous and non-hydrous accessory minerals, most commonly clay, anhydrite, polyhalite and quartz (Stein, 1985; Owen and Schwendiman, 1987). The water content of salt horizons correlates with the presence of hydrous minerals, in particular clay (Deal et al., 1989).

Stein (1985) describes the difficulty in determining the distribution of accessory minerals including clay within bedded salt deposits of the Salado Formation:

> "*It is much more difficult, however, to describe and quantify the distribution of non-NaCl minerals dispersed in a halite core... [clay] could be present as fine particles evenly disseminated throughout the halite; it may occur as intergranular in-fillings or as large blebs; it may be present as a single discrete layer or seam in otherwise "clean" halite; or it may be some combination of all of these*."

Stein (1985) describes five lithologies within the Salado Formation that can be distinguished in cores cut from 50-foot sections above and below the WIPP emplacement horizon: 1) clean halite, 2) polyhalitic halite 3) argillaceous halite, 4) mixed argillaceous-polyhalitic halite, and 5) clay seams and anhydrite beds (Figure I-2). This is a typical depositional sequence seen in many bedded evaporites. Stein (1986) separated insoluble residue minerals by dissolving the halite and found that "clean" salt generally has the lowest concentration of accessory minerals, while argillaceous and mixed halites have higher concentrations. Excluding anhydrite beds and clay seams, 45 samples from the cores contained an average of 1.5 wt% insoluble minerals, with a range of 0.05% to almost 10%. The insoluble minerals included quartz, magnesite, anhydrite, gypsum, polyhalite, alkali feldspar, and clays. No results are provided for the absolute amount of each mineral in the samples. Pfeifle and Hurtado (1998) measured the mineral content of eight samples of clean and argillaceous salt from the WIPP horizon using x-ray diffraction and found that clean salt contains 3-7 wt% accessory minerals with polyhalite > clay, while argillaceous salt contains 1-7 wt% accessory minerals with clay > magnesite > anhydrite > quartz.

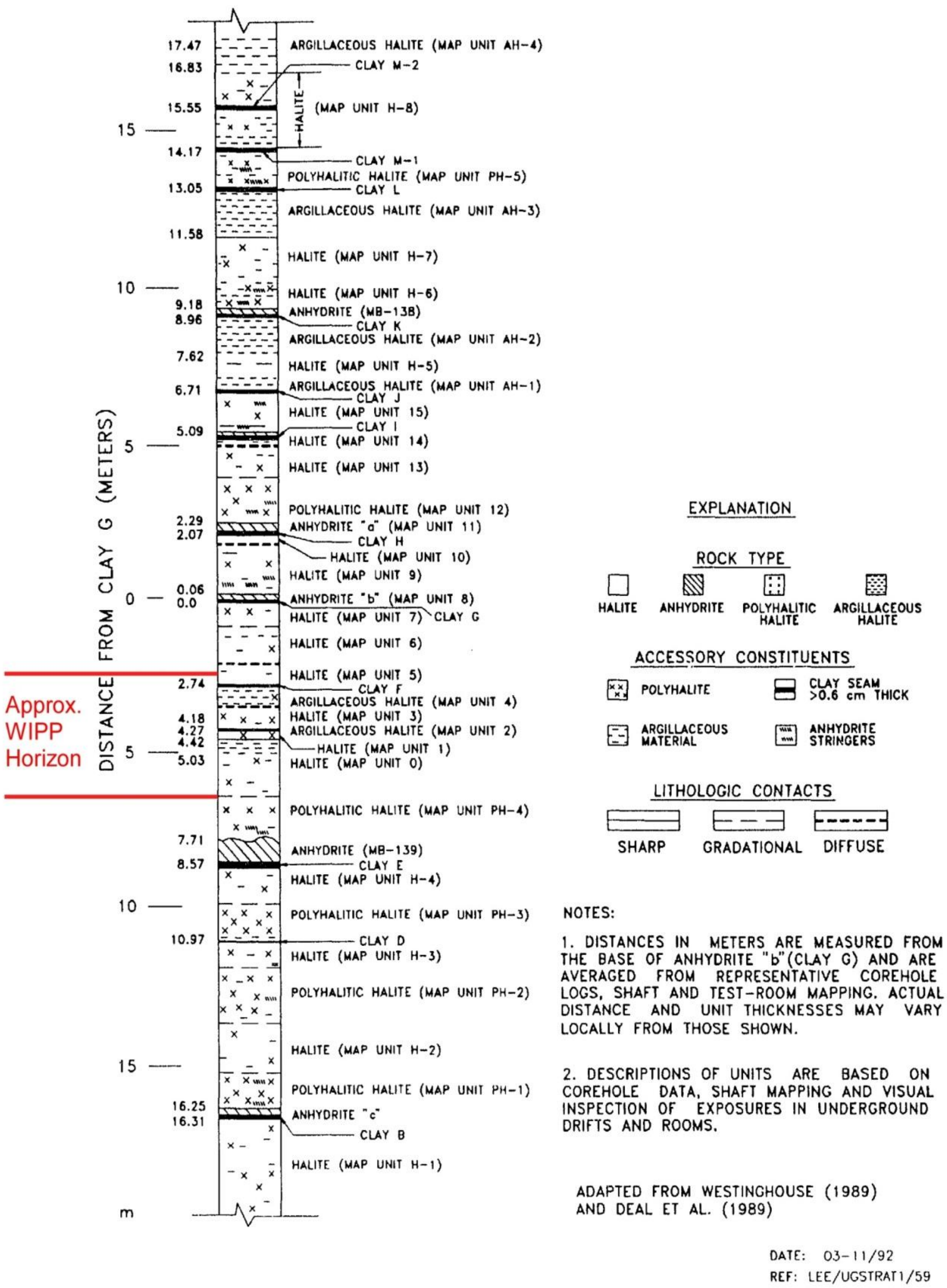

Figure A-1. Detailed Stratigraphy Near the WIPP Underground Facility.

Figure I-2. Bedded salt stratigraphy near the WIPP horizon from Jenson et al. [1993; based on information presented in Deal et al. (1989)].

The evaporite depositional sequence in the Lower San Andres Formation in the Palo Duro Basin of west Texas includes the Unit 4 depositional cycle, which was identified as the proposed repository host rock for potential HLW disposal by DOE (1986) during the 1980s. Much of the mineralogy data obtained for Unit 4 (as well as water content) is summarized in the Environmental Assessment of Deaf Smith County, Texas (DOE, 1986). Unit 4 is an evaporite depositional cycle that includes approximately 50 meters of bedded salt in its upper portion. The salt is interbedded with mudstone and anhydrite intervals that comprise approximately 8 and 4% respectively by volume of the bedded sequence. Anhydrite typically occurs as thin partings that occur throughout the salt horizon of Unit 4. Mudstone is composed of approximately 65% clay, 15% anhydrite and 20% halite, with traces of quartz, feldspars and other trace minerals (DOE, 1986). About half of the mudstone volume occurs as thin seams (average thickness of 2-3 cm) while the rest is disseminated throughout the salt intervals as chaotic clay/salt mixtures or less abundantly as masses within clean salt intervals. Discrete clay seams are distributed irregularly but frequently throughout the bedded salt with an average spacing of about one half meter (DOE, 1986). The estimates of the volume percent mudstone in Unit 4 and the volume of clay within the mudstone translate to about 5 wt% clay in Unit 4 as a whole.

Measurements of insoluble residue from core samples of San Andres Unit 4 salt indicate an insoluble residue of about 1.9% (Owen and Schwendiman, 1987), which is somewhat lower than the percentage of accessory minerals estimated using visual methods (DOE, 1986). The clay content of the residue determined by XRD is about 60 wt% for samples that contain clay (Owen and Schwendiman, 1987). About one third of the samples contain anhydrite as the primary accessory phase with only a trace or no clay.

The stratigraphy of the Hutchinson salt was described by Lomenick (1963) from cores obtained from below and above the floor of the Lyons mine. Lomenick (1963) describes the Hutchinson salt interval as being about 90 meters thick and containing 60% halite with shale and anhydrite comprising the rest. The bedded salt is characterized by salt horizons that are typically 3-5 meters thick separated by shale layers up to 30 centimeters thick. The salt horizons consist of relatively pure 2-15 cm salt layers separated by 1mm layers of shale and clay that constitute the major impurity in the salt. Lessor amounts of anhydrite are associated primarily with the shale as thin discontinuous layers.

Jones (1965) described the petrography of the Hutchinson salt member in detail. The salt layers (constituting about 60% of the formation) are estimated to contain 95% or greater halite with accessory minerals of anhydrite, clay, quartz, feldspars and lessor abundances of trace minerals including polyhalite and magnesite.

Water Content of Bedded Salt

Measuring the water content of a bedded salt deposit presents difficulties because water within a bedded salt sequence occurs in several forms (Roedder 1984). Water (i.e., brine) can occur:

1. Along intergranular or pore water between crystals
2. As fluid inclusions within crystals

3. Within hydrous accessory minerals within halite crystals (e.g., clay and other minerals in “argillaceous salt”
4. Within hydrous minerals and pore spaces of interbeds, as part of the larger bedded salt stratigraphic sequence.

Measurement of water in salt is also difficult because of differences in sampling, sample handling and sample preparation that can lead to water loss prior to measurements and inaccurate characterization of the *in situ* water content (Roedder and Basset, 1981; Roedder and Chou, 1982). The amount of water released from bedded salt is a function of temperature with water along grain boundaries released at low temperature and waters in inclusions or bound in accessory minerals released at increasing temperature points depending on the pressure within heated inclusions and the dehydration temperatures of accessory minerals included within halite or in interbeds.

As far as can be determined (with the possible exception of work by Kopp and coworkers), no attempt has ever been made to simultaneously measure and compare the water content of bedded salt from different salt formations using the same sample collection, handling and preparation techniques and laboratory measurement methods.

Water content of the Salado Formation has been characterized through extensive sampling and analysis as part of the WIPP Brine Sampling and Evaluation Program (BSEP). Deal et al. (1989) summarized the results of the program in which hundreds of samples in and near the WIPP horizon were measured for weight loss of water at temperatures of 95°C and 150°C. These temperatures were chosen to determine the quantity of “unbound” water present as intergranular water or absorbed water that would be likely to easily move in a low to moderate temperature repository environment or where pressure gradients exist due to mining. The temperatures are presumably not high enough to result in the release of water from brine inclusions due to decrepitation or release of water bound structurally in hydrous minerals. No significant weight loss was observed between samples heated to 95°C and 150°C (Deal et al., 1989, Table 4-3, additional mean relative weight loss of ~5% occurred at 150°C). Based on these measurements, Deal et al. (1989) concluded that near-field average water content for the bedded salt near and including the WIPP horizon is between 0.5 and 0.75 wt%. The weighted average water content of the mined horizon (Units 0-4) is approximately 0.6 wt% with the argillaceous beds (Units 2 and 4) having a slightly higher average water content of 0.74 and 0.88 wt%, respectively, due to higher clay content (Figure I-2, Table I-1). These water contents do not include water in “Clay F” that lies above Unit 4 (Table I-1).

Water measurements have also been obtained for salt in depositional Unit 4 of the San Andres Formation as part of salt repository studies conducted in the Palo Duro Basin of west Texas during the 1980s.Much of this information is summarized in the DOE Environmental Assessment (DOE, 1986). Based on information from Fisher (1984) summarized in the DOE Environmental Assessment (the original Fisher report could not be obtained), water content of Unit 4 ranges from 0.1 to 0.8 wt% and includes both intergranular water and water from fluid inclusions. The average water content for halite intervals is reported as 0.4 wt%. The temperature of these measurements is not stated, but apparently was high enough to release water from fluid inclusions by decrepitation.

Table I-1. Summary of Unit Moisture Content (Weight Percent; Samples Heated to 95°C. [Reproduced from Deal et al. (1989). Map Units correspond to map units identified in Figure 2.]

MAP UNIT	MAXIMUM	MINIMUM	N	MEAN	STANDARD DEVIATION
14	0.31	0.15	3	0.23	0.08
13	0.21	0.05	3	0.12	0.08
12	0.17	0.05	11	0.13	0.04
11 (Anhydrite "a")	0.98	0.16	6	0.58	0.36
9	0.11	0.05	28	0.08	0.02
8 (Anhydrite "b")	1.44	0.07	5	0.47	0.57
Clay G	2.44	1.34	9	1.75	0.34
7	1.64	0.13	20	0.42	0.34
6	0.59	0.02	22	0.16	0.14
5	2.76	0.86	2	1.81	1.34
Clay F	3.94	0.87	3	2.23	1.56
4	3.75	0.04	104	0.88	0.82
3	0.84	0.01	62	0.24	0.15
2	1.70	0.22	53	0.74	0.37
1	0.94	0.03	69	0.20	0.15
0	6.67	0.08	136	0.66	0.70
*Solution Pits	0.71	0.11	10	0.39	0.22
All Units	6.67	0.01	545	0.55	0.64
0	6.67	0.08	136	0.66	0.70
*Solution Pits	0.71	0.11	10	0.39	0.22
All Units	6.67	0.01	545	0.55	0.64

*Penecontemporaneous feature having distinct lithology characteristics.

Another series of water measurements using was reported by Owen and Schwendiman (1987). They measured water content from weight loss in 12 core samples from Unit 4 at stepped temperatures ranging from 110°C to 500°C Measurements made at temperatures of 110°C, 175°C and 500°C yielded average water contents of 0.06 wt%, 0.10 wt% and 0.59 wt%. Decrepitation typically occurred at a temperature of 250-350°C but did not occur in all samples.

Data on water content for the Hutchinson salt is sparse. Measurements of water content from eight samples collected from the Lyons and Carey Mines were heated to 400°C as part of the Project Salt Vault Studies (Bradshaw and McClain, 1971). Four samples from the Carey Mine had average measured water content of 0.08 wt.%, while five samples from the Lyons Mine (including an "atypical" crystal containing visible fluid inclusions) had an average water content of 0.37 wt% with a maximum of 1.1 wt% (crystal with visible fluid inclusions). The difference in water content in salt from the two mines was ascribed to spatial variability in the abundance of brine inclusions in the salt.

Kopp and coauthors (Kopp and Fallis, 1973; Kopp and Combs, 1975) measured water content by weight loss in both the Hutchinson and Salado salts, allowing some comparison of water contents measured in the same laboratory. Water loss was measured at a temperature of ~102°C for multiple samples from both formations. Water content measured for the Salado salt ranged from 0.0 wt% to 3.5 wt%, with most values less than 0.5 wt% (Kopp and Combs, 1975), while water content for the Hutchinson salt ranged from 0.4 to 19.0 wt% (Kopp and Fallis, 1973, as reported in Kopp and Combs, 1975; the 1973 report could not be obtained). Based on these results, Kopp and Combs (1975) concluded that the Salado Formation releases less water at these temperatures than the Hutchinson salt. They note that higher water content is associated with higher clay content and that that less clay was present in the Salado samples compared to the Hutchinson samples.

Summary

The Salado, San Andres and Hutchinson bedded salt sequences share similar origins and similar lithologic sequences (primarily clean to argillaceous halite with interbeds of anhydrite and shale/clay). The abundance and type of accessory minerals with the bedded sequences are similar, except for the higher prevalence of polyhalite (a hydrous calcium sulfate) in the Salado Formation. Water contents in all these salts appears to correlate with clay content, with more argillaceous halites and clay horizons containing the primary water content within the bedded sequences (Kopp and Combs, 1975; Deal et al., 1989). Water content of relatively pure (clean) halite horizons averages about 0.5 wt% or less in all three bedded salts, with individual samples containing as much as 1 wt%, depending on the specific amount of clay and brine inclusions. Individual argillaceous halite samples within sequences can have water contents that exceed 5 wt% . The weighted average (based on thickness) of water content in clean and argillaceous salt in the WIPP horizon is estimated at 0.6 wt% (Deal et al., 1989). Except for the conclusion of Kopp and Combs (1975) that the Hutchinson Formation has a higher water content due to more clay (consistent with frequent shale and clay layers noted by Lomenick, 1963), there is no evidence from the data reviewed in this report that the water content of Salado Formation differs significantly from the water content of other "typical" bedded salts. The lithology of other salt beds in the U.S. reviewed by Perry (2012) supports this view. Therefore, with respect to mineralogy and water content and their influence on salt behavior upon heating, there is no reason to believe that the results of a thermal test at WIPP would not be applicable to other major bedded salt deposits in the U.S.

Acknowledgments

Discussions with Florie Caporuscio concerning clay and salt mineralogy contributed to the development of this report.

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Appendix J:
SALT RD&D WORKSHOP PRESENTATIONS

This appendix includes the presentations given at the March 2013 Workshop, as indicated in Appendix E, which shows the Workshop agenda.

Exceptional service in the national interest

Sandia National Laboratories

Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt: Objectives, Background, and Structure

Robert J. MacKinnon
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY NNSA

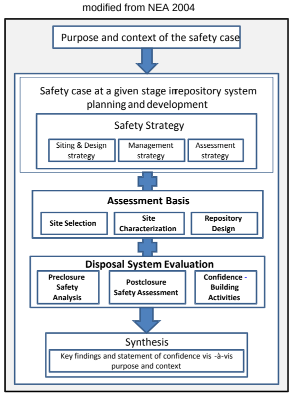
Outline

- Safety Case
- Goals of Workshop
- Agenda
- Background
- Safety Case and RD&D Importance Ratings
- Breakout Groups and Tasks

Research, Development, and Demonstration (RD&D) to Support a Generic Safety Case for Disposal of HLW and SNF

- A *safety case* is an integrated collection of evidence, analyses, and qualitative and quantitative arguments used to substantiate and demonstrate the safety of a *system*
- Although the post-closure safety assessment is a key element of the safety case, *there are several other elements that are also important*
- A safety case must present multiple lines of evidence and reasoning to support all elements of repository development and safety
- Development of the safety case should start early in the process of repository development

modified from NEA 2004

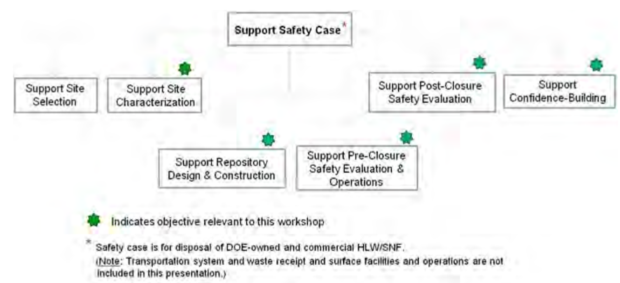


Overview of the Elements of a Safety Case

Safety Case Structure for Organizing RD&D

RD&D to build a sound technical basis for safe disposal of HLW and SNF

A Safety Case provides a structured framework to assist in planning, organizing, and prioritizing the technical work



Goals of Workshop

- Goals
  - Identify a comprehensive set of RD&D needs and approaches to addressing them
  - Elicit input to a decision-making framework that will be used subsequent to the workshop to formulate a RD&D plan
  - Plan will address RD&D in the areas of thermal field testing, underground testing to support design, laboratory testing, and modeling

•Safety Case Obj(s) addressed
•Importance of issues addressed
•Why data is necessary

•UFD R&D Roadmap and FEPs list
•Hansen and Leigh 2011
•F. Hansen 2013 IHLRWMC paper
•SDDI proposal
•SDI proposal
•Gorleben FEPs list
•Expert judgment

- Inputs to this Workshop
  - Status of Salt R&D
  - Strawman set of technical issues and their relative importance
  - Strawman set of activities to be conducted in the underground
  - Strawman plan for Salt Defense Disposal Investigations (SDDI) and Salt Defense Investigations (SDI) thermal field tests

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Agenda

Wednesday Morning Plenary, March 6

0830 – 0845	Welcome and Purpose – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
0845 – 0900	DOE Perspectives – Prasad Nair (DOE-NE), Mark Senderling (DOE-EM) and Roger Nelson (DOE-EM)
0900 – 1000	Workshop Objective, Goals, Structure, and Approach – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1000 – 1015	Break
1015 – 1100	Continue - Workshop Objectives, Background, and Structure – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1100 - 1200	Summary and Status of US Salt Repository Technical Basis - Christi Leigh (SNL), Don Reed (LANL), Jens Birkholzer (LBNL)

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Agenda cont.

Wednesday Afternoon Breakouts, March 6

1200 – 1315 Lunch
1315 – 1345 Structure and Goals of Breakout Sessions – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1345 – 1415 Instructions to Breakout Groups – Dave Sevougian (SNL)
1415 – 1700 Breakout Group 1: Post-Closure Repository System (EBS post-closure processes within the excavation and NBS post-closure processes in the host salt formation) Chairs – David Sevougian (SNL), Don Reed (LANL); Rapporteur – Dan Levitt (LANL)
Breakout Group 2: Pre-closure Repository System (design, demonstration, and pre-closure issues) Chairs – Frank Hansen (SNL), Ned Elkins (LANL); Rapporteur – Ernie Hardin (SNL)
MacKinnon (SNL) and Rob nson (LANL) will act as roving participants to ensure Pre-Closure/Post-Closure Integration.

Breakout Groups will:
- Review RD&D strawman issue list
- Propose additional issues/remove issues as necessary
- Define specific tests/modeling needed to advance the state of the art to address Post-Closure System issues and Pre-Closure System issues
- Input to decision making framework

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Agenda cont.

Thursday Morning Session on Field Testing at WIPP, March 7

0815 – 0900 Reconvene and Synthesis of Breakout Session results – Session Chairs and Rapporteurs
0900 – 0910 Introduction to Field-Testing Session –Bruce Robinson (LANL) and Bob MacKinnon (SNL)
0910 – 1145 Field-Testing Session
  0910 – 0930 Summary of Past Field Tests Relevant to Disposal of Heat Generating Waste in Salt – Kris Kuhlman (SNL)
  0930 – 1015 Underground Research at WIPP – Frank Hansen (SNL)
  1015 – 1030 Break
  1030 – 1115 Thermal Field Testing at WIPP – Doug Weaver (LANL)
1115 – 1145 Re-Entry into the North Experimental Area of WIPP – Doug Weaver (LANL) and Michael Schuhen (SNL)
1145 – 1300 Lunch

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Agenda cont.

Thursday Afternoon Wrap Up, March 7

1300 – 1500	Resume Field-Testing Session Define specific tests/modeling/path forward Input to Decision Making Framework
1500 – 1515	Break
1515 – 1615	Plenary on workshop summary and future actions – Bob MacKinnon (SNL) and Bruce Robinson (LANL)
1615 – 1630	Concluding Remarks – Prasad Nair (DOE), Nancy Bushman (DOE), Roger Nelson (DOE)

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Background

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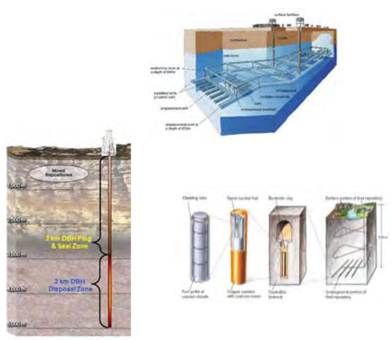
Background: DOE-NE's R&D Focus for SNF and HLW Disposal

- Provide a sound technical basis that will increase confidence in the robustness and safety of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation



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Background: Salt Attributes and Distribution

Attributes and Distribution

SALT ATTRIBUTES
- Easily mined
- Deforms plastically
- Fractures self-heal
- High thermal conductivity
- Very low permeability and porosity
- Has existed underground for millions of years
- Deposits are often in stable tectonic regions and exist in many locations with geographic distribution in the U.S.

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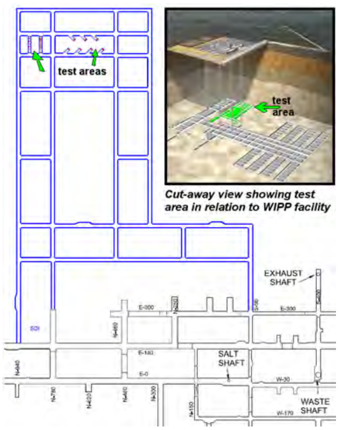
Background: Generic Salt Repository at Depth



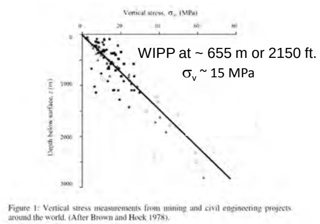
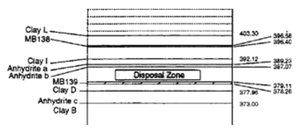
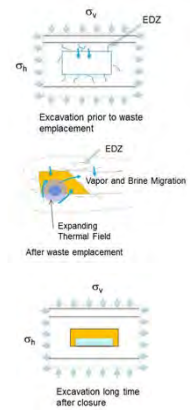


Figure 1: Vertical stress measurements from mining and civil engineering projects around the world. (After Brown and Hoek 1978).



Salado stratigraphy near the excavated regions

Background: Host Rock and EBS Barrier Functions



- The host rock is the most important barrier
- Excavations will creep towards closure and potential flow paths for brine and gas will be sealed under the action of the in situ stresses
- Creep closure is accelerated under higher temperatures
- To maintain the low permeability of the host rock fracturing of the host rock during convergence of the excavation should be avoided
- Excavations will be backfilled with crushed salt to stabilize converging host rock and limit excavation volume reduction
- Due to rock stress the backfill consolidates into a mass comparable to intact salt with low permeability
- In addition to acting as an impermeable barrier and stabilizing the host rock, the backfill conducts decay heat away from the waste container
- Waste Canister prevents water from contacting the waste and provides containment of the waste for an adequate period of time
- Waste Form limits the release rate of radionuclides subsequent to container breach

Expected evolution of the system will result in negligible radionuclide releases to the geosphere

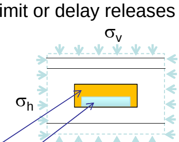
Less likely events such as human intrusion might affect performance of the system

Background: Host Rock and EBS Barrier Functions cont.

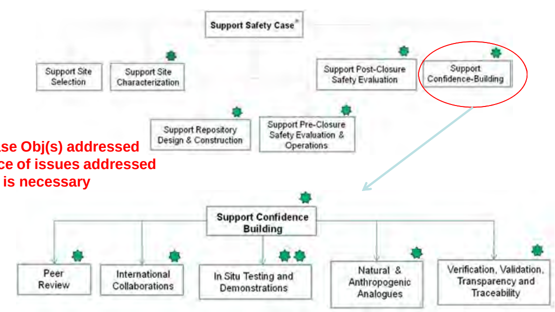
- Host rock (and EDZ) – strongly limits or prevents the flow of brine into the waste emplacement drift, self heals, and greatly limits the release or prevents the release of dissolved radionuclides to the geosphere
- Crushed Salt Backfill – strongly limits or prevents the release of radionuclides, stabilizes and limits drift closure, provides a long-term barrier to inflowing brine, and conducts heat to the host rock
- Waste Canister – prevents water from contacting the waste and provides containment of the waste for an adequate period of time (e.g., retrievability)
- Waste Form – limits the release rate of radionuclides subsequent to container breach

Containment

Limit or delay releases



Structure for Organizing Proposed RD&D and Documenting Workshop Results



- **Safety Case Obj(s) addressed**
- **Importance of issues addressed**
- **Why data is necessary**

Activities that build not only our confidence in the understanding of key processes but also activities that build confidence in stakeholders that DOE's science is sound

What are you tasked do in this workshop?

This afternoon we will break into two breakout groups:

Breakout Group 1: Post-Closure Repository System (EBS post-closure processes within the excavation and NBS post-closure processes in the host salt formation) Chairs – David Sevougian (SNL), Don Reed (LANL); Rapporteur – Dan Levitt (LANL)

Breakout Group 2: Pre-closure Repository System (design, demonstration, and pre-closure issues) Chairs – Frank Hansen (SNL), Ned Elkins (LANL); Rapporteur – Ernie Hardin (SNL)

Breakout Groups will:

- Review RD&D strawman issue list and ranking; provide comments/revisions as necessary
- For high-priority items not currently being addressed define specific tests/modeling needed to advance the state of the art to address Post-Closure System issues and Pre-Closure System issues
  - Answer questionnaire for each activity

What are you tasked do in this workshop?

Tomorrow we will work together as one group. The goals are twofold:

(1) Develop input necessary to design a thermal field test/demonstration, starting with strawman
(2) Develop input on potential additional research activities in the underground, starting with strawman

Specific questions and topics that are to be addressed include:

- What are the objectives of the proposed activity?
- Which objective(s) of the safety case does the proposed activity support and why?
- Define the data that will be collected/measured (e.g., process(es)/parameter(s), time duration, frequency, accuracy) to accomplish the objective(s).
- Specify how the collected data will be used to support activity objectives.
- Define the instrumentation that will be used to measure process(es)/parameter(s) and define the instrumentation placement or layout.
- Define the pre-and post-test modeling/simulation needs for the activity.
- Define the laboratory tests needed to support activity.

Questions/Thoughts?

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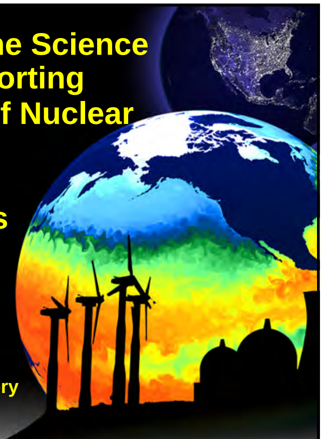
Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt



Opening Remarks

Bruce A. Robinson

Program Director
Civilian Nuclear Programs
Los Alamos National Laboratory

March 6, 2013

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Slide 1 NNSA

UNCLASSIFIED

Outline

- National context for nuclear waste disposal in the U.S.
- Potential role for salt in the disposal of heat-generating waste
- Thermal testing in salt: WIPP and elsewhere
- A proposed path forward
- Concluding remarks

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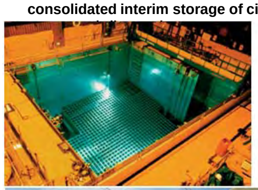
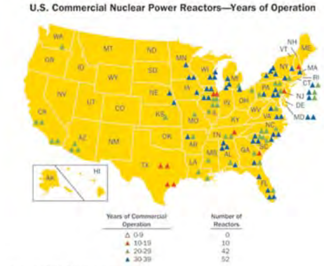
2 NNSA

Status of Disposal of Civilian Spent Nuclear Fuel

National SNF/HLW disposal program is delayed: The Administration's response to the Blue Ribbon Commission's recommendations will lead to the nation employing consolidated interim storage of civilian used nuclear fuel for decades. before





BRC Report, January 2011 recommends "prompt efforts to develop one or more geologic disposal facilities"

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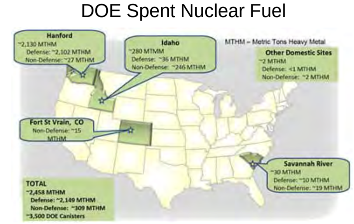
3 NNSA

DOE-Managed SNF/HLW Disposal Must Also Be Solved

Timetable for defense and DOE-managed waste is more urgent – geologic disposal is an enabler for legacy waste cleanup and transformation of the DOE Complex

DOE Spent Nuclear Fuel



DOE High Level Waste

Source: http://www.brc.gov/sites/default/files/meetings/presentations/environmental_management_brc_03252010.pdf

Applicable Agreements with Host States

- Hanford Tri-Party Agreement
- Idaho Settlement Agreement
- South Carolina Federal Facility Agreement

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4 NNSA


Waste Disposal Costs are Large, and Progress is Slow
Nuclear Waste Disposal expenditures to date have not led to progress toward a disposal solution for HLW and SNF - National budget constraints require new thinking
• Current law mandates that civilian SNF and defense HLW/SNF be commingled in a single repository
• Expenditures from Nuclear Waste Fund (Civilian): $6.8B
• Defense Appropriations (DOE-Managed HLW/SNF): $3.8B
Yucca Mountain Project
Negative consequences to DOE (~$1B costs for interim storage, and negative local public perception) could be avoided with an expeditious repository solution
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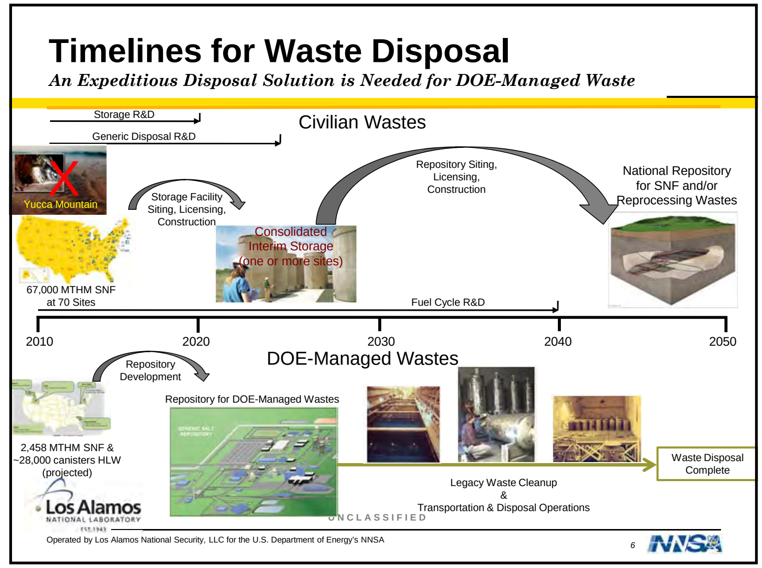
Timelines for Waste Disposal
An Expeditious Disposal Solution is Needed for DOE-Managed Waste
Storage R&D
Generic Disposal R&D
Civilian Wastes
Yucca Mountain
Storage Facility Siting, Licensing, Construction
Repository Siting, Licensing, Construction
National Repository for SNF and/or Reprocessing Wastes
Consolidated Interim Storage (one or more sites)
67,000 MTHM SNF at 70 Sites
Fuel Cycle R&D
2010
2020
2030
2040
2050
DOE-Managed Wastes
Repository Development
Repository for DOE-Managed Wastes
2,458 MTHM SNF & ~28,000 canisters HLW (projected)
Waste Disposal Complete
Legacy Waste Cleanup
&
Transportation & Disposal Operations
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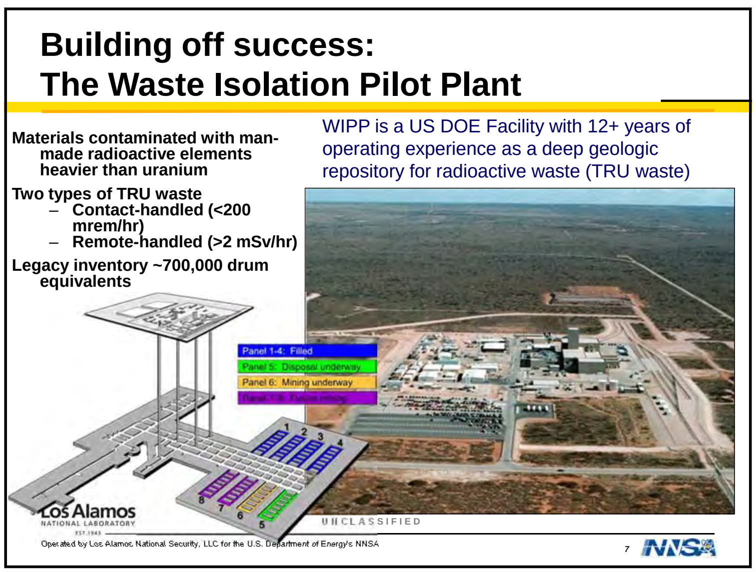
6


Building off success:
The Waste Isolation Pilot Plant
Materials contaminated with man-made radioactive elements heavier than uranium
Two types of TRU waste
– Contact-handled (<200 mrem/hr)
– Remote-handled (>2 mSv/hr)
Legacy inventory ~700,000 drum equivalents
WIPP is a US DOE Facility with 12+ years of operating experience as a deep geologic repository for radioactive waste (TRU waste)
Panel 1-4: Filled
Panel 5: Disposal underway
Panel 6: Mining underway
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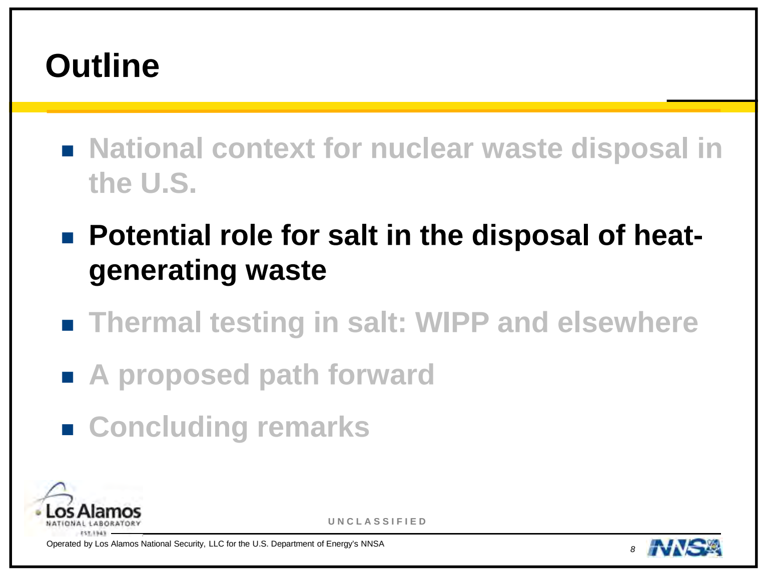
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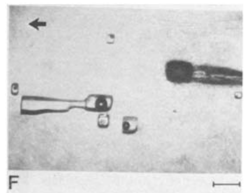
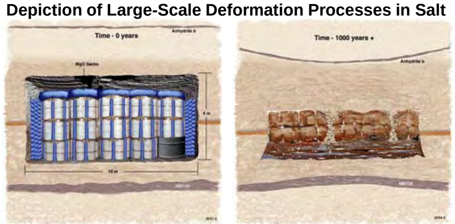
Is Disposal of Heat-Generating Waste in a Salt-Based Repository the Answer?

- Salt is an attractive geological medium due to its impermeability and self-sealing features.
- The response of salt to decay heat from the waste must be well understood.
- There are small amounts of water in salt. This water could be liberated and mobilized, leading to alteration of the salt mechanical properties and potential degradation of the waste package system.



Fluid inclusions migrating under a thermal gradient – Carter and Hansen, Technophysics, 93, 1983.

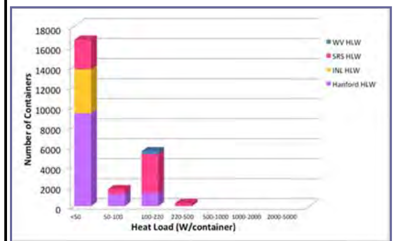
Depiction of Large-Scale Deformation Processes in Salt



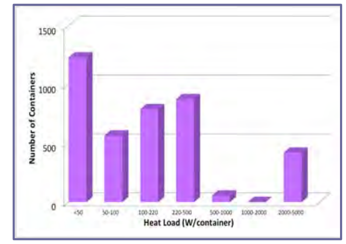
Erickson and Dials, RadWaste Solutions, Jan.-Apr., 24-34, 2011.

Distribution of Heat Loads: DOE-Managed Waste

High-Level Waste



DOE Spent Nuclear Fuel

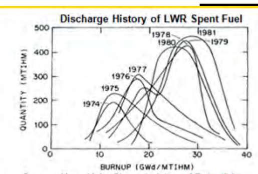


Carter, J.T., A.J. Luptak, J. Gastelum, C. Stockman, A. Miller. 2012. *Fuel Cycle Potential Waste Inventory for Disposition*. DOE Office of Nuclear Energy Report FCR&D-USED-2010-000031, Rev 5.

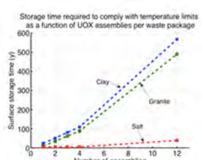
Heat Loads for Civilian Wastes

- **YMP EIS "Baseline" values:**
  - 21-PWR Canisters: 4239 containers, 8800 W/container
  - 44-BWR Canisters: 2784 containers, 6200 W/container
- **Oldest civilian fuel also has a much lower burnup**
  - Roughly one-half the heat output of the baseline values
- **DOE-NE UFD studies have focused on generic concepts (closed designs) with fewer assemblies per disposal package than YMP (open design)**
  - Example: 4 assembly PWR disposal package - 1676 W/container
  - Example: 12 assembly, old, low burnup BWR SNF – 850 W/container

Conclusion: There is overlap in the per-canister heat loads of the defense and civilian waste inventories, but in general, civilian SNF heat loads are greater unless packaged in small quantities.



Source: Notz, K.J., *Characteristics of Potential Repository Wastes*, First Annual International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, CONF-900406-11, April 1990.



Source: Hardin et al., 2011, "Generic Repository Design Concepts and Thermal Analysis (FY11)." SAND2011-6202.

Prevailing Opinion About Heat-Generating Waste in Salt

The Perception:

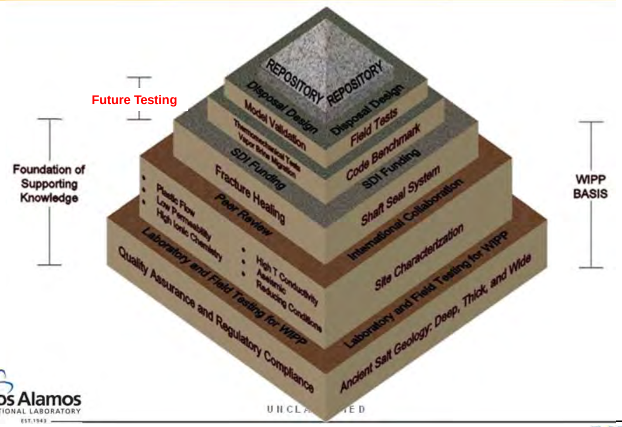
"Salt is nice, in some senses, from a geologic perspective. But if the salt is heated, the watery inclusions mobilize and flow toward the heat, so burying spent fuel there would require waiting until the hot waste products cool down a bit—somewhere around the second half of this century."

Expert opinion presented in Wald, M. L. Scientific American. *What Now for Nuclear Waste?* August 2009, 46-53.

The Reality:

The actual situation is likely more complex, with multiple processes occurring at multiple scales. The interplay of these processes will control the degree to which water influences the salt repository system.

Salt R&D Builds on a Foundation Developed in the WIPP Repository Program



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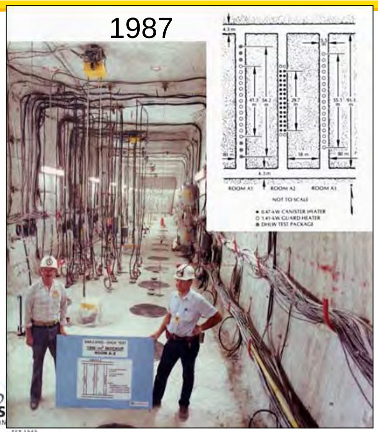
WIPP as the Host Site for Underground Science



Early concepts at WIPP included thermally hot canisters placed vertically in the floor

- 18 W/m²
- Coupons, brine, temperature monitored
- Peak temperatures never reached
- Tests terminated abruptly

Worldwide Experience: Field-Scale Heater Testing in Salt

Testing in the Asse Salt Mine, Germany

Site	Emplacement Concept		Geology	Thermal Characteristics of Tests[1]
	Borehole	In-drift		
Lyons, Kansas (Project Salt Vault)	X		Bedded salt	• Peak salt T ~200°C • 2 year heating duration • Power – 10.4 kW/heater
Avery Island	X		Salt dome	• Peak salt T ~160°C • ~3 year heating duration • Power – 3-6 kW/heater
Asse	X	X	Salt dome	• Peak salt T ~210°C • 10 year heating duration • Power – 6.4 kW/heater
Gorleben	X	X	Salt dome	• N/A
Morsleben		X	Salt dome	• N/A
WIPP (historical)	X		Bedded salt	• Power – 64 kW total power between 3 rooms and 59kW in a single room
WIPP – Proposed Testing Program				
SDDI		X	Bedded salt	• Peak salt T ~80-150°C • 1-2 year heating duration • Power – 0.5-2 kW/heater
SDI		X	Bedded salt	• Peak salt T >200°C • 4 year heating/cooling duration • Power – 8.5 kW/heater

1. Multiple heater tests were conducted at most sites. This column describes the tests most applicable to the SDI/SDDI testing concepts.

Reference: Callahan, G., Guerin, D.C., Levitt, D.G., Newell, D.L., Robinson, B.A., and Van Sambeek, L., "*Salt Repository Synthesis Data of Non-Delaware Basin and International Programs for the Storage/Disposal of Nuclear Waste*," FCRD-UFD-2012-000312, Dated October 2012.

Water in Salt in the Presence of Heat

- **Small-Scale Mechanisms**
  - Intragranular fluid inclusions migrate up the thermal gradient
  - Grain-boundary pore water travels through microfractures, vaporizes
  - Water from mineral dehydration reactions adds to source term
  - Localized rock failure via decrepitation (high temperature only: >250°C?)
- **Large-Scale Effects**
  - Fracture creation in the EDZ during mining (increased permeability and formation of pathways)
  - Visco-plastic deformation (salt creep)
  - Water-assisted, thermally accelerated fracture healing
  - Water and heat-induced changes in salt material properties
  - Compaction and reconsolidation of run-of-mine salt backfill (water assisted)
  - Redistribution of water in the vapor phase: ventilation, condensation in cooler regions

The interplay of these processes can only be investigated through a combination of theory/modeling, laboratory scale testing, and field testing. Field testing is required to examine competing processes and to validate models.

Reference: Robinson, B.A., N.Z. Elkins, J.T. Carter, 2012, Development of a U.S. Nuclear Waste Repository Research Program in Salt, *Nuclear Technology*, 180, 122-138.

Outline

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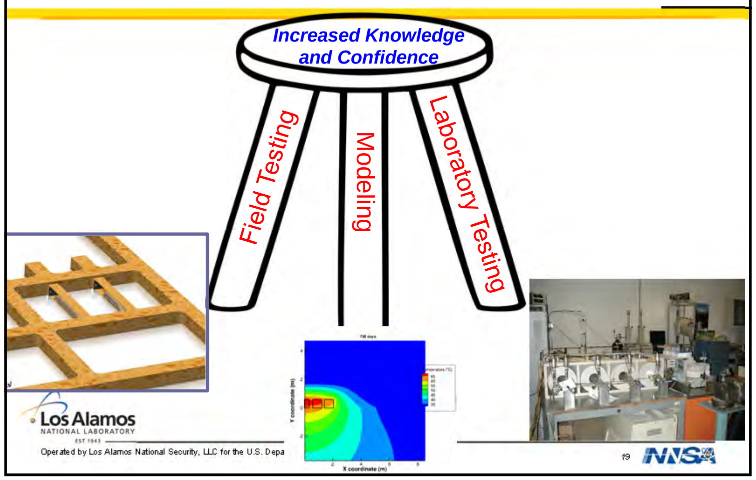
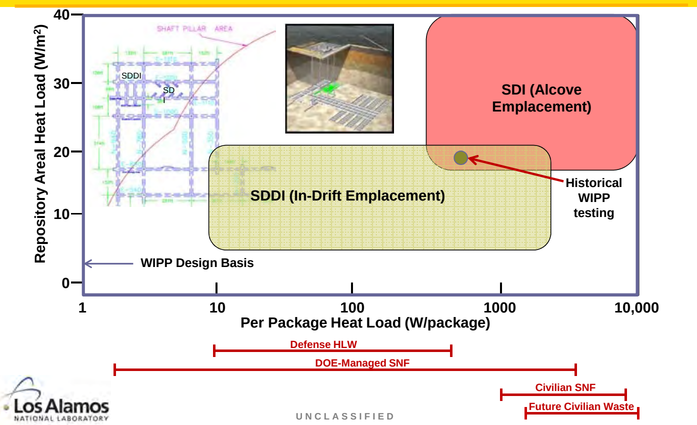
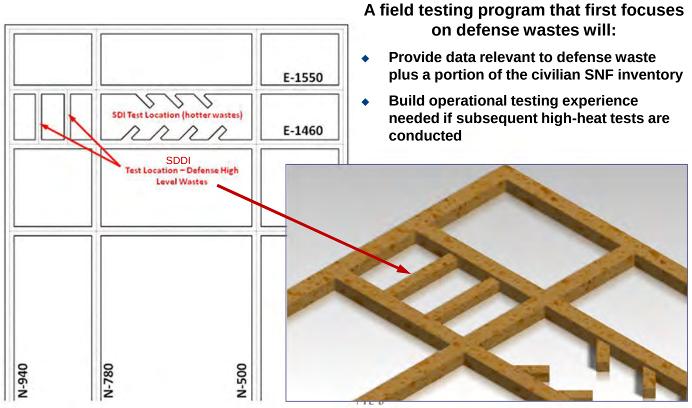
Integrated, Multiscale Science is Required



Heat Loads and Disposal Concepts Proposed for Testing in the WIPP Test Area



A Staged Approach to Field Testing, Starting With Defense Wastes



A field testing program that first focuses on defense wastes will:

- **Provide data relevant to defense waste plus a portion of the civilian SNF inventory**
- **Build operational testing experience needed if subsequent high-heat tests are conducted**

Outline

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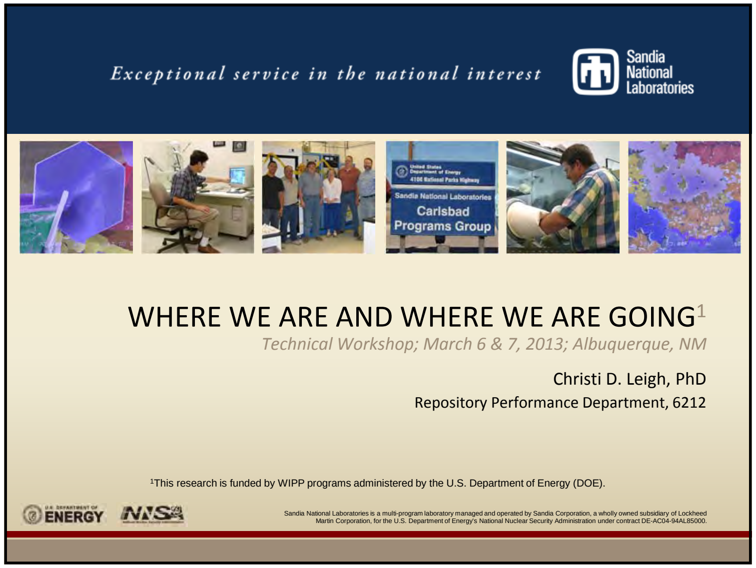
- **Concluding remarks**

Concluding Remarks

- ***Disposal in salt could provide an expeditious solution for some wastes while a long-term R&D effort is needed for other wastes***
- ***One rational approach:***
  - *Near Term Focus: Defense Wastes*
  - *Longer Term Focus: Civilian Wastes*
- ***When proposing a future research need, specificity is important:***
  - *Instead of: "We need better understanding of process x" …*
  - *… Think: "For waste stream y, we need better understanding of process x at…conditions… because experiments have not been performed at those conditions, which will be present in an operating repository for waste stream y"*
- ***It's OK to say that we don't need to study something, but the reasons should be given, they should be specific, and (ideally) the conclusion should be based on adequacy of published scientific studies, and not based solely on a model result.***

Concluding Remarks

- ***Field testing is the end-game for studying the integral behavior of a nuclear waste repository***
  - *Observation of multiple, interacting processes at scale*
  - *Model validation*
  - *Confirmation of disposal concept*
  - *Confidence building*
- ***The opportunity for thermal testing in the short term lies on the defense waste side***
- ***The responsibility of R&D scientists is to maximize the scientific value of a field test, which may have multiple purposes, beyond hypothesis-driven research***
  - *What measurements are most important?*
  - *How do we instrument the test?*
  - *What conceptual and numerical models are we testing?*
  - *What constitutes model validation or model discrimination?*


Exceptional service in the national interest
Sandia National Laboratories
Sandia National Laboratories
Carlsbad Programs Group
WHERE WE ARE AND WHERE WE ARE GOING[1]
Technical Workshop; March 6 & 7, 2013; Albuquerque, NM
Christi D. Leigh, PhD
Repository Performance Department, 6212
[1]This research is funded by WIPP programs administered by the U.S. Department of Energy (DOE).
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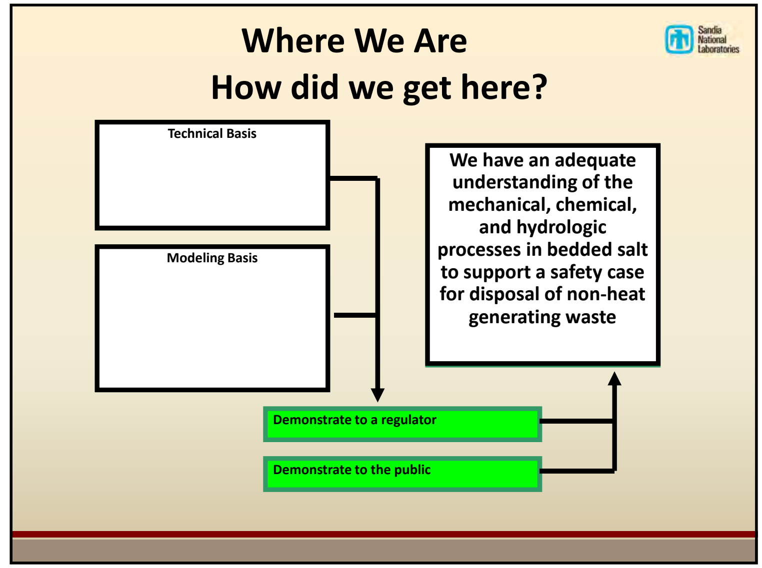
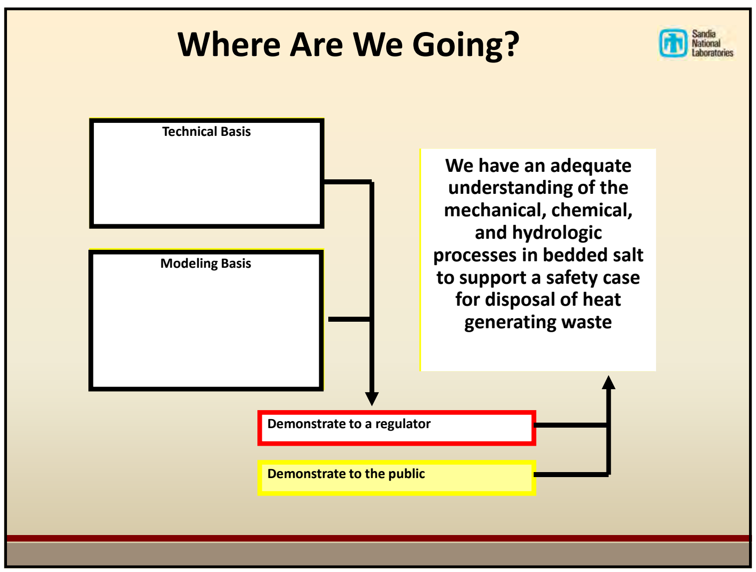

Where We Are
How did we get here?
Sandia National Laboratories
Technical Basis
Modeling Basis
We have an adequate understanding of the mechanical, chemical, and hydrologic processes in bedded salt to support a safety case for disposal of non-heat generating waste
Demonstrate to a regulator
Demonstrate to the public


Where Are We Going?
Sandia National Laboratories
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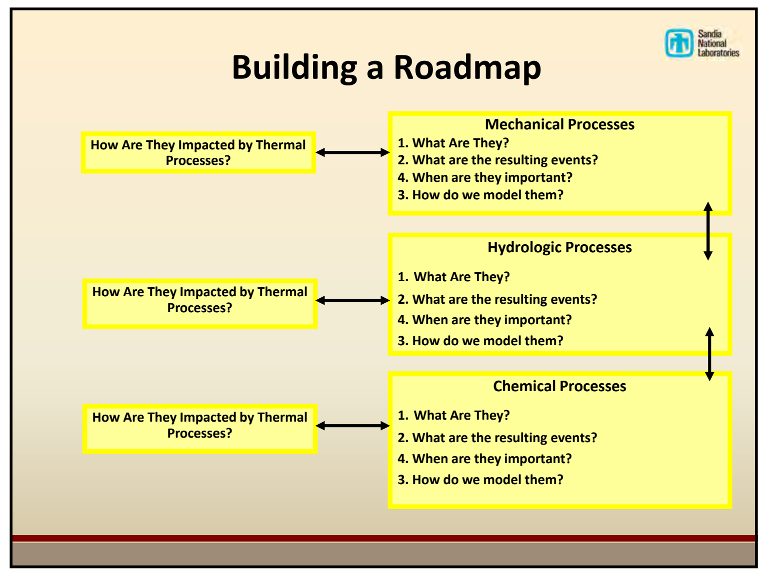
Building a Roadmap
Sandia National Laboratories
How Are They Impacted by Thermal Processes?
Mechanical Processes
1. What Are They?
2. What are the resulting events?
4. When are they important?
3. How do we model them?
How Are They Impacted by Thermal Processes?
Hydrologic Processes
1. What Are They?
2. What are the resulting events?
4. When are they important?
3. How do we model them?
How Are They Impacted by Thermal Processes?
Chemical Processes
1. What Are They?
2. What are the resulting events?
4. When are they important?
3. How do we model them?

Where Are We Going

We have an adequate understanding of and modeling capability for the coupled thermal-mechanical processes in bedded salt to support a safety case for disposal of non-heat generating waste

We have an adequate understanding of and modeling capability for the coupled thermal-hydrologic processes in bedded salt to support a safety case for disposal of non-heat generating waste

We have an adequate understanding of and modeling capability for the coupled thermal-chemical processes in bedded salt to support a safety case for disposal of non-heat generating waste

Thermal Processes

What Are They?

- Heat Conduction
- Heat Radiation
- Convection

What Are The Resulting Events?

Preclosure Events

- Temperature Increases/Decreases
  - Repository Design
    - Ventilation System Design
    - Underground Layout Design
    - Access Shafts/ Drift Design
    - Ground Support
    - Waste Package Design
    - Power Supply
    - Backfill Design
    - Seals Design
  - Site Operations
    - Transfer of Waste Packages
    - Receipt of Waste Packages Underground
    - Transport of Waste Packages to Emplacement Area
    - Emplacement of Waste Packages
    - Emplacement of Backfill Material
    - Operation of Ventilation System
  - Pre-Closure Safety Evaluations
    - Explosive Hazard Analysis
    - Radiological Hazard Analysis
    - Chemical Hazard Analysis
    - Mining Hazard Analysis

Thermal Processes

What Are They?

- Heat Conduction
- Heat Convection
- Radiation

What Are The Resulting Events?

Post Closure Events

- Temperature Increases/Decreases
  - Post-closure Safety Evaluations
    - Engineered Barrier System
      - –Waste Form (material property changes)
      - –Waste Package (material property changes)
      - –Backfill (material property changes)
      - –Seals (material property changes)
      - –Other Materials?
    - Natural Geologic System
      - –EDZ
      - –Host Rock (material property changes)
      - –Interbeds (material property changes)
      - –Water Bearing Units (material property changes)

Mechanical Processes

What Are They?

- Creep
- Fracturing
- Healing
- Reconsolidation
- Buoyancy
- Decrepitation

What Are The Resulting Events?

Preclosure Events

- Porosity Increases/Decreases, Room Closure, Roof Fall, Floor Heave
  - Repository Design
    - Ventilation System Design
    - Underground Layout Design
    - Access Shafts/ Drift Design
    - Ground Support
    - Waste Package Design
    - Power Supply
    - Backfill Design
    - Seals Design
  - Site Operations
    - Transfer of Waste Packages
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    - Explosive Hazard Analysis
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    - Chemical Hazard Analysis
    - Mining Hazard Analysis

Mechanical Processes

What Are They?
- Creep
- Fracturing
- Healing
- Reconsolidation
- Buoyancy
- Decrepitation

What Are The Resulting Events?
Post Closure Events
- Porosity Increases/Decreases, Room Closure, Roof Fall, Floor Heave
  - Post-closure Safety Evaluations
    - Engineered Barrier System
      - Waste Form
      - Waste Package
      - Backfill
      - Seals
      - Other Materials?
    - Natural Geologic System
      - EDZ
      - Host Rock
      - Interbeds
      - Water Bearing Units

Hydrologic Processes

What Are They?
- Brine Movement
- Vapor Movement

What Are The Resulting Events?
Preclosure Events (Changes in Saturation, Changes in Pressure)
- Repository Design
  - Ventilation System Design
  - Underground Layout Design
  - Access Shafts/ Drift Design
  - Ground Support
  - Waste Package Design
  - Power Supply
  - Backfill Design
  - Seals Design
- Site Operations
  - Transfer of Waste Packages
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  - Mining Hazard Analysis

Hydrologic Processes

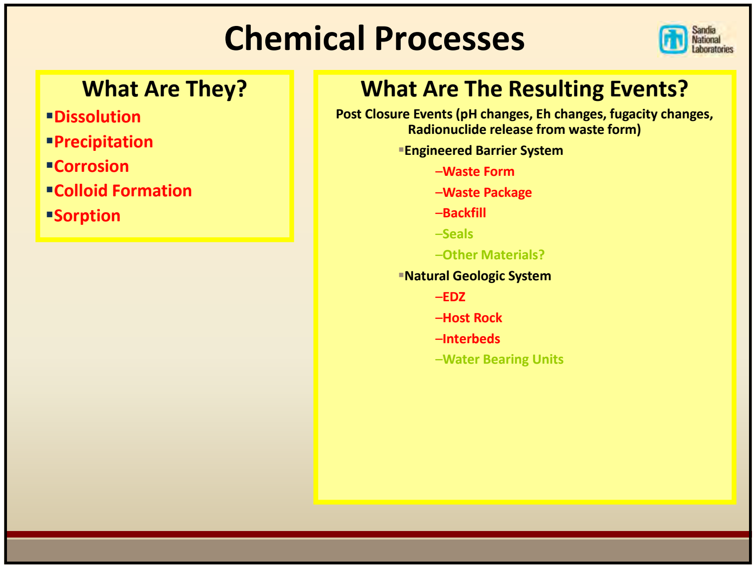
What Are They?
- Brine Movement
- Vapor Movement

What Are The Resulting Events?
Post Closure Events (Changes in Saturation, Changes in Pressure)
- Post-closure Safety Evaluations
  - Engineered Barrier System
    - Waste Form
    - Waste Package
    - Backfill
    - Seals
    - Other Materials?
  - Natural Geologic System
    - EDZ
    - Host Rock
    - Interbeds
    - Water Bearing Units

Chemical Processes

What Are They?
- Dissolution
- Precipitation
- Corrosion
- Colloid Formation
- Sorption

What Are The Resulting Events?
Preclosure Events (pH changes, Eh changes, fugacity changes, Radionuclide release from waste form)
- Repository Design
  - Ventilation System Design
  - Underground Layout Design
  - Access Shafts/ Drift Design
  - Ground Support
  - Waste Package Design
  - Power Supply
  - Backfill Design
  - Seals Design
- Site Operations
  - Transfer of Waste Packages
  - Receipt of Waste Packages Underground
  - Transport of Waste Packages to Emplacement Area
  - Emplacement of Waste Packages
  - Emplacement of Backfill Material
  - Operation of Ventilation System
- Pre-Closure Safety Evaluations
  - Explosive Hazard Analysis
  - Radiological Hazard Analysis
  - Chemical Hazard Analysis
  - Mining Hazard Analysis


Chemical Processes
What Are They?
Dissolution
Precipitation
Corrosion
Colloid Formation
Sorption
What Are The Resulting Events?
Post Closure Events (pH changes, Eh changes, fugacity changes, Radionuclide release from waste form)
Engineered Barrier System
–Waste Form
–Waste Package
–Backfill
–Seals
–Other Materials?
Natural Geologic System
–EDZ
–Host Rock
–Interbeds
–Water Bearing Units

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Summary and Status of US Salt Technical Basis: Actinide and Brine Chemistry

Donald T. Reed
Team Leader: Actinide Chemistry and Repository Science Project
Earth and Environmental Sciences Division
Los Alamos National Laboratory, Carlsbad Operations

Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt
March 6 - 7, 2013, Albuquerque, NM

LA-UR 13-21580

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Overview

- Role and importance of actinide and brine chemistry
  - Repository concept
  - Regulator interactions and influence
- Actinide and brine chemistry in the WIPP safety case
  - Brine chemistry models and experimental results
  - Mobile actinide concentrations
  - Role of reactive barriers
- Gaps in the current "non-thermal" salt repository safety case
- Status of issues specific to HLW/SF

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Successful Safety Case for a Nuclear Repository

Key Concepts for the Geologic Disposal of Nuclear Waste

•Geologic isolation

•Favorable thermodynamics

•Reducing conditions

•Reactive redox control

•Cost is an issue

•Favorable Local politics

Microbial activity can influence both the near-field and far-field in repository performance

WIPP – Existing TRU Repository

HLW?

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Actinide and Brine Chemistry in High Ionic-Strength Systems

Low probability intrusion scenarios lead to the mixing of brine and the TRU wasteform. This leads to the formation of dissolved mobile actinide concentrations that contribute to dissolved brine release (DBR) release scenarios.

The concentration of mobile actinides is defined by the following:

1) Solubility of actinides (thermodynamic "Pitzer" models, empirical solubility data, organic complexation, oxidation-state distribution by expert opinion)
2) Enhancements to the mobile concentration due to the potential for colloid formation are added
3) Isotope-specific waste inventory limits overall availability of actinides

Brine-inundation and associated DBR, although a low probability event, defines the "worst case" scenario for release and is a key driver for the overall safety case

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Importance of the Regulatory Process

The regulatory process (in the WIPP case) is the key driver of the actinide/brine chemistry issues

- **Numerous actinide/brine FEPs exist**
- **There is a sustained expectation/requirement by the EPA regulator that DOE continue to explain the expected actinide/brine chemistry**
- **An understanding of the chemistry associated with the "worst case" scenario of brine inundation greatly strengthens the overall safety case and provides an added assurance that the repository will meet the expected release criteria (no matter what happens)**

The extension of the salt safety case beyond the WIPP/TRU case to HLW/SF will invoke more stringent regulatory requirements (not lower ones)

Current Status of WIPP Brine Chemistry

Current models/data are adequate to support the WIPP safety Case

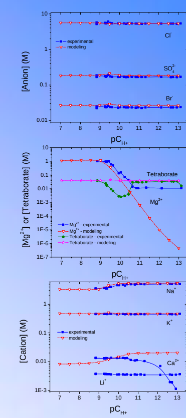
Expected repository conditions:

- **Temperature 28 ± 3 °C**
- **pC_{H+} ~ 9.4 to 9.7**
- **High ionic-strength (>5 M) Mg/Na brines**

Comparison of model predictions to experiment:

- **Good agreement between experimental data and modeling predictions for Cl^-, SO_4^{2-}, Br^-, Na^+, and K^+**
- **Discrepancies are noticed for Mg^{2+} and Ca^{2+} at pC_{H+} > 10**
- **Discrepancies are noticed for tetraborate around pC_{H+} 9-11: Explainable by speciation**

1. DOE Appendix SOTERM 2009
2. Report LCO-ACP-15: WIPP Actinide-Relevant Brine Chemistry (2013)
3. SNL Report: Predictions of the Compositions of Standard WIPP Brines as a Function of pcH for Laboratory Studies of the Speciation and Solubilities of Actinides (2011)



Current Status of Actinide Solubility

Thermodynamic models (Pitzer), although limited, are conservative and adequate for An(III) and An(IV) oxidation states. A regulator-mandated 1 mM solubility for U(VI) is in place.

Table 3. Oxidation-state-specific solubility of actinides in Salado (high magnesium) and Castile (high sodium chloride) brines

	Brine	PAVT 1999	PABC 2004	PABC 2009
An(III)	Salado	$1.2x10^{-7}$	$3.9x10^{-7}$	$1.7x10^{-6}$
An(III)	Castile	$1.3x10^{-8}$	$2.9x10^{-7}$	$1.5x10^{-6}$
An(IV)	Salado	$1.3x10^{-8}$	$5.6x10^{-8}$	$5.6x10^{-8}$
An(IV)	Castile	$4.1x10^{-9}$	$6.8x10^{-8}$	$6.8x10^{-8}$

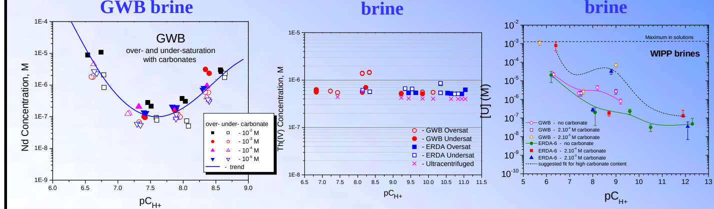
Current Status of Actinide Solubility

Thermodynamic models (Pitzer), although limited, are conservative and adequate for An(III) and An(IV) oxidation states. A regulator-mandated 1 mM solubility for U(VI) is in place. These are supported by empirical solubility date obtained in simulated brine

Nd^{3+} solubility in GWB brine

Th^{4+} solubility in brine

U(VI) solubility in brine



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Importance of Actinides and Oxidation State Distribution in the WIPP

Overall Release: Pu ~ Am >> U > Th >> Np, Cm and fission products

Oxidation State: III > IV >> VI > V

Oxidation State Distribution of Key Actinides in WIPP Performance Assessment

Actinide	Oxidation State III	IV	V	VI	Speciation Data used in Model Predictions
Uranium		50%		50%	Thorium for U(IV), 1 mM fixed value for U(VI)
Plutonium	50%	50%			Am/Nd for Pu(III) and thorium for Pu(IV)
Americium	100%				Americium/neodymium

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Pu(V/VI) Reduction by Lower-Valent Fe

Overall trend

Pu(V/VI)

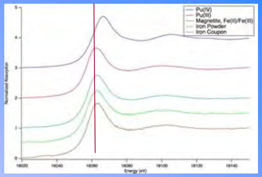
Rapid (aqueous)

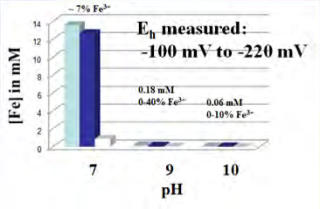
Pu(IV)

Slow (solid phase?)

Pu(III)

~ 5.5-year Analyses





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Role of Colloids in Calculating Dissolved Actinide Concentrations

Actinide Solubility

- **Intrinsic Colloids** → Added concentration of actinide colloids
- **Mineral Fragment Colloids** → Added concentration of minerally-associated actinide colloids
- **Microbial Colloids** → Proportion-ality constant that has a fixed limited contribution
- **Humic Colloids** → Proportion-ality constant that has a fixed limited contribution

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Colloid Data and Current Enhancement Parameters

Table 1 Summary of CRA-2009 and recommended/updated enhancement parameters for mineral and intrinsic colloids

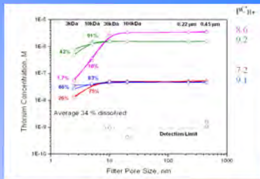
Actinide Oxidation State	Mineral Colloid Enhancement Parameter: CRA-2009	Mineral Colloid Enhancement Parameter: Proposed	Intrinsic Colloid Enhancement Parameter: [1]CRA-2009	Proposed Oxidation-State Specific	[2]Proposed Element-Specific
Th(IV)	2.6×10^{-8} M	2.6×10^{-8} M	0	2×10^{-8} M	2×10^{-8} M
U(IV)	2.6×10^{-8} M	2.6×10^{-8} M	0	2×10^{-8} M	2×10^{-8} M
U(VI)	2.6×10^{-8} M	2.6×10^{-8} M	0	1×10^{-8}M	
Np(IV)	2.6×10^{-8} M	2.6×10^{-8} M	0	2×10^{-8} M	2×10^{-8} M
Np(V)	2.6×10^{-8} M	2.6×10^{-8} M	0	ND	
Pu(III)	2.6×10^{-8} M	2.6×10^{-8} M	1×10^{-9} M	4×10^{-9} M	2×10^{-8} M
Pu(IV)	2.6×10^{-8} M	2.6×10^{-8} M	1×10^{-9} M	2×10^{-8} M	
Am(III)	2.6×10^{-8} M	2.6×10^{-8} M	0	4×10^{-9} M	4×10^{-9} M

1 - for CRA-2009, only plutonium intrinsic colloids are considered
2 – for the element-specific case, the highest value is proposed
ND – not determined

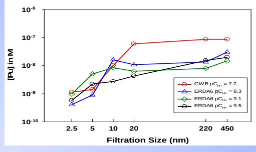
Table 3 Summary of CRA-2009 and recommended/updated element-specific enhancement parameters for microbial colloids

Actinide Oxidation State	[1]PROPMIC: CRA-2009 (M)	[1]PROPMIC: Proposed (M) Archaea	[1]PROPMIC: Proposed (M) Bacteria	[1]CAPMIC (M): CRA-2009	[1]CAPMIC (M): Proposed (M) Archaea	[1]CAPMIC (M): Proposed (M) Bacteria
Th(IV)	3.1	0.15	1.2	0.0019	6.2E-8	2.3 E-7
U(IV)	0.0021	0.15	1.2	0.0021	6.2E-8	2.3 E-7
U(VI)	0.0021	0.15	1.2	0.0021	6.2E-8	2.3 E-7
Np(IV)	12	0.15	1.4	0.0027	6.2E-8	4 E-7
Np(V)	12	0.15	1.4	0.0027	6.2E-8	4 E-7
Pu(III)	0.3	0.15	1.2	6.8E-5	6.2E-8	2.3 E-7
Pu(IV)	0.3	0.15	1.2	6.8E-5	6.2E-8	2.3 E-7
Am(III)	3.6	0.031	0.46	1.0	6.7E-10	7.6 E-9

ND – not determined, no new recommendation
1 – highest value for a particular element is recommended for the element, this is extended to all oxidation states even if they are "ND"



Size –Fractionation of Thorium(IV)



Size –Fractionation of Plutonium(III)

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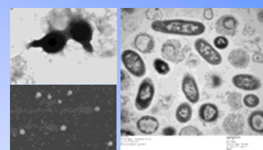
Microbial Ecology in the WIPP: Aerobic

- Extremely halophilic *Archaea* (all members of class *Halobacteria*):
  - *Halobacterium* (sorption experiments)
  - *Halorubrum*-like (unclassified; sorption experiments)
  - *Halolamina*
  - *Natronomonas*
- Halotolerant to moderately halophilic *Bacteria*:
  - *Proteobacteria*
  - *Actinobacteria*
  - *Firmicutes* (Vreeland et al., 2000)
- Halotolerant to moderately halophilic *Fungi* (all members of phylum *Ascomycota*):
  - *Cladosporium*
  - *Coniothyrium*
  - *Tritirachium*



Halobacterium noricense *Chromohalobacter sp.*

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WIPP Groundwaters—Anaerobic

- Moderate to extremely halophilic *Archaea* (all *Halobacteria*), viable but not growing anaerobically:
  - *Natrinema*
  - *Haloferax*
  - *Haloarcula*
- Halotolerant to moderately halophilic *Bacteria:*
  - *Proteobacteria* (including iron- and sulfate-reducers)
  - *Bacteroidetes*
  - *Firmicutes* (including iron-reducers and fermenters)

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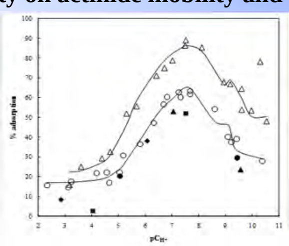
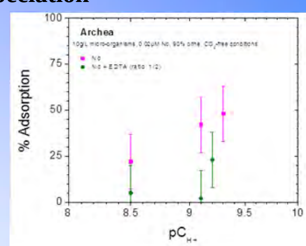
Actinide-Microbial Interactions: Biosorption

Microbial interaction studies are being conducted as a function of ionic strength to establish the potential effects of microbial activity on actinide mobility and speciation



Biosorption of Np(V) onto bacteria



Biosorption of Nd(III) onto archaea

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Gaps in our Current Understanding

The WIPP model is adequate and has been certified three times. Many conservatisms, however, are used to bridge gaps that exist in our current understanding. The most important gaps are:

- **Pitzer parameter availability is limited and some additional data are needed:**
  - **Magnesium data**
  - **Borate complexation of actinides**
  - **Fe, Pb, U and Pu**
  - **Many parallel activities are underway – need to coordinate this better**
- **Mechanistic understanding of redox control:**
  - **Fe reactions as f(I), bioreduction pathways**
  - **Role and stability of Pu(III) el**

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Gaps in our Current Understanding - continued

- Colloid model that reflects current understanding
  - o Additional studies to establish time-dependence, structure, and stability
  - o Reconfiguration and assessment of the overall mod
- Microbial Interactions and Effects
  - o Continued characterization of salt and saline-indigenous microorganisms
  - o Biodegradation pathways under anaerobic conditions
  - o Actinide effects and interactions

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Issues/needs Introduced by the Consideration of HLW/SF

- Effects of elevated temperature on many processes
  - Water and gas migration and availability
  - Actinide solubility and redox processes
  - Microbial activity and viability
  - Key link to exploratory and confirmatory underground tests
- Effects of radiolysis on redox and actinide speciation
  - In the WIPP, this is excluded based on the Fe interactions and relatively low activity of the waste
  - For HLW/SF, activities are much higher, availability of reductants (e.g., Fe) is unknown
- A broader range of radionuclides
  - Np, Cs/Sr, I, Tc

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Dehydration Experiments - Autoclaves

Left: Rocking autoclave rack (400 oC/600 bar) Center: AE (Bridgeman seal-type) pressure vessel, for 600 oC/1.5 kbar furnaces (vessel is ~24" tall). Right: Furnace for Cold Seal reaction vessels. Note that inner mullite sleeve is not yet inserted in this photograph.

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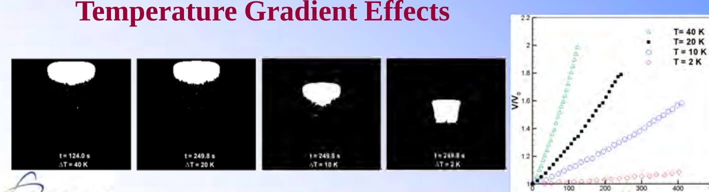
Modeling Study: Effects of inclusion size and temperature

Inclusion Size Effects

Temperature Gradient Effects



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Summary of Observations: Perspective of Actinide and Brine Chemistry

- **Regulatory interactions and requirements are the key drivers that require us to address the low-probability event of brine inundation and associated brine and actinide chemistry**
- **The WIPP safety case adequately addresses the actinide and brine chemistry issues by using conservative assumptions to fill in the gaps**
- **Key gaps in the current safety case are 1) additional Pitzer parameter data and 2) a more mechanistic understanding of key processes**
- **HLW/SF (thermal) nuclear waste introduces uncertainties associated with elevated temperature, radiolysis, and broader and much higher activity set of radionuclides that need to be addressed.**
- **Brine/actinide chemistry issues are coupled with brine migration and availability. Understanding this, especially at elevated temperature, is the key connection with this field and laboratory/in-situ testing in salt.**

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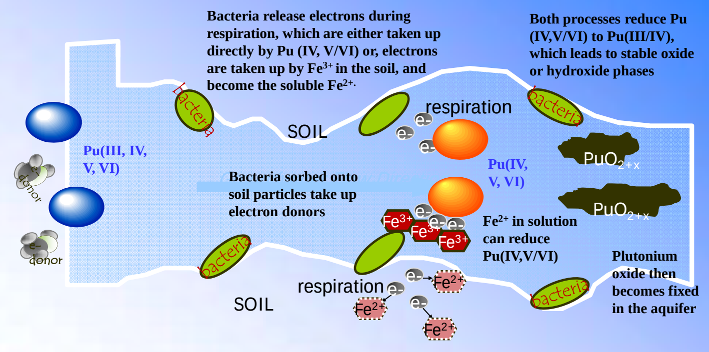
Microbial Interactions lead to Multiple Effects on Actinide Speciation that Affect Mobility



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Used Fuel Disposition Campaign

Modeling Coupled THM Processes in Salt: Technical Status and Some LBNL Research Examples

Jens Birkholzer, Jonny Rutqvist, Laura Blanco-Martin, and Jim Houseworth
Lawrence Berkeley National Laboratory

Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt
Albuquerque, March 6 - 7, 2013

Used Fuel Disposition

Salt Rock for Nuclear Waste Disposal

- Salt is attractive for nuclear waste disposal
  - Very low permeability in its undisturbed state
  - Low water content
  - Visco-plastic behavior leads to self-sealing following mechanical damage
- Emplacement of heated waste in salt rock leads to coupled THM processes
  - Excavation and heat change rock stress and cause large deformation
  - Deformation can cause permeability increase
  - Thermal and mechanical perturbation can mobilize water present in salt
    - *vapor-phase transport in intergranular micro-fractures*
    - *thermal (upgradient)migration through dissolution/precipitation mechanisms*
    - *stress-induced water flow*
    - *thermal effects can also release water through mineral dehydration (e.g., gypsum)*
    - *fluid pressure changes from rock deformation and temperature increase*
  - Crushed salt backfill sealed by convergence of host rock through thermo-mechanical creep
- Water and vapor-phase flow can lead to alteration of salt mechanical properties and potential degradation of waste package system (the latter depending on quantity and chemistry of water)

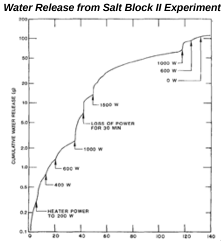
2

Used Fuel Disposition

Quantities and Nature of Water in Salt

- Water Content (excluding hydrous minerals)
  - Bedded Salt: typically 0.1 to 1% by weight (WIPP salt ranges from <0.1% 1.7% and is highly spatially variable)
  - Domal Salt: much lower water content (e.g., Louisiana salt domes are of the order of 0.003% by weight)
- Nature of the water in salt
  - Fluid inclusions (intragranular water present as unconnected, water filled pores)
  - Grain-boundary fluid-filled pores
  - Hydrous minerals
- Hydrous Minerals (e.g. anhydrite, clays) – impure halite can have water-containing minerals with quantities exceeding the pure brine. Mineral dehydration reactions can be a source of additional liberated water.

Water Release from Salt Block II Experiment



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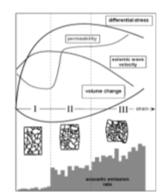
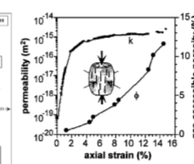
Hohlfelder, 1979, SAND79-1519.

Used Fuel Disposition

Thermo-Hydro-Mechanical Coupling

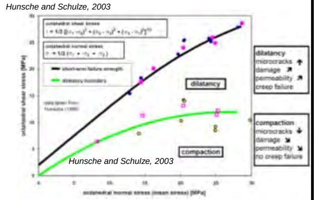
- Permeability damage can be induced by thermal-mechanical strain in salt rock
  - appears to be related to connecting micropores or microcracks
  - shows strong anisotropic permeability enhancement
- Salt rock shows significant dilatancy regime
  - dilatancy damage regime results in more stable rock damage behavior (ductile) caused by mechanical stress or pore pressure
  - fracture development only at even higher differential stress or pore pressure
- Observations of natural invasion of fluids in fractured or dilatant salt as a result of excess fluid pressure (Schléder et al., 2007; Schoenherr et al., 2007)





Popp et al., 2001

Hunsche and Schulze, 2003



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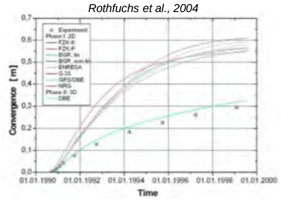
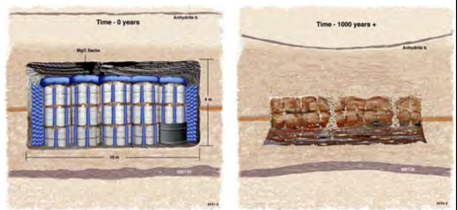
Used Fuel Disposition

Thermal-Hydro-Mechanical Modeling and Testing

- Modeling, lab testing, and field testing are important to understand and predict potential salt rock behavior in response to coupled processes
- Field studies at WIPP and elsewhere have led to good understanding of thermal-mechanical effects, but transport of water, though observed, is less well understood
- Several models for thermal-mechanical coupled processes in salt rock have been benchmarked against the Thermal Simulation of Drift Emplacement (TSDE) conducted in the Asse Salt Mine in Northern Germany
- Experimental data and models specifically addressing thermal-hydro-mechanical behavior are much more limited and require further investigation
- Particularly complex is coupled hydro-mechanical modeling with large deformation

Rothfuchs et al., 2004





Erickson and Dials, RadWaste Solutions, Jan.-Apr., 24-34, 2011.

Used Fuel Disposition

Coupled Models for Salt

- **Codes with Focus on Thermal-Mechanical Processes (with complex constitutive relationships for salt M and T; simple H)**
  - Sierra Mechanics
  - Abaqus
  - FLAC^{3D}
- **Codes with Focus on Thermal-Hydrological-Mechanical Processes (not developed with salt mechanical complexities in mind)**
  - **TOUGH coupled to FLAC^{3D} (ongoing developments for salt applications)**
  - FEHM (elastic M)
  - CODEBRIGHT
- **Next Generation Codes (High Performance Computing based)**
  - ASCEM – THC is prioritized, M may be considered in the future
- **Long-Term Goal**
  - Fully coupled THM, possibly C, on HPC platform

6

Used Fuel Disposition

LBNL Salt Coupled THM Processes Modeling

TOUGH-FLAC coupled THM simulator combined with Salt Coupled THM constitutive models:

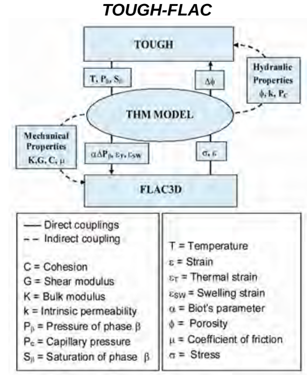
- **The TOUGH-FLAC simulator was developed and used for modeling thermally-driven coupled processes in fractured unsaturated tuff.**
- **The FLAC^{3D} geomechanics code is widely used for modeling of salt geomechanics; includes visco-plastic creep models for both solidified and crushed salt.**
- **Combining FLAC^{3D} with TOUGH2 provides a modeling tool for salt coupled processes at high-temperature, including multi-phase flow and transport processes.**
- **Professor Lux and his group at Clausthal University currently collaborate with LBNL in applying TOUGH-FLAC for modeling salt coupled THM processes in Germany.**

7

Used Fuel Disposition

TOUGH-FLAC and Lux/Wolters Constitutive Model

TOUGH-FLAC



Lux/Wolters constitutive model

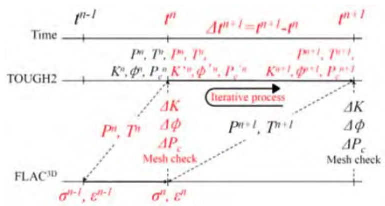
Developed at Clausthal University on the basis of laboratory investigations designed to study, from a phenomenological-macroscopic viewpoint, the mechanisms involved in the damage and healing of rock salt formations.

The strain rate tensor includes:

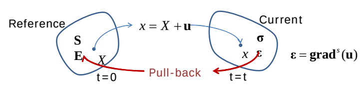
1) *Elasticity*
2) *Constant-volume viscoplasticity (nonlinear, damage-free Burgers model, including stationary and transient creep)*
3) *Damage-induced phenomena at non-constant volume (shear and tensile failure),*
4) *Sealing and healing processes (i.e., reduction of dilatancy and damage).*

Used Fuel Disposition

TOUGH-FLAC and Large Strain Coupling



- *Standard FLAC3D developed for modeling problems of strong non-linearity and large strain*
- *Current approach is to update mesh in TOUGH2 based on FLAC3D large strain results*



$$\mathbf{S} = J\mathbf{F}^{-1}\boldsymbol{\sigma}\mathbf{F}^{-T}, (S_{AB} = J\frac{\partial X_A}{\partial x_a}\sigma_{ab}\frac{\partial X_A}{\partial x_b})$$

$$\delta\Phi = \underbrace{\left(\frac{b_B-\Phi_0}{K_s^0}+\frac{b_B^2}{K_{dr}^0}\right)}_{\Phi_0 c_p}\delta p + \underbrace{3\alpha_T b_B}_{\Phi_0 c_T}\delta T - \frac{b_B}{K_{dr}^0}\delta S_v$$

- *Alternative approach being developed and implemented in which the original undeformed mesh (reference configuration) is used in TOUGH2 with a porosity correction based on Second Piola Kirchhoff stress*

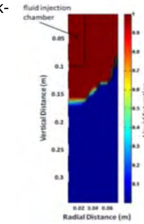
Used Fuel Disposition

Modeling Overpressured Salt Damage Infiltration Experiment

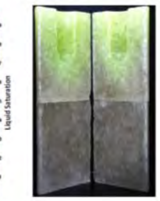
At pressures in excess of the minimum confining pressure, rock salt is damaged and causes the rock-salt permeability to increase, such that fluid infiltration into the rock salt can occur (Lux, 2009).

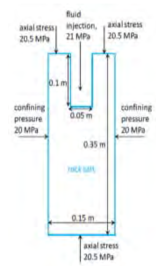
Use of Lux/Wolters constitutive model in TOUGH2 with hydraulically induced damage

TOUGH Saturation profiles at 6 days

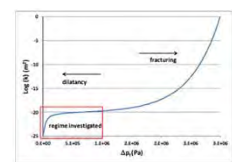


Fluorescent green dye pattern from rock salt fluid-injection experiment (Lux, 2009)

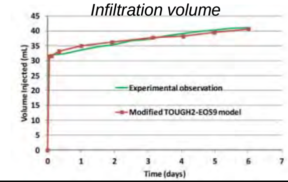




Lux/Wolters model for Permeability vs Overpressure

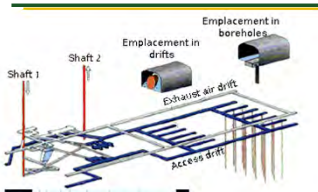


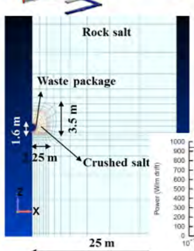
Infiltration volume

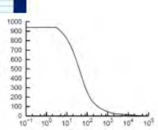


Used Fuel Disposition

TOUGH-FLAC Modeling of Coupled THM Response of a Hypothetical Repository







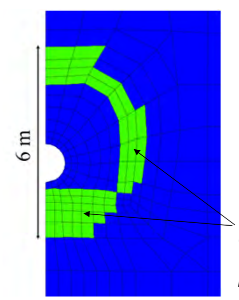
- *For testing the applicability of the modeling approach to a realistic generic salt repository case*
- *German repository concept and geometry with emplacement in a horizontal tunnel backfilled with crushed salt*
- *Heat load from UFD GDSE*
- *2D vertical cross-section including both EBS and salt host rock*
- *High temperature (up to 200°C), including relevant coupled processes*
- *Large strain compaction of crushed salt*
- *Application of Lux/Wolters constitutive model for creep and thermomechanical permeability damage*
- *Evaluate the preservation of the initial mechanical and hydraulic barrier integrity of the host rock over the long-term*

Used Fuel Disposition

TOUGH-FLAC Modeling of Coupled THM Response of a Hypothetical Repository

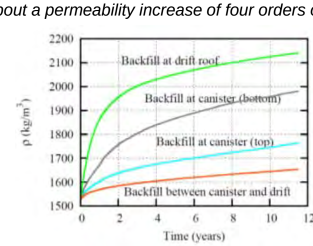
THM large strain analysis with Lux/Wolters constitutive model

- *At 12 years, the vertical convergence of the drift is approximately 30 cm, with a major contribution from the floor uplift. The sidewall displacement is about 20 cm.*
- *The crushed salt near the drift roof has almost attained the density of intact salt (see figure below).*
- *The thermomechanically-induced damage in the disturbed zone brings about a permeability increase of four orders of magnitude.*



THM induced damage zone with increased permeability

THM results in deformed mesh configuration at 12 years



Used
Fuel
Disposition

TOUGH-FLAC and Salt Coupled Processes

Current work

- Testing the applicability of TOUGH-FLAC and Lux/Wolters constitutive model on generic repository at high temperatures
- Development and validation of more efficient algorithms for THM coupling under large strain

Next

- Simulate TSDE (Thermal Simulation of Drift Emplacement) at Asse Mine in which two simulated emplacement drifts were heated to between 170 °C and 200 °C (thermal mechanical study of crushed salt compaction)

Used
Fuel
Disposition

Conclusions

- **Salt mechanical properties and long-term creep behavior are impacted by the presence of water, which in turn can be liberated and mobilized by thermal and mechanical perturbation**
- **The interplay of THM processes over multiple scales must be investigated through lab-scale and field–scale experiments and related modeling**
- **Experimental data and models specifically addressing T and M effects on H are limited and require further investigation**
- **Advanced laboratory characterization methods and advanced field monitoring tools will help evaluate the multi-scale nature and behavior of water in salt under relevant repository conditions**
- **Long-term modeling goal is the ability to simulate full THM (maybe C) coupling and large deformation with high-performance simulators**

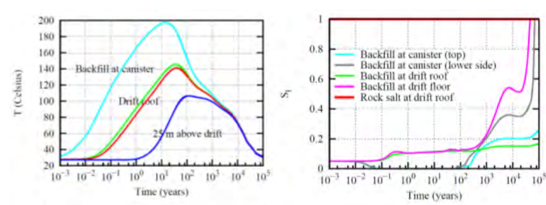
Used
Fuel
Disposition

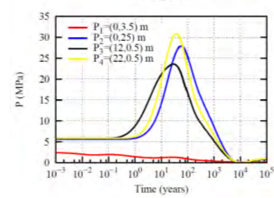
Backup

Used
Fuel
Disposition

TOUGH-FLAC modeling of coupled THM response of a hypothetical repository

Thermal-hydrological results over 100,000 years without geomechanical coupling





- *Peak temperature 200 °C in the backfill at 14 years and 140 °C in the drift wall at about 40 years*
- *Slow brine infiltration from rock and gravity flow towards the bottom of the drift*
- *Thermal pressurization within the saturated low porosity (0.2%) and low permeability (1e-22 m²) host rock.*

Exceptional service in the national interest

Sandia National Laboratories

Day 1 Breakout Group Instructions Salt R&D Workshop

S. David Sevougian

Workshop on Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt

Albuquerque, NM, USA
March 6, 2013

U.S. DEPARTMENT OF ENERGY NNSA

Major Tasks of the Breakout Groups

1) Review strawman R&D issue list and the associated importance ratings—provide comments/revisions as necessary
2) For high importance (H) items that are not currently being addressed by UFD R&D tasks (see issue table), define specific activities/ tests/modeling needed to advance the state of the art
3) Answer the test questionnaire for each newly proposed activity/ test/model
4) If you move any medium importance (M) or low importance (L) issues to a high (H) ranking, define specific activities/ tests/modeling to address these issues (if these items are not currently being addresses by UFD R&D activities)

Major Tasks of the Breakout Groups (cont.)

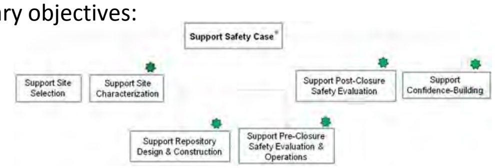
5) Group 1 (Postclosure) assignments:
   - Concentrate on issues and test design from a postclosure perspective (EBS postclosure processes within the excavation and NBS postclosure processes in the host salt formation)
   - Look at all feature/process issues (the first 30 issues) but concentrate on your assigned feature/process issues ("1")
   - Modeling issues are also assigned to your group
   - If time, look at confidence-building issues
6) Group 2 (Preclosure) assignments:
   - Group 2: Concentrate on issues and test design from a preclosure perspective (design, demonstration, and preclosure)
   - Look at all feature/process issues (the first 30 issues) but concentrate on your assigned feature/process issues ("2")
   - *In-Situ* Testing/Design/Operations issues are also assigned to your group
   - If time, look at confidence-building issues

Basis for Formulation of R&D Issue List

- Sources for Salt R&D Issues:
  - UFD R&D Roadmap and FEPs list
  - Hansen and Leigh 2011
  - F. Hansen 2013 IHLRWMC paper
  - SDDI proposal
  - SDI proposal
  - Gorleben FEPs list
  - Expert judgment
- In a safety or licensing case, *all* R&D issues and FEPs must ultimately be addressed with technical arguments and evidence:
  - But at this earlier stage of the safety case (still generic) and with the currently limited resources, prioritization of issues for R&D is important
  - Existing broad technical basis for salt (WIPP, Germany) implies a reduced set of high importance issues, with most of those related to the effects of heat generation

General Basis for Importance Ratings of Issues

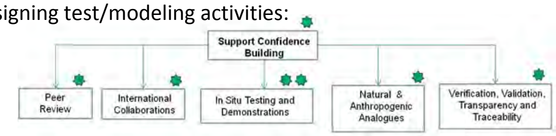
- What determines "importance"? This refers to importance to achieving a *successful safety case*, which has the following primary objectives:



- Strawman salt R&D issue list is primarily based on importance to *postclosure safety* ("…arguably the most important part of the safety case..." NWTRB 2011):
  - Postclosure safety and repository design are strongly linked in that the repository design should facilitate safety—but they are included as two separate objectives here and in the R&D Roadmap
  - Design is also important in the preclosure stage

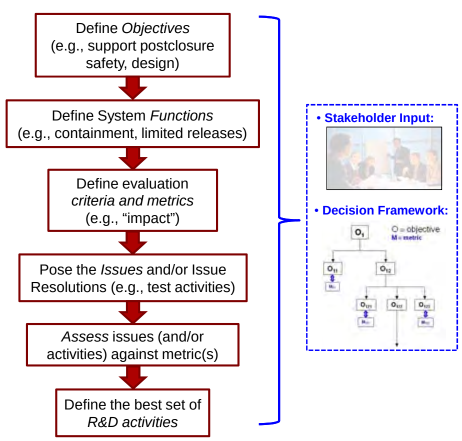
General Basis for Importance Ratings (cont.)

- *Confidence-building* is the other key objective to be considered in designing test/modeling activities:



  - Can be used to refine/revise the strawman R&D list, e.g., to move a current "M" issue to an "H" level, based on current *"state-of-the-art" knowledge:*
    - Confidence-building activities (or any R&D activities) are more justified for an "M" issue with high parameter/model uncertainty than for an "H" issue with low uncertainty—uncertainty or "state-of-the art" evaluation is included in the test questionnaire
  - Confidence-building activities are critical to a subset of key stakeholders
- Decision-makers will decide what weight or importance to give to the confidence-building objective versus the postclosure safety objective:
  - Given a more mature technical basis, confidence-building activities may receive a higher rating than FEPs-specific R&D activities (e.g., constituitive model development)

General Process for Importance Ratings of Issues



System Functions and Impact Metric

- **Postclosure Safety and Design Functions:**

Function	Type	Importance	Definition	Examples of Key Associated Parameter(s) or Characteristic(s)
Isolation/stability	Safety	Primary (P)	Aspects of the repository that isolate the waste and the EBS from external events or changes, and therefore help maintain the integrity and longevity of the barriers.	(high) seal integrity; (thick) host rock zone horizon; non-communication between salt beds and interbeds
Containment	Safety	Primary (P)	Aspects of the repository that prevent fluid contact with the waste.	(very low) permeability
Limited or delayed releases	Safety	Secondary (S)	Aspects of the repository that reduce the transfer of radionuclides to the accessible environment after the containment function is compromised.	(high) sorption, (low) solubility, (low) dissolution rates
Retrievability	Design	Primary (P)	Aspects of the repository that allow for retrievability of the emplaced waste without any releases, for a specified period of time after closure.	(sufficient) WP thickness

- **Impact of an R&D Issue on Performance of a Safety/Design Function (for process/parameter issues), or on Confidence in the Demonstration of that Performance (for models or *in situ* tests):**

Impact of an R&D Issue on the Performance of a Postclosure Safety or Design Function	
D	Direct and potentially significant impact on the success of a safety or design function
I	Indirect but potentially significant impact on the success of a safety or design function
W	Weak impact (whether direct or indirect) on the success of a safety or design function

Importance Value Ratings and Issue Categories

- **Importance Value Ratings (H, M, or L) for R&D Issues (based on function type and impact category):**

Impact of Issue \ Function Type	Primary (P) safety function	Secondary (S) safety function
Direct (D) impact	High	Low
Indirect (I) impact	Medium	Low
Weak (W) impact	Low	Low

(Note: An R&D Issue receives a rating according to its highest function-impact combination, i.e., it may receive an L rating for one function but if it gets an H for another function, it inherits that highest rating.)

- R&D Issue categories:
  - Feature/process issues (this is the primary focus of the breakout groups)
  - Modeling issues
  - *In-Situ* Testing/Design/Operations Issues
  - Confidence-Building Issues

Salt R&D Feature/Process Issues

(Please concentrate on your assigned issues but look at all issues)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction, PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure, 2 = Preclosure & Design, 3 = Field Testing	Current UFD Salt R&D Activity
Wastes and Engineered Features (EBS) Feature/Process Issues					
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)	D, PrSO, PoS	2	
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)	D, PrSO, PoS	1, 2	
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability	D, PrSO, PoS	1, 2	3.1 3.2 4.4
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent gas generation (M) Indirectly related to limited and delayed releases (L)	D, PoS	1	3.6 4.4
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)	D, PrSO, PoS	2	3.1 3.2 4.4
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability	D, PoS	2	

Salt R&D Feature/Process Issues (cont.)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction, PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure, 2 = Preclosure & Design, 3 = Field Testing	Current UFD Salt R&D Activity
Wastes and Engineered Features (EBS) Feature/Process Issues					
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation	D, PrSO, PoS	1, 2	4.4
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository	D, PoS	1	2 3.5 3.6
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases	D, PoS	1	
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases	D, PoS	1	
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	Indirectly related to limited and delayed releases		1	3.6
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	D, PoS	1	3.7
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases	D, PoS	1	

Salt R&D Feature/Process Issues (cont.)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) / High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction, PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure, 2 = Preclosure & Design, 3 = Field Testing	Current UFD Salt R&D Activity
Natural Barriers (Host Rock and EDZ) Feature/Process Issues					
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design	D, PrSO, PoS	2	Site-specific
15. Changes in physical-chemical, properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)	D, PrSO, PoS	1, 2	2 3.3 4.3 4.4
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)	D, PrSO, PoS	2	3.3 4.3 4.4
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone	D, PrSO, PoS	2	4.4
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion)	D, PoS	1, 2	3.4 4.4
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases	PoS	1	
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)	D, PoS	1	4.4

Salt R&D Feature/Process Issues (cont.)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing	Current UFD Salt R&D Activity
Natural Barriers (Host Rock and EDZ) Feature/Process Issues					
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases	PoS	1	3.7
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases	PoS	1	
Repository System (EBS and NBS combined) Feature/Process Issues					
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constituitive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).	D, PrSO, PoS	2	3.2 4.4
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation	D, PoS	2	
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing	D, PrSO, PoS	1	
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases	PoS	1	
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases	PoS	1	
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository	D, PoS	2	
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions	D, PrSO, PoS	2	
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing) Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides	D, PrSO, PoS	2	

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R&D Modeling Issues (Group 1)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing	Current UFD Salt R&D Activity
Modeling Issues					
31. Appropriate constituitive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	D, PoS	1, 3	3 4.4
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	D, PoS	1, 3	4.4
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	PoS	1, 3	4.2 4.4
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	D, PoS	1, 3	4.2 4.4
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions	PoS	1, 3	4.2
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions	PoS	1, 3	
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	PoS	1, 3	4.3
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)	D, PrSO, PoS	1, 3	1

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R&D *In-Situ* Testing/Design/Operations Issues (Group 2)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing	Current UFD Salt R&D Activity
***In-Situ* Testing/Design/Operations Issues**					
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of in situ stresses and rock movement (H) and brine and vapor/gas movement (M)	PrSO, PoS	2, 3	2.1 6.1 6.2
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function	D, PrSO, PoS	2, 3	
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)	May not be possible in the time frame of an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function	PoS	2, 3	
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions	PrSO, PoS	2, 3	4.3

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R&D Confidence-Building Issues (Groups 1 and 2, if time)

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type) High Heat Load ratings	Explanation of Issue Importance Rating	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing	Current UFD Salt R&D Activity
Confidence-Building Issues					
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety	D, PrSO, PoS	1, 2, 3	4.1
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes	PoS	1, 2, 3	
45. International peer review and collaboration	M	Adds credibility with the scientific community	D, PrSO, PoS	1, 2, 3	5
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42	D, PrSO, PoS	1, 2, 3	
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs	PrSO, PoS	1, 2, 3	
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency	PoS	1, 2, 3	

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R&D Issues Cross-walked to UFD FEPs

- Additional information about each feature/process issue
- Example page:

R&D Technical Issue	Issue Importance Rating (H = High, M = Medium, L = Low) Based on (impact, function type)	UFD FEP Crosswalk	Safety Objective: D = Design & Construction PrSO = Preclosure Safety & Operations, PoS = Postclosure Safety	Breakout Group: 1 = Postclosure 2 = Preclosure & Design 3 = Field Testing	Current UFD Salt R&D Activity
Natural Barriers (Host Rock and EDZ) Feature/Process Issues					
17. The formation and evolution of the EDZ	H (= D,P)	1.1.02.02 Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 1.1.02.03 Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock 2.1.07.10 Mechanical Degradation of EBS 2.2.01.01 Evolution of EDZ - Salt 2.2.07.01 Mechanical Effects on Host Rock - Salt 2.1.07.02 Drift Collapse - Drift deformation (EDZ) 2.2.08.06 Flow Through EDZ - Salt 2.2.08.07 Mineralogic Dehydration - Salt 2.2.09.01 Chemical Characteristics of Groundwater in Host Rock - Salt 2.2.09.03 Chemical Interactions and Evolution of Groundwater in Host Rock - Salt 2.2.11.04 Thermal Effects on Chemistry and Microbial Activity in Geosphere - Salt 2.2.11.06 Thermal-Mechanical Effects on Geosphere - Salt 2.2.11.07 Thermal-Chemical Alteration of Geosphere - Salt 2.2.12.02 Effects of Gas on Flow Through the Geosphere - Salt	D, PrSO, PoS	2	4.4

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Test Questionnaire

1) Name of Test:
2) Test Objectives, Description, and Type (lab, field, etc.):
3) R&D Issue(s) Addressed by Test (field tests should include one or more “H”-rated issues):
4) Safety case objectives addressed by test (e.g., postclosure safety; preclosure safety; confidence building) and why the test is important to the safety case:
   - List objectives in order of applicability (e.g., 1. Postclosure safety, 2. Confidence-building, etc.)
5) For the proposed test describe the current “state of the art” knowledge regarding the issue(s) it addresses; in other words, why is this data necessary?
6) Define the data that will be collected/measured (e.g., name and description of process(es)/parameter(s), time duration, spatial scale, frequency, accuracy):
   - Describe how the data will be collected
7) Define the instrumentation that will be used to measure process(es)/ parameter(s) and define the instrumentation placement or layout:

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Test Questionnaire (cont.)

8) Define the pre-and post-test modeling/simulation needs for the activity, including:
   - Description and type of model addressed by test (constituitive; process; coupled process; N/A if testing for constructability)
9) List system features involved in test (e.g., waste package; backfill; seal system; EDZ; pristine host rock; etc.):
10) Time period of applicability for data gathered: pre-emplacement; preclosure, postclosure:
    - E.g., data gathered applies to processes occurring during first 300 years after closure; data gathered applies to processes that occur over 10,000 years after closure; etc.
11) For field tests define additional lab tests or other separate activities/data needed to support this test:

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All Reference Materials (handouts)

- Primary Handouts:
  - Salt R&D Issues table with importance ratings
  - Test proposal questionnaire
- Backup Material:
  - Table of R&D issues crosswalked to UFD FEPs
  - Table of FEPs considered in the formulation of the R&D issues for this workshop, along with “state of the art” explanations for each FEP from UFD Roadmap
  - Table of *all* UFD FEPs (208) from FCRD-UFD-2012-000320, Rev. 0
  - Current Salt R&D Study Plan (3/23/2012)
  - F. Hansen 2013 IHLRWMC paper
  - Proceedings of 3rd U.S./German Workshop (held in October 2012)
  - SDDI Proposal
  - Hansen and Leigh 2011

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Breakout Group Assignments

Group 1 (Postclosure)

Name	Org	Breakout Group
Brush, Larry	SNL	1
Caporuscio, Florie	LANL	1
Dunagan, Sean	SNL	1
Freeze, Geoff	SNL	1
Harp, Dylan	LANL	1
Jove-Colon, Carlos	SNL	1
Kneafsey, Tim	LBNL	1
Kuhlman, Kris	SNL	1
Levitt, Dan	LANL	1
Nair, Prasad	DOE	1
Reed, Don	LANL	1
Roselle, Greg	SNL	1
Rutqvist, Jonny	LBNL	1
Sevougian, David	SNL	1
Swanson, Julie	LANL	1
van Luik, Abe	DOE	1
Wang, Yifeng	SNL	1
Wolery, Tom	LLNL	1
Xu, Hongwu	LANL	1

Name	Org	Breakout Group
MacKinnon, Robert	SNL	roving
Robinson, Bruce	LANL	roving

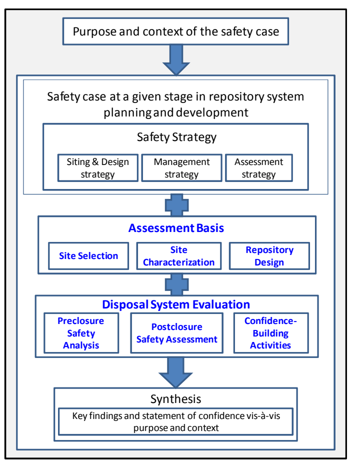
Group 2 (Preclosure)

Name	Org	Breakout Group
Bauer, Steve	SNL	2
Birkholzer, Jens	LBNL	2
Boukalfa, Hakim	LANL	2
Buschman, Nancy	DOE	2
Carter, Joe	SRNL	2
Cheshire, Mike	LANL	2
Daley, Tom	LBNL	2
Elkins, Ned	LANL	2
Hansen, Frank	SNL	2
Hardin, Ernie	SNL	2
Icenhower, Jonathan	LBNL	2
Kang, Qinjun	LANL	2
Leigh, Christi	SNL	2
Nelson, Roger	DOE	2
Rehfeldt, Ken	LANL	2
Schuhen, Mike	SNL	2
Senderling, Mark	DOE	2
Shoemaker, Paul	SNL	2
Stauffer, Phil	LANL	2
Stroud, Cliff	LANL	2
Weaver, Doug	LANL	2

Backup Slides

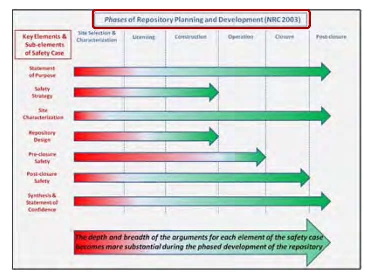
Elements of the Safety Case

- Purpose and Context
- Safety Strategy
- Assessment Basis
  - Site Selection
  - Site Characterization
    - Natural Barriers
  - Repository Design
    - Disposal Concept
    - Waste Inventory
    - Engineered Barriers
- Disposal System Evaluation
  - Preclosure Safety Analysis
  - Postclosure Safety Assessment
  - Confidence-Building Activities
- Synthesis of Findings
  - Statement of Confidence

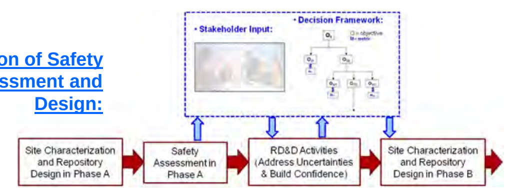


Evolution of the Safety Case

- Safety understanding and the associated technical bases evolve with phases of repository development
- Safety case provides a structured framework to assist in prioritizing the technical work in the next phase, to reduce uncertainties and enhance confidence

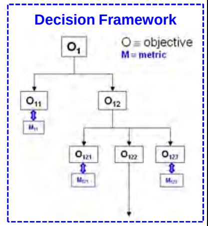


Iteration of Safety Assessment and Design:

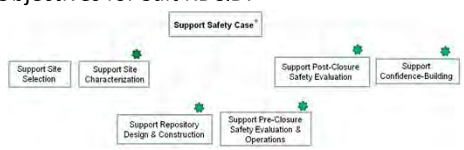


Decision-Making Framework

- Building of Decision-Making Framework for RD&D Needs
  - Objectives Hierarchy and Criteria/Metrics
  - Use the Elements of the Safety Case as high-level objectives, i.e., *site characterization, repository design, preclosure safety, postclosure safety, and confidence-building*
  - Design metrics to measure ability to meet objectives, e.g., how important is an R&D need relative to the Safety Case: low (1), medium (2), high (3)
  - Identify alternatives, i.e., RD&D "projects" (see Roadmap) or RD&D "activities" for meeting the objectives



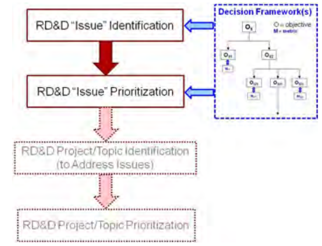
- High-Level Objectives for Salt RD&D:



Related DOE R&D Prioritization Efforts: UFD Roadmap

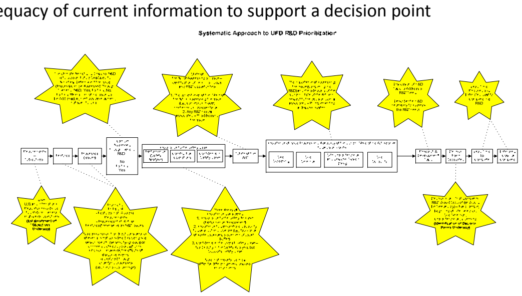
- Prioritization of Salt RD&D could be conducted as a four-step process (similar to UFD Roadmap):
  - *Identification of RD&D "Issues"*
  - *Prioritization ranking of RD&D "Issues"*
  - *Identification of RD&D "projects" or "topics" to address "Issues"*
  - *Prioritization ranking of RD&D projects/topics*
- UFD Roadmap addressed the first two steps and provided an importance ranking for the identified set of RD&D issues for generic repositories in four possible host rock media
- UFD Roadmap stated that the last two steps—identifying and prioritizing RD&D projects/topics will be accomplished later

UFD Roadmap
Elicitation and Prioritization Process



UFD Roadmap Objectives

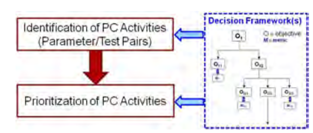
- Highest-level objectives (evaluation criteria) not explicitly stated but can inferred from the prioritization process:
  - Importance to safety assessment
  - Importance to design, construction, and operations
  - Importance to overall confidence in the safety case
  - Importance to one of four decision points (e.g., site screening, site selection, …)
  - Adequacy of current information to support a decision point



Related DOE R&D Prioritization Efforts: YMP Performance Confirmation

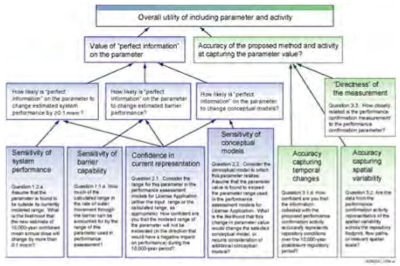
- Prioritization of Salt RD&D could be conducted as a two-step process (similar to YMP PC Plan):
  - *Identification of* PC parameters and associated tests (data acquisition methods) to measure them
  - Prioritization ranking of parameter/data-acquisition pairs (called "performance confirmation activities")
- Salt RD&D plan can directly use this PC two-step process by identifying "pairs" of salt RD&D needs and an associated test (data acquisition method) to address the need—called an RD&D "activity"
- Ok to identify more than one test to address an RD&D need—each need-test combination can be ranked
  - PC Plan usually had only one test per parameter but had up to six different test-parameter combinations for some parameters)

YMP Performance Confirmation Plan
Elicitation and Prioritization Process



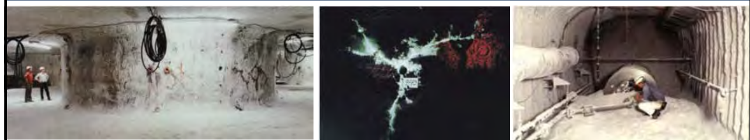
YM Performance Confirmation Objectives

- Four highest-level objectives (evaluation criteria) stated (but later implemented in a more complex fashion):
  - Sensitivity of total system performance and barrier capability to the parameter being measured
  - Confidence in the current representation of the parameter being measured
  - Accuracy of the proposed data acquisition method at measuring the parameter
  - Cost and difficulty of measuring the parameter (not used directly for total utility or score, but used later in a cost-benefit analysis)



Exceptional service in the national interest

Sandia National Laboratories



Heated Salt Testing History

Kris Kuhlman

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.
SAND NO. 2013-1758P

Outline

- ORNL Kansas Carey Salt Mines
  - Liquid waste testing ('57 – '61) Hutchinson, KS
  - Project Salt Vault ('62 – '67) Lyons, KS
- Avery Island ('78 – '83) New Iberia, LA
- Sandia Laboratory experiments ('77 – '79)
- Waste Isolation Pilot Plant ('84 – '90) Carlsbad, NM
- Asse II Mine, Germany
  - Brine Migration testing ('83 – '85)
  - DEBORA borehole disposal testing ('97 – '98)
  - TSDE drift emplacement testing ('90 – '99)

2

Early '50s Testing

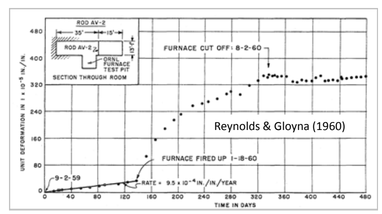
- NAS panel recommended direct disposal of *liquid* reprocessing waste in salt cavities (Hess et al., 1957).
- U Texas Austin performed early lab testing
  - Creep (up to 410° C)
  - Cavity closure
  - Salt permeability to He, brine and kerosene
  - Grand Saline Mine (Dallas, TX)
- ORNL performed early field testing

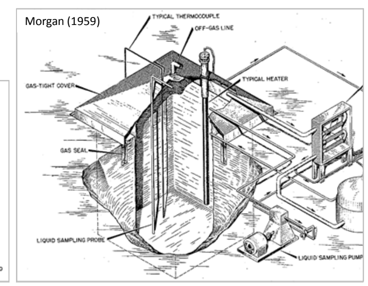
Serata & Gloyna (1959)

3

ORNL Hutchinson, KS

- First developed lab-scale pits in large salt blocks
- Two 7.5' × 7.5' × 10' cavities mined into floor
- Off-gas cover, heater, condensate collector, room closure
- Complications:
  - Cavity stability
  - Off-gas containment

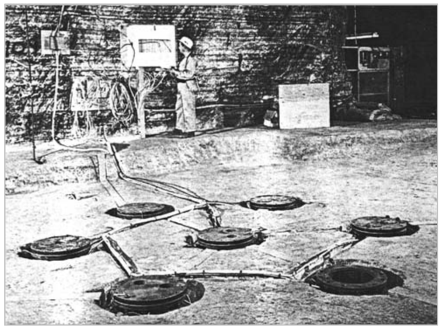




4

ORNL Project Salt Vault

- Lyons salt mine for AEC solid waste demonstration
- 3 vertical-borehole heater tests ('65 – '67)
  - 7 boreholes (10.5 kW)
  - radioactive sources
  - brine migration
  - salt to >200° C
- Heated Pillar ('66 – '67)
  - 33 kW (22 heaters)
- Hot borehole (July '62)
  - Two 5-kW heaters
  - salt to > 350° C
  - Decrepitation!



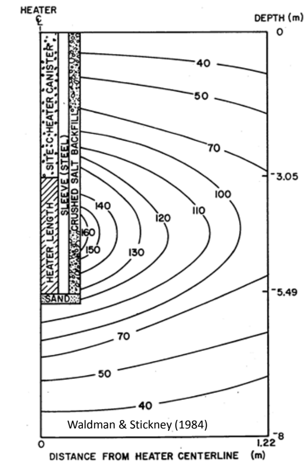
Bradshaw & McClain (1971)

5

Avery Island, LA (1)

- OWI/ONWI-led heated salt test ('78 – '83) – site C
  - 4-kW central heater
  - Eight guard heaters (5.6 kW total)
  - Crushed salt backfill
  - Operated 5 years

photo by Wes Deyonge

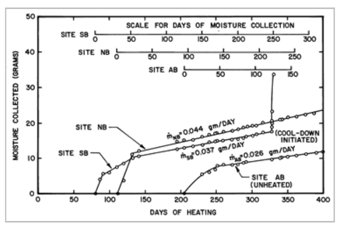


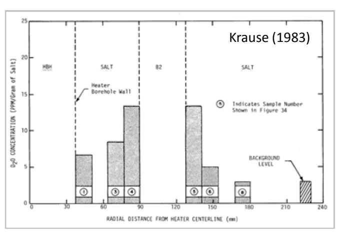
Waldman & Stickney (1984)

6

Avery Island, LA (2)

- OWI/ONWI-led brine migration test ('79 – '80)
- Three sites
  - AB: unheated
  - NB: heated natural brine
  - SB: heated tracer brine
- Tracer test (Deuterium)
- Gas permeability tests
  - 10^4 permeability *decrease* during heating
  - 10^5 permeability *increase* during cooling



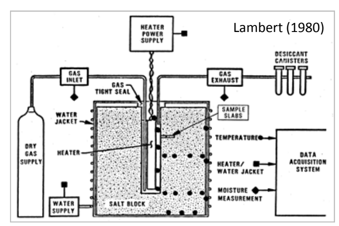


Krause (1983)

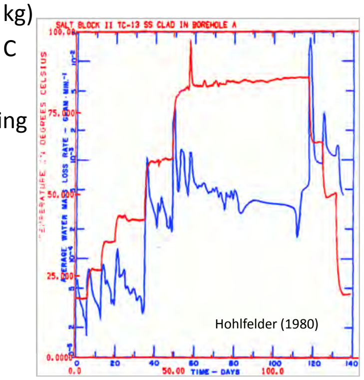
7

Lab Test (1): Salt Block II ('78 – '79)

- 1 m × 1 m salt cylinder (1700 kg)
- Axially heated in steps to 200° C
- Cooled in steps
- High-frequency brine monitoring
- Embedded thermocouples
- Post-test petrofabric analysis



Lambert (1980)



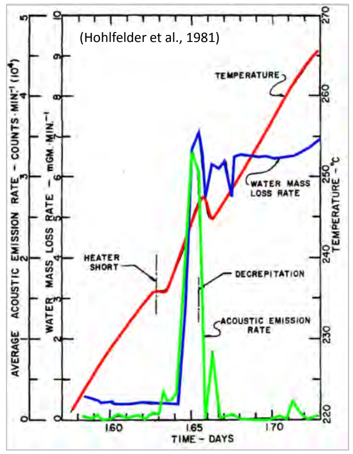
Hohlfelder (1980)

Temperature changes lead to spikes in brine inflow

8

Lab Test (2): Salt Cracker ('80)

- Two 1.6-kg salt cylinders
- Heated to 200 & 300° C
- Acoustic Emissions
  - Decrepitation
  - Change in heater power
- Brine inflow
  - Decrepitation
  - Change in heater power
- Even after decrepitation, brine inflow spiked during cooling



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Waste Isolation Pilot Plant*

- Thermal/Structural Interactions Tests (TSI)
  - Rooms A1-A3 (18 W/m² DHLW mockup)
  - Room B (DHLW overtest)
  - Room H (Heated axisymmetric pillar)
  - Room D (Isothermal version of Room B)
- Waste Package Performance Tests (WPP)
  - Room T (TRU waste mockup)
  - Room J (TRU waste overtest)
  - DHLW materials tests piggybacked with TSI in Rooms A1/B
    - Waste Package materials tests
    - Borehole backfill materials tests
- Plugging and Sealing Program (PSP)
  - Brine migration test piggybacked with TSI in Rooms A1/B

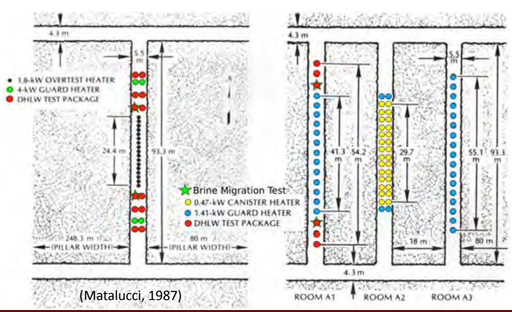
* Tyler et al. (1988)

10

WIPP (1): Rooms A/B

- Room A2: "design" DHLW thermal load (470 W heaters)
- Room B: "overtest" conditions (1800 W heaters)
- 4 brine migration tests
- 18 Waste Package Performance tests (7 retrieved)

Room B
17 @ 1.8 kW
4 @ 4.0 kW
8 @ 1.5 kW
58.6 kW total

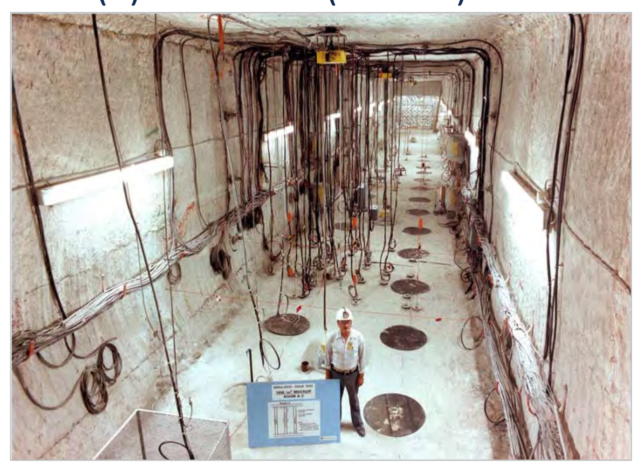


Rooms A1-A3
34 @ 0.47 kW
34 @ 1.41 kW
63.9 kW total

(Matalucci, 1987)

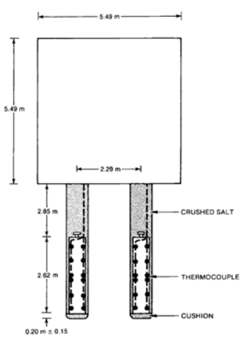
11

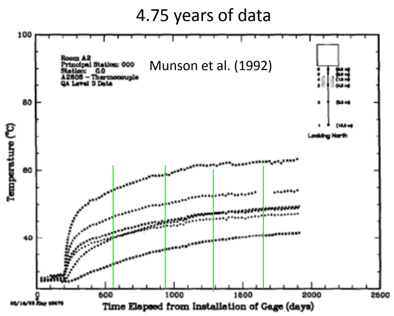
WIPP (2): Room A2 ('85-'90)



12

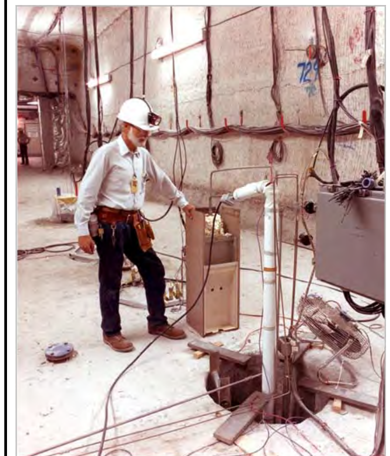
WIPP (3): Room A2

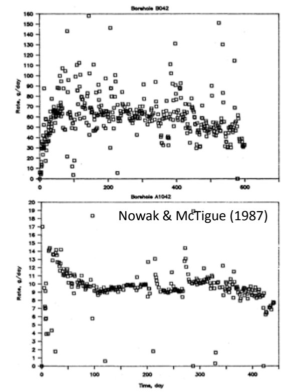




- Rooms A/B included thousands of measurement points:
  - Temperature, differential creep, oriented stress (pressure), brine inflow, room closure, heat flux, and heater power.

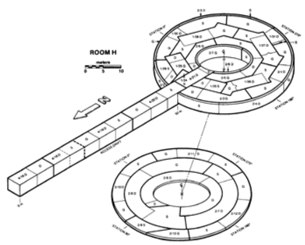
WIPP (4): Room A1/B Brine Inflow

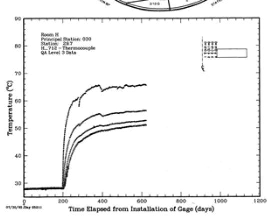




Room B: 130° C, 35 L brine/borehole
Room A1: 50° C, 4.5 L brine/borehole

WIPP (5): Room H ('86-'95)



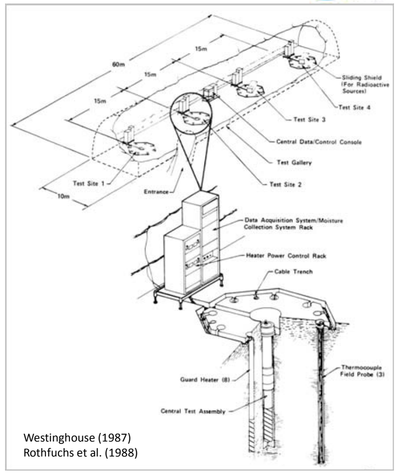


Asse II Mine

- Heated Brine Migration test ('83 – '85)
- Waste Emplacement Demonstrations (BAMBUS I & II)
  - Vertical Boreholes (DEBORA-1 and DEBORA-2)
    - One-year heated tests ('97 – '98)
    - Crushed salt reconsolidation in boreholes
  - In-drift, backfilled with crushed salt (TSDE)
    - Ten-year heated test ('90 – '99)
    - Six large heated canisters in two drifts
    - Backfilled drifts with crushed salt

Asse II Mine (1)

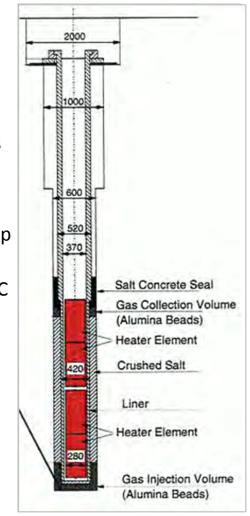
- Brine Migration Test
- Four heated sites
  - Two with ^{60}Co sources
  - Two sites pressurized
- Measurements of:
  - Room closure
  - Temperature
  - Brine inflow
  - Borehole gas content
  - Acoustic emissions
- <200 mL brine inflow during tests per borehole
- 90% of brine collected during cooling



Westinghouse (1987)
Rothfuchs et al. (1988)

Asse II Mine (2)

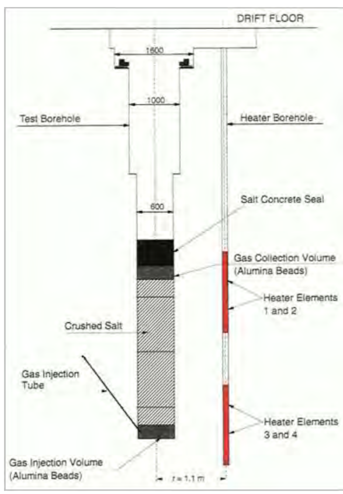
- Borehole tests:
  - corrosion, temperature, pressure, borehole convergence, and salt gas permeability in crushed salt.
- DEBORA-1 (Feb '97 – Mar '98)
  - 9-kW heater backfilled in 15-m deep borehole
  - Crushed salt compaction @ 185° C
    - Reconsolidated 38% → 9%
    - Permeability reduction $5 \times 10^{-12} \rightarrow 7 \times 10^{-14}$ m^2



Bechthold et al. (1999)

Asse II Mine (3)

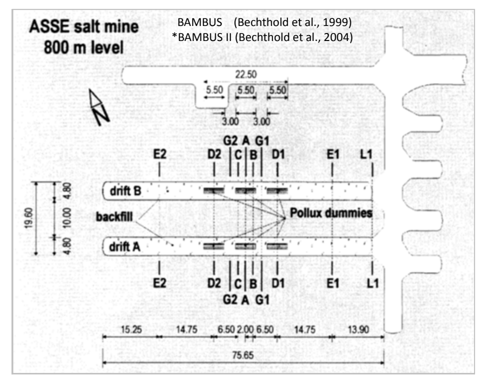
- DEBORA-2
  (Sep '97 – Dec '98)
  - 15-kW heaters near 15-m deep backfilled borehole
  - Crushed salt compaction @ 135° C
    - Reconsolidated 37% → 12%
    - Permeability reduction $1 \times 10^{-10} \rightarrow 4 \times 10^{-13}$ m^2



Bechthold et al. (1999)

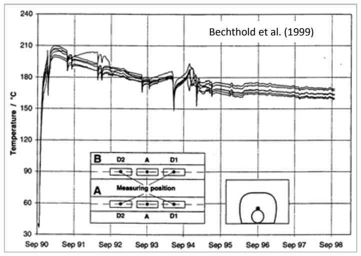
Asse II Mine (4)

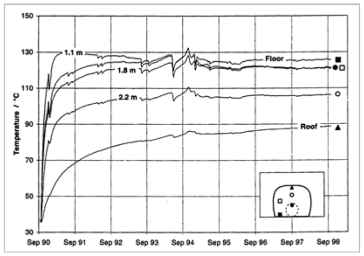
- Thermal Simulation of Drift Emplacement (TSDE)
- Six Pollux casks
  - 1.5 m × 5.5 m
  - 6.4-kW heater
  - 65 tons
- Crushed salt backfill
- Instrumented
  - Temperature
  - Closure
- Observation bores completed from nearby drifts
- Extensive Post-mortem tests*



Asse II Mine (5)

- Heater *T* decreased (at constant power)
  - Backfill thermal conductivity increasing with decreasing porosity
  - Dependence of salt thermal conductivity on temperature
- Steady-state *T* reached near heaters (but not at roof)

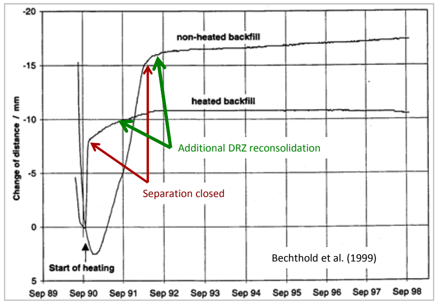




21

Asse II Mine (6)

- Backfill compaction
  - ≤25-mm separation of crushed salt from roof
    - heated backfill: closed in 4-7 weeks
    - unheated backfill: closed in 1-2 years



22

50+ years of testing!

Thank You

23

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Exceptional service in the national interest

Sandia National Laboratories

Underground Salt Research Laboratory at the Waste Isolation Pilot Plant

Frank Hansen PhD PE

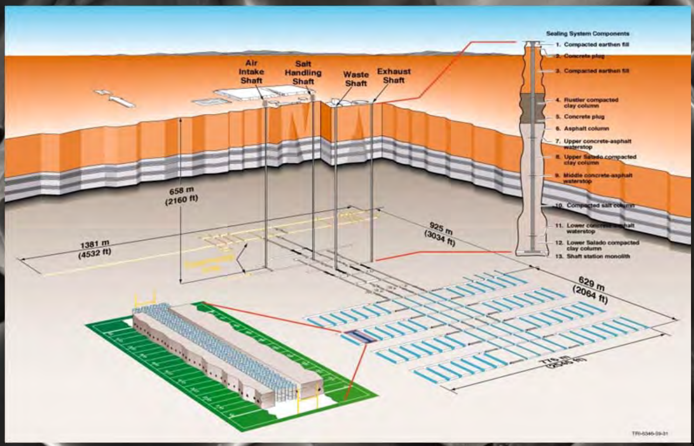
3rd US/German Workshop on Salt Repository Research, Design and Operations

Albuquerque, NM, USA

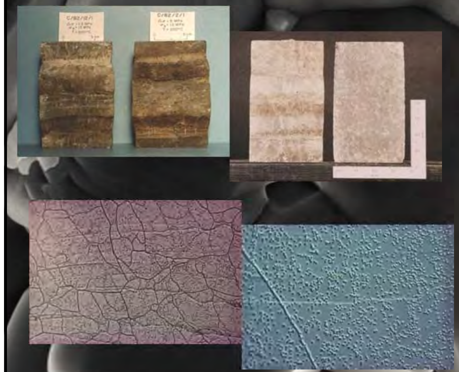
October 9-10, 2012

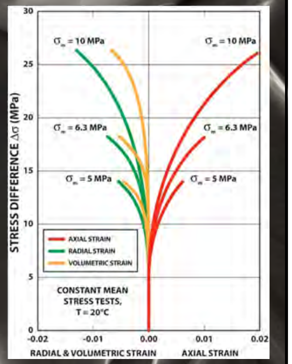
SAND 2012-8035P

WIPP Underground Layout



Salt Behavior is Well Understood

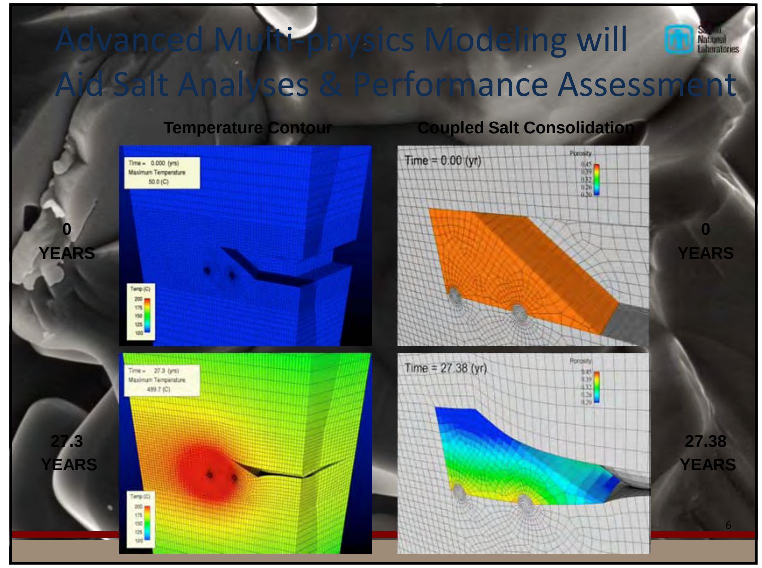


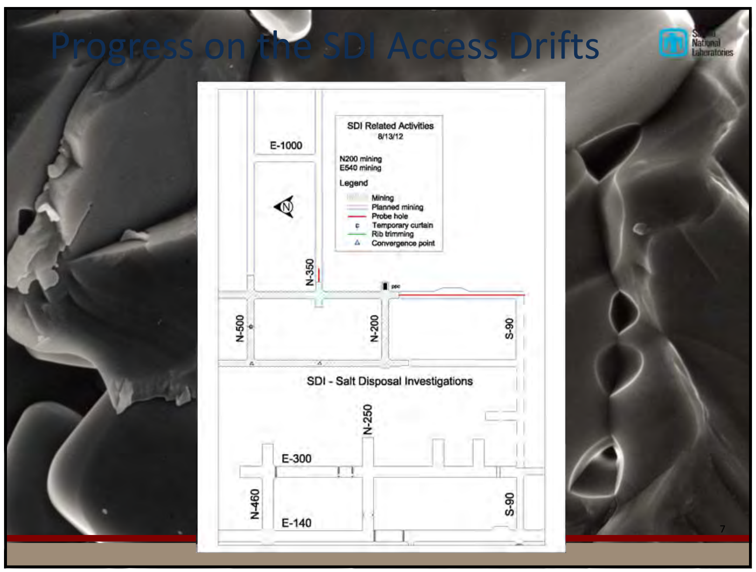


Full-Scale Tests in Salt

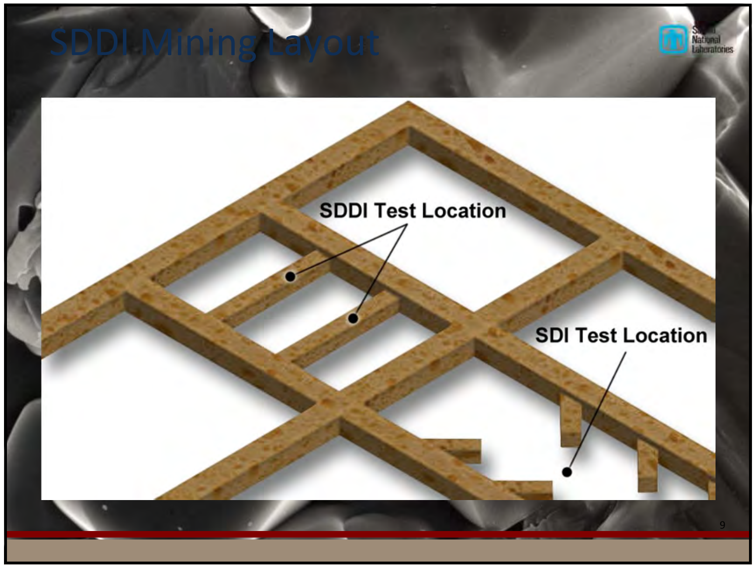
YEAR	PROJECT	LOCATION	DESCRIPTION
1965-1969	Lyons mine, Project Salt Vault	Lyons, Kansas	Irradiated fuel & electric heaters
1968	Asse salt and potash mine	Germany	Electric heaters
1979-1982	Avery Island	Louisiana	Brine migration
1983-1985	Asse (U.S./German Cooperative)	Germany	Brine migration under heat & radiation
1984-1994	WIPP	Carlsbad, NM	1.Defense HLW Mockup 2.Defense HLW Over-test 3.Heated axisymmetric

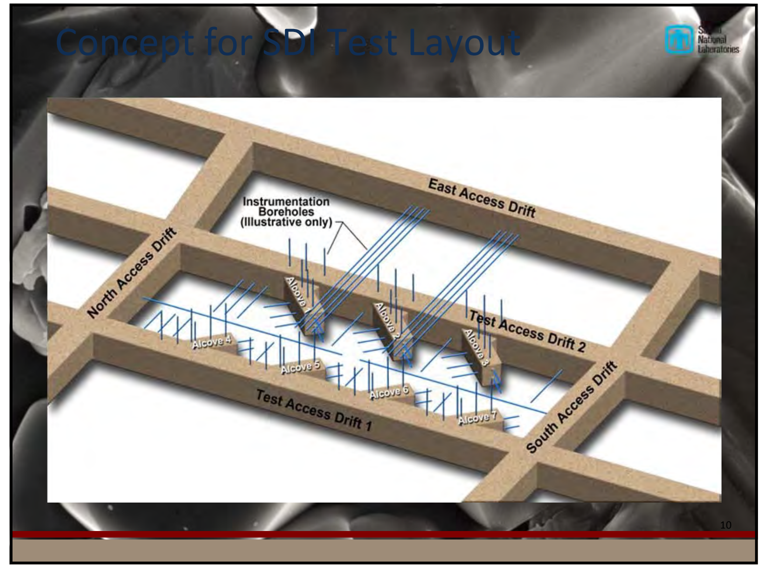

Large-Scale Underground Experiments
Room H
DHLW
BAMBUS II

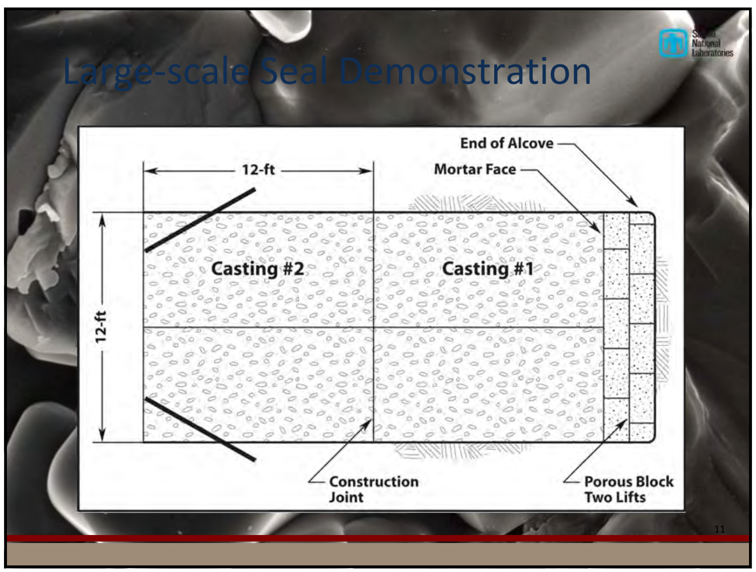

Advanced Multi-physics Modeling will Aid Salt Analyses & Performance Assessment
Temperature Contour
Coupled Salt Consolidation
0 YEARS
0 YEARS
27.3 YEARS
27.38 YEARS
Time = 0.00 (yr)
Time = 27.38 (yr)

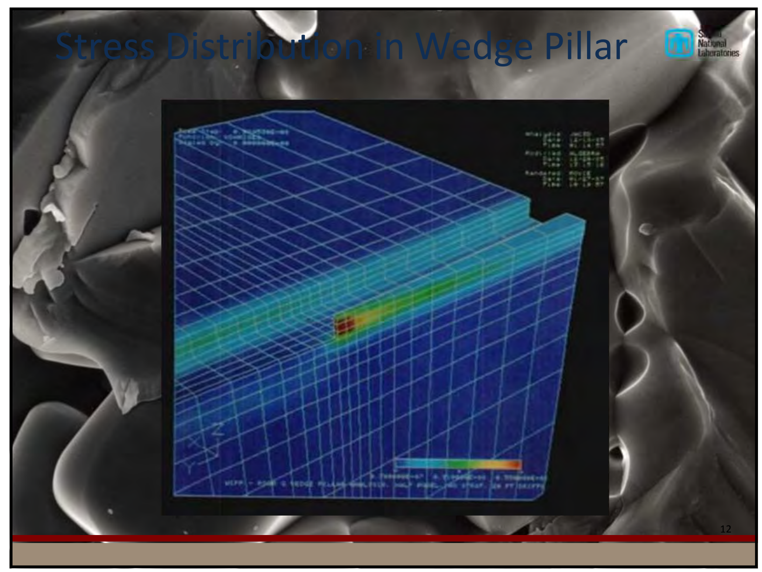

Progress on the SDI Access Drifts
SDI Related Activities
8/13/12
N200 mining
E540 mining
Legend
Mining
Planned mining
Probe hole
Temporary curtain
Rib trimming
Convergence point
E-1000
N-350
N-500
N-200
S-90
SDI - Salt Disposal Investigations
N-250
E-300
N-460
E-140
S-90

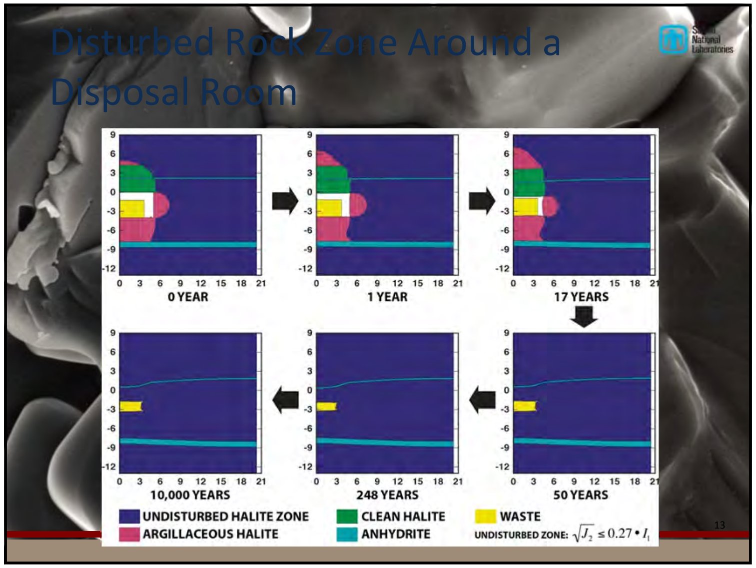

URL Potential Activities at WIPP
Salt Defense Disposal Investigations (SDDI)
Salt Disposal Investigations (SDI)
Large-Scale Seal Demonstration
Mining Research
Wedge Pillar Test
Mine-By DRZ Measurement
International Test Bed


SDDI Mining Layout
SDDI Test Location
SDI Test Location

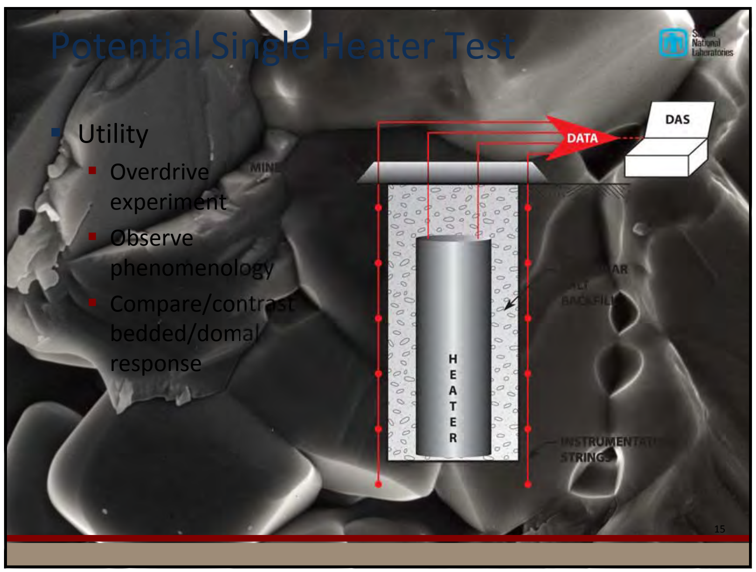

Concept for SDI Test Layout
East Access Drift
North Access Drift
Instrumentation Boreholes (Illustrative only)
Test Access Drift 2
Test Access Drift 1
South Access Drift


Large-scale Seal Demonstration
12-ft
12-ft
End of Alcove
Mortar Face
Casting #2
Casting #1
Construction Joint
Porous Block Two Lifts


Stress Distribution in Wedge Pillar


Disturbed Rock Zone Around a Disposal Room
0 YEAR
1 YEAR
17 YEARS
10,000 YEARS
248 YEARS
50 YEARS
UNDISTURBED HALITE ZONE
ARGILLACEOUS HALITE
CLEAN HALITE
ANHYDRITE
WASTE
UNDISTURBED ZONE: $\sqrt{J_2} \le 0.27 \bullet I_1$
13


Elevated Temperature Tests on WIPP Salt
Decrepitation at 275C
Plastic flow at 250C
14


Potential Single Heater Test
Utility
Overdrive experiment
Observe phenomenology
Compare/contrast bedded/domal response
DATA
DAS
HEATER
15


Extended RD&D Consideration
Develop and exchange rock salt information among nations currently pursuing or considering rock salt as a candidate deep geological repository medium.
Collaborate with international peers and stimulate interest in salt as a viable repository host medium.
Identify and perform fundamental joint research into areas where understanding is incomplete.
Exchange and transfer advanced methods and tools developed for salt disposal to industry
Characterize and qualify the information available.
Promote information exchange on approaches, methods, methodologies, and technologies
Outreach to other salt related applications.
Afford technical experts access to and interchanges with the latest international developments in salt mechanics sciences.
Inform and provide advice on conceptual topics, performance descriptions and modeling.
Publish results, models, reliability, data quality, and evaluate national and international RD&D activities.
Develop a central library of acquired salt data, information, and knowledge with broad access provided via the internet.
Address the fundamental issue of knowledge management.
Reinvigorate the science (chemistry and physics) of rock salt through education, training development of new researchers and students.
Perform fundamental research.
16

Los Alamos NATIONAL LABORATORY

Thermal Field Testing at WIPP

Presented by:
Doug Weaver
Los Alamos National Laboratory

March 6-7, 2013
Albuquerque, NM USA

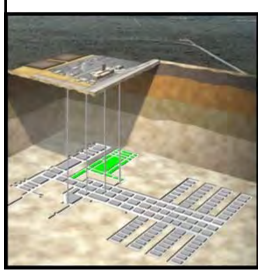
Thermal Field Testing at WIPP

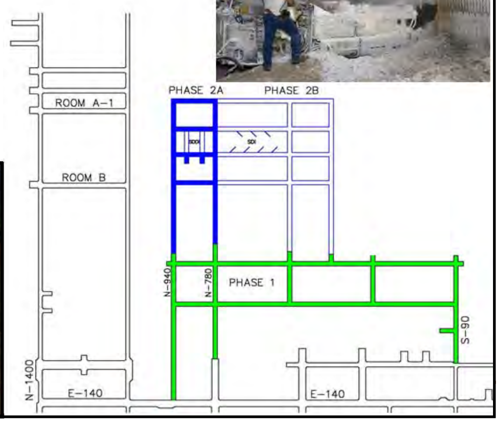
- **Status of the Salt Defense Disposal Investigations (SDDI) Program**
- **Past Thermal Tests in Salt**
- **Rational for a Field-Scale Thermal Test**
- **In-Drift Emplacement Concept**
- **Test Design Considerations**
- **Preliminary Temp/Hydro Modeling**
- **Thermal Test**
  - **Current Concept**
  - **Schedule**
  - **Instrumentation Strategies**

SDI Research Area - Status

Excavation Status

- Completed mining of Phase I drifts (green) on Feb 14, 2013.
- Efficiencies were found in the overall layout of Phase 2A and 2B allowing for a shorter planned excavation.
- Excavation of 2A (solid blue) is commencing with a planned completion date of August, 2013.
- Excavation of 2B (blue outline) will be mined concurrent with Panel 8 at a rate commensurate with resource availability and WIPP infrastructure constraints.

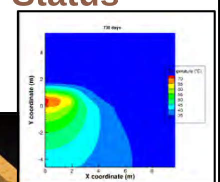


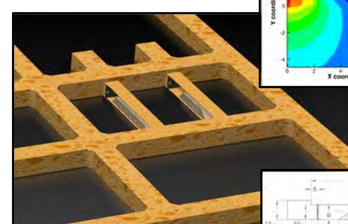


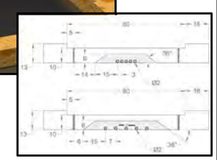
Thermal Testing Program Status

Test Planning Status

- The Salt Defense Disposal Investigations (SDDI) test program is being modeled and designed to investigate the affects of heat-generating waste in salt, both for cooler DHLW (~200W packages) and hotter SNF packages (~500W - ~1000W).
- Two drifts will accommodate each of the thermal loading scenarios.
- The proposed five year heater test includes preparation of the access drifts and test alcoves, performance of a two year heater test, data evaluation, and examination of the post-heater test bed.
- Heating is anticipated to begin in late FY2015.
- DOE-EM intends to fund this test program beginning in FY2014.







Test Program Status

- Work is continuing (through modeling, test instrumentation development, and test planning) on the refinement of the test geometry and test specifics (e.g. heat loads).
- A management structure to coordinate and implement this testing program is being instituted by the DOE-CBFO:
  - Establishment of an Integrated Project Team
  - Test Coordination Office
  - SDDI specific processes and procedures

Past Field Heater Tests in Salt

- Existing information from past thermal experiments, many conducted at WIPP, will be comprehensively evaluated to extract maximum possible benefit from these investments.
- Most of the test configurations of early thermal experiments were based on the premise of waste emplacement in vertical boreholes or conducted in domal salt.
- When the DHLW thermal test program was terminated at WIPP in 1987, there were several test programs in process or that had not started, and the country lost an opportunity to fully understand important processes (e.g. water migration under thermal loads).
- Therefore, this past work needs to be verified through confirmatory testing and augmented to address specific uncertainties and a specific disposal concept.

Past Field Heater Tests in Salt

Site	Emplacement Concept		Geology	Thermal Characteristics of Tests[1]
	Borehole	In-drift		
Lyons, Kansas (Project Salt Vault)	X		Bedded salt	• Peak salt T ~200°C • 2 year heating duration • Power – 10.4 kW/heater
Avery Island	X		Salt dome	• Peak salt T ~160°C • ~3 year heating duration • Power – 3-6 kW/heater
Asse	X	X	Salt dome	• Peak salt T ~210°C • 10 year heating duration • Power – 6.4 kW/heater
Gorleben	X	X	Salt dome	• N/A
Morsleben		X	Salt dome	• N/A
WIPP (historical)	X		Bedded salt	• Power – 64 kW total power between 3 rooms and 59kW in a single room
WIPP – Proposed Testing Program				
SDDI		X	Bedded salt	• Peak salt T ~80-150°C • 1-2 year heating duration • Power – 0.5-2 kW/heater
SDI		X	Bedded salt	• Peak salt T >200°C • 4 year heating/cooling duration • Power – 8.5 kW/heater

1. Multiple heater tests were conducted at most sites. This column describes the tests most applicable to the SDI/SDDI testing concepts.

Reference: Callahan, G., Guerin, D.C., Levitt, D.G., Newell, D.L., Robinson, B.A., and Van Sambeek, L., "*Salt Repository Synthesis Data of Non-Delaware Basin and International Programs for the Storage/Disposal of Nuclear Waste*," FCRD-UFD-2012-000312, Dated October 2012.

Rationale for a Field-Scale Thermal Test for Heat-Generating Defense Waste

- Operational Demonstration
- Confirmation of Past Thermal Studies / New Science in a Particular Emplacement Configuration
- Stakeholder Considerations

Demonstrate DOE's inventory of waste isn't difficult to handle

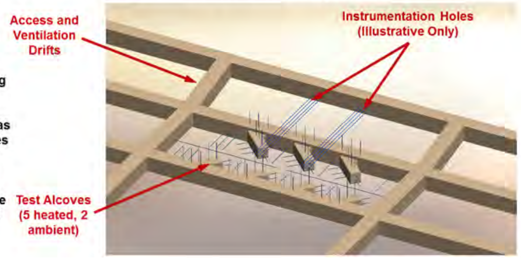
Concepts for Field-Scale Thermal Testing

- Salt Disposal Investigations (SDI)
  - Alcove Disposal Concept for hot (commercial) wastes
  - DOE EM. 2011. *A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP.* US DOE Report DOE/CBFO-11-3470.
- Salt Defense Disposal Investigations (SDD)
  - In-Drift Disposal Concept for cooler (defense) wastes
  - DOE EM. 2012. *A Conceptual Plan for Salt Defense Disposal Investigations for the Disposal of DOE-EM Managed Wastes.* US DOE Report DOE/CBFO-12-3485.

SDI Field Test

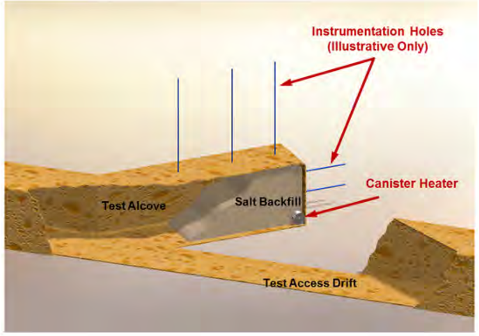
- The test design is modeled after a proof-of-principle layout and operational strategy for an alcove emplacement repository in salt
- The design consists of an array of alcoves (7 alcoves, 5 heated) with access and ventilation drifts
- Boreholes will be drilled to contain monitoring instrumentation

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.



SDI Field Test

- Electrical heaters placed in the back of the alcoves are used to simulate waste packages (8.5 kW per heater - 40 W/m^2 aerial loading)
- This thermal loading will produce temperatures in excess of 160ºC in the nearby undisturbed salt
- The alcoves will be instrumented to measure:
  - water movement
  - temperature
  - deformation
  - alcove closure
  - crushed salt pressure
  - ventilation conditions
- At least two years heating
- At least two years cooling
- Post-test forensics will confirm measured data



Goals of the SDDI Thermal Test

- Demonstrate a proof-of-principle concept for in-drift disposal in salt.
- Investigate, in a specific emplacement concept, the response of the salt to heat, in particular the evolution of the small but non-negligible quantities of water within the salt as the heat diffuses into the surrounding geologic medium (water budget).
- Develop full-scale response for dry, run-of-mine salt.
- Develop a validated coupled process model for disposal of heat-generating wastes in salt.
- Evaluate the environmental conditions post facto.

Rationale for the SDDI Thermal Test Operational Demonstration

- Direct placement of HLW canisters in open drifts on disposal room floors, rather than in boreholes, offers the possibility of vastly more efficient and flexible disposal operations.
- The concept of disposing waste packages on the floor of a disposal room and covering them with crushed salt has not been tested at WIPP or in bedded salt, and therefore the behavior of the system under these conditions must be thoroughly investigated.
- Testing of this specific disposal concept may have benefit to future emplacement of TRU wastes at WIPP.

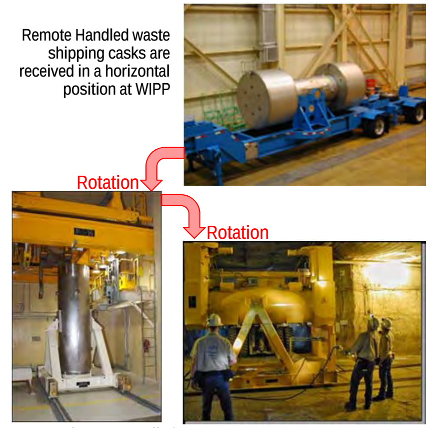
Rationale for the SDDIThermal Test Operational Demonstration (cont.)

- **By conducting the demonstration test in a configuration that mimics the disposal of defense HLW packages, we will establish the early-time evolution of the system for conditions in which packages are placed on the floor, and covered with run-of-mine salt.**
- **Such an operationally focused test, conducted under current QA requirements and processes, will be invaluable as a proof of principle experiment that establishes, through direct observation rather than only models, the efficacy of this disposal concept for a repository in bedded salt.**

Emplacement Experience at WIPP

Large, complex, heavy and hard to maintain equipment

Remote Handled waste shipping casks are received in a horizontal position at WIPP

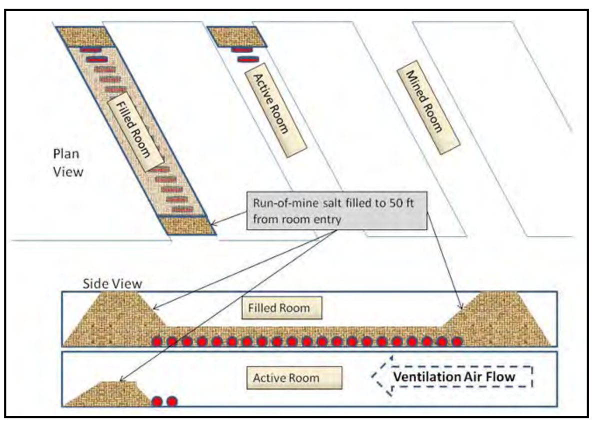


Waste canisters are pulled from the shipping cask behind shield doors and placed into a shielded facility cask for handling

In the underground, the facility cask is removed from the hoist and transported to a disposal room by a 41-ton fork lift

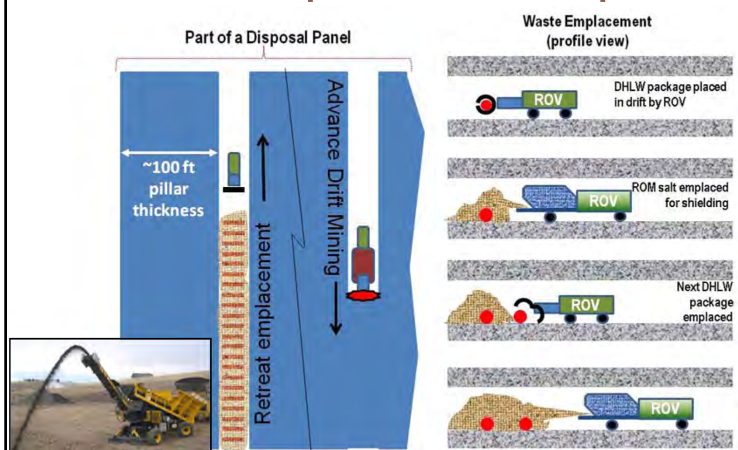
RH waste in the canister is emplaced in boreholes pre-drilled into the walls of disposal rooms, and a concrete shield plug is inserted afterwards

Emplacement and Closure Concept



Emplacement concept adapted from Carter, J.T., P.O. Rodwell, B. Robinson, and B. Kehrman. 2012. *Defense Waste Salt Repository Study*. DOE Office of Nuclear Energy Report FCRD-UFD-2012-000113.

In-Drift Emplacement Concept



Rationale for SDDI Thermal Test Technical Considerations

- Most of the test configurations of early thermal experiments were based on the premise of waste emplacement in vertical boreholes or conducted in domal salt.
- For the tests conducted at WIPP, the evolution of the water contained in the salt was not the primary focus of those past field tests, so measurement systems were not optimized to study the phenomenon of water movement.
- It is hypothesized that temperature-driven water movement for the in-drift emplacement configuration could be significantly different than that for the borehole configuration.
- A key focus of future testing will be to develop and deploy instruments that track brine and water vapor movement, which was not adequately considered in past field tests, and has never been measured in this configuration.

Rational for SDDI Thermal Test Technical Considerations (cont.)

- For the in-drift emplacement design, the hypothesis is that significant quantities of water would be expelled from the disposal horizon during the first few decades after waste emplacement, leading to a lesser amount of water contacting waste packages.
- This thermal testing program will consider both pre and post-closure hydrologic conditions, partly because in the post-closure condition, either accidental or purposeful intrusion into the emplacement horizon will require in-depth understanding or the evolution, status, and potential ES&H affects associated with that intrusion.

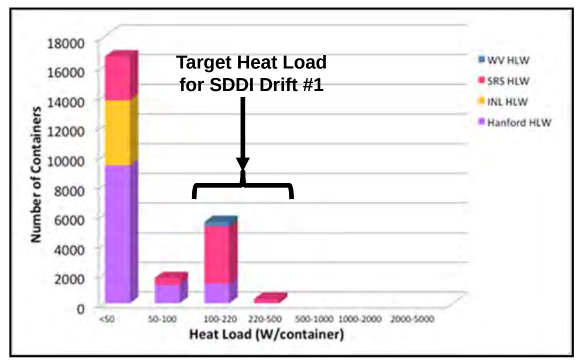
Rationale for the SDDI Thermal Test Stakeholder Considerations

- Positions of key stakeholders include:
  - Political leaders of southeastern New Mexico, who are generally supportive of new waste disposal missions, require testing to increase public confidence in DOE activities.
  - The Governor of the State of New Mexico, states that heater testing is required in order for the state to consider new waste disposal missions within the state.
  - Former Senator Bingaman has asked DOE to consider in situ thermal testing at WIPP.

References:

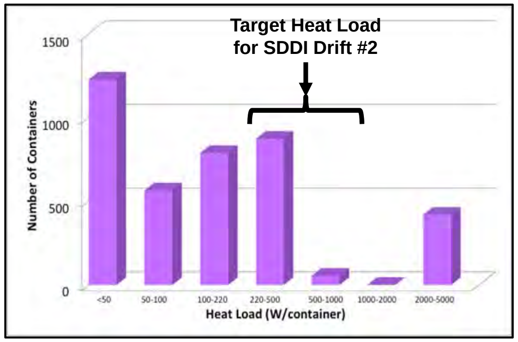
State of New Mexico County of Eddy, Resolution R-12-55, August 7, 2012.
City Council of Carlsbad, Resolution No. 2012-39, August 14, 2012.
Proclamation of State Senators Asbill and Leavell, and State Representatives Brown and Gray, July 26, 2012.
Governor's letter to Secretary Chu, June 1, 2011.
Governor's letter to Senator Bingaman, May 2, 2012.
Secretary Chu's letter to Governor Martinez, November 1, 2011.
Senator Bingaman's letter to Huizenga and Lyons, June 5, 2012.

SDDI Test Design Considerations Heat Loads



Heat loads for the current and planned DOE-owned HLW inventories adapted from Carter, J.T., A.J. Luptak, J. Gastelum, C. Stockman, A. Miller. 2012. *Fuel Cycle Potential Waste Inventory for Disposition*. DOE Office of Nuclear Energy Report FCR&D-USED-2010-000031, Rev 5.

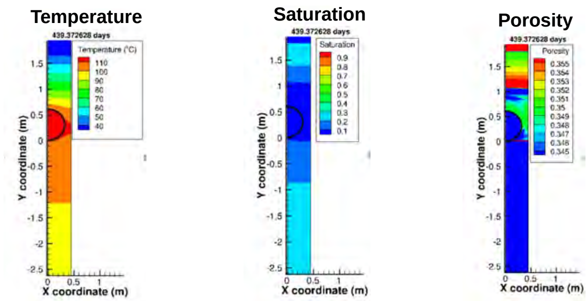
SDDI Test Design Considerations Heat Loads



Heat loads for the defense SNF inventory adapted from Carter, J.T., A.J. Luptak, J. Gastelum, C. Stockman, A. Miller. 2012. *Fuel Cycle Potential Waste Inventory for Disposition*. DOE Office of Nuclear Energy Report FCR&D-USED-2010-000031, Rev 5.

SDDI Test Design Considerations - Preliminary T-H-C Modeling Results

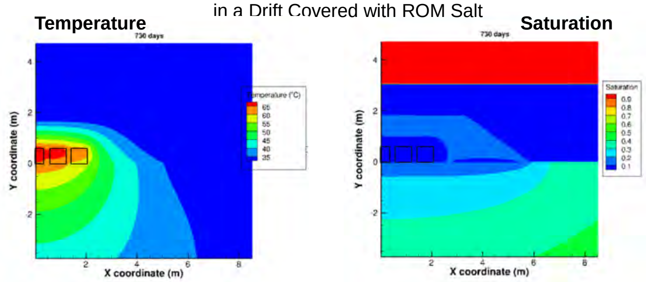
0.02 ft Mesh:
Infinite Line of 200W Canisters 3' center-center spacing
in a Drift Covered with ROM Salt



Reference: FEHM: A control volume finite element code for simulating subsurface multi-phase multi-fluid heat and mass transfer" 2007 LA-UR-3359, George A. Zyvoloski

SDDI Test Design Considerations - Preliminary T-H-C Modeling Results

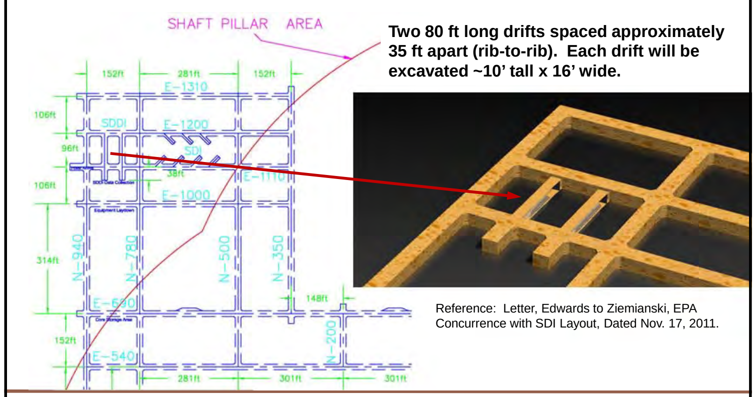
Fine Mesh:
5-200W Canisters 3' center-center spacing
in a Drift Covered with ROM Salt



As was done with the YMP Drift Scale Test, we'll determine what the correct wattage will be for five canister heaters to represent an "infinite" line of 200W waste packages. The same will be done for higher wattage scenario.

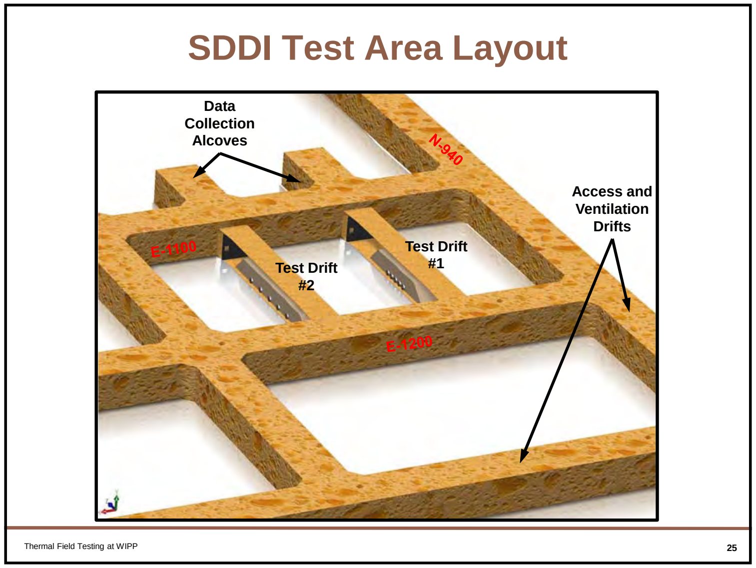
SDDI Test Area Layout

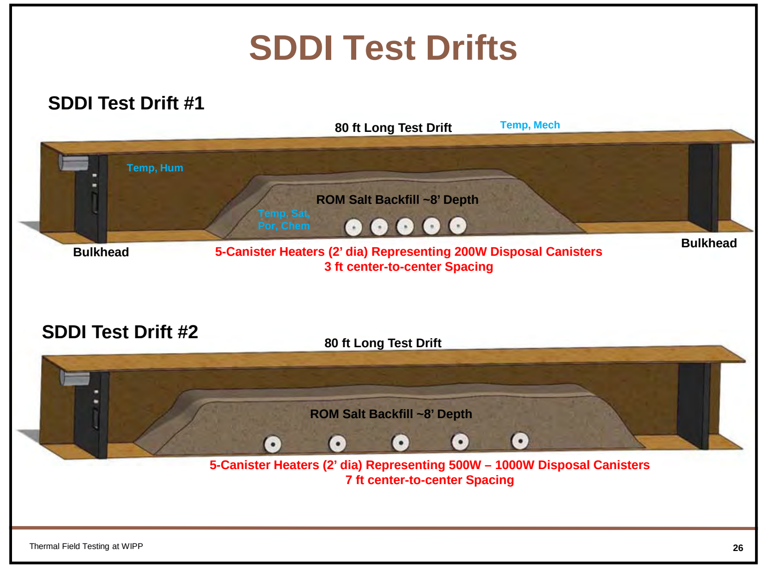
- The SDDI thermal test will be conducted in two drifts near the north-east corner of the newly developed SDI Research Area.

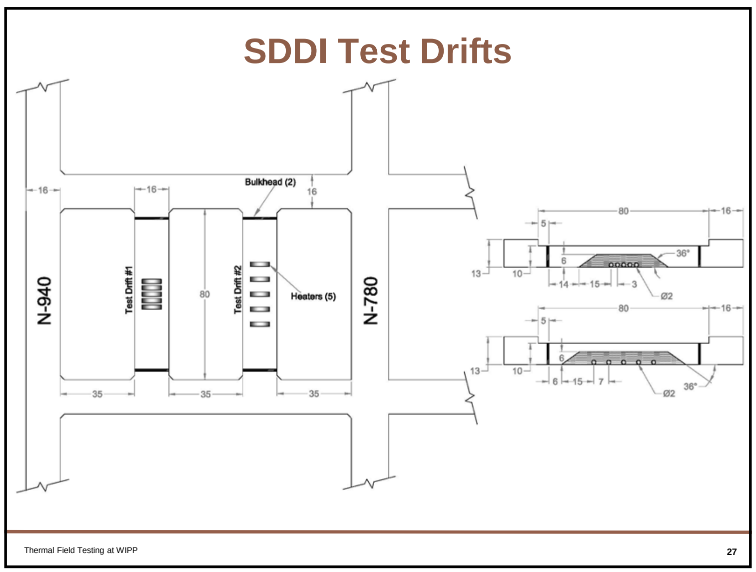


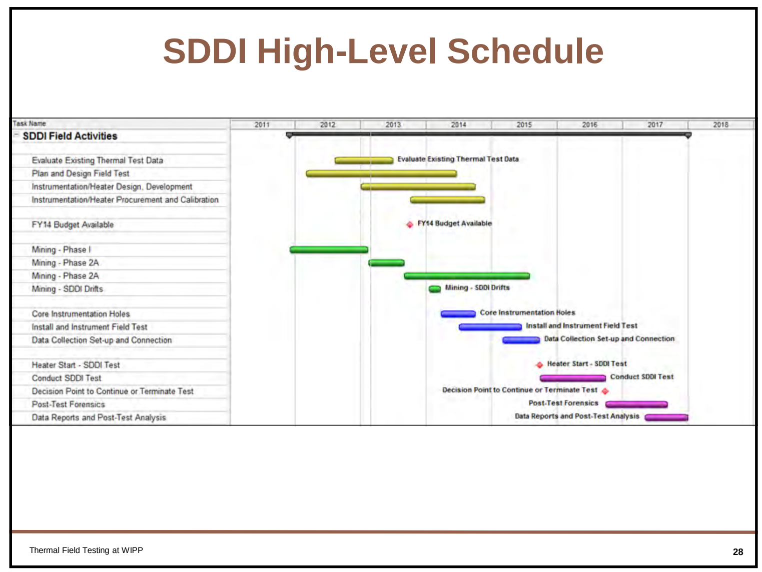
Two 80 ft long drifts spaced approximately 35 ft apart (rib-to-rib). Each drift will be excavated ~10' tall x 16' wide.

Reference: Letter, Edwards to Ziemianski, EPA Concurrence with SDI Layout, Dated Nov. 17, 2011.


SDDI Test Area Layout
Data Collection Alcoves
N-940
Access and Ventilation Drifts
E-1100
Test Drift #2
Test Drift #1
E-1200
Thermal Field Testing at WIPP
25


SDDI Test Drifts
SDDI Test Drift #1
80 ft Long Test Drift
Temp, Mech
Temp, Hum
ROM Salt Backfill ~8' Depth
Temp, Sat, Por, Chem
Bulkhead
5-Canister Heaters (2' dia) Representing 200W Disposal Canisters
3 ft center-to-center Spacing
Bulkhead
SDDI Test Drift #2
80 ft Long Test Drift
ROM Salt Backfill ~8' Depth
5-Canister Heaters (2' dia) Representing 500W – 1000W Disposal Canisters
7 ft center-to-center Spacing
Thermal Field Testing at WIPP
26


SDDI Test Drifts
Bulkhead (2)
N-940
Test Drift #1
Test Drift #2
Heaters (5)
N-780
Thermal Field Testing at WIPP
27


SDDI High-Level Schedule
Task Name
SDDI Field Activities
Evaluate Existing Thermal Test Data
Plan and Design Field Test
Instrumentation/Heater Design, Development
Instrumentation/Heater Procurement and Calibration
FY14 Budget Available
Mining - Phase I
Mining - Phase 2A
Mining - Phase 2A
Mining - SDDI Drifts
Core Instrumentation Holes
Install and Instrument Field Test
Data Collection Set-up and Connection
Heater Start - SDDI Test
Conduct SDDI Test
Decision Point to Continue or Terminate Test
Post-Test Forensics
Data Reports and Post-Test Analysis
2011 2012 2013 2014 2015 2016 2017 2018
Thermal Field Testing at WIPP
28

Next Steps?

- Continue with the SDI Research Area development
- Continue with T-H-C modeling efforts, working toward incorporating Mechanical effects
- Continue with Laboratory Studies, in particular, studying brine migration mechanisms
- Test planning
  - Finalize the goals and objectives of the SDDI field-test
  - Develop canister heater specifics
  - Instrumentation identification/design
  - Develop an integrated scientific test plan and the F&ORs for the test
- Begin long-lead time procurements

Potential Instrumentation Concepts

- Expected Conditions
  - Hot, dusty, humid, mobile brine
- Instrument Planning and Selection Considerations
  - Redundant instrumentation
  - Robust gage design
  - Pre and post-test gage calibration
  - Gage maintenance (where feasible)

Potential Instrumentation Concepts

- Temperature Measurements
  - Thermocouples/Resistance Temperature Detectors
  - Fiber Optic Temperature Array
- Mechanical Measurements
  - Multi-Point and Single-Point Borehole Extensometers
  - Room Closure Gages
  - Active time-lapse in situ seismic wave transmission measurements and monitoring
  - Pressure Cells
  - Passive Seismic Event Monitoring

Potential Instrumentation Concepts

- Hydrologic Measurements
  - Time Domain Reflectometers
  - Heat Dissipation Probes
  - Electrical Resistivity Tomography
  - Active Neutron Probe
  - Ground Penetrating Radar
  - Gas and Brine Sampling Ports
- Miscellaneous Measurements
  - Thermal Flux Meters
  - Power Meters

Potential Instrumentation Concepts

- Air Velocity Gages
- Gas/Air Pressure Transducers
- Air Humidity Sensors/Chilled Mirror Hygrometers
- Real-Time Remote Video

Example Relevant References:

Munson, D.E., D.L. Hoag, D.A. Blankenship, W.F. DeYonge, D.M. Schiemeister, R.L. Jones, and G.T. Baird. 1997. *Instrumentation of the Thermal/Structural Interactions In Situ Tests at the Waste Isolation Pilot Plant (WIPP).* SAND87-2686. Albuquerque: Sandia National Laboratories.

Droste, J. and T. Rothfuchs. *Long-Term Instrument Performance – Experience from a Large Scale Test in Rock Salt.* 2003. Swets & Zeitlinger, Lisse, ISBN 90 5809 602 5.

Rothfuchs, T., J. Dittrich, J. Droste, J. Muller, and C. Zhang. *Final Evaluation of the Project "Thermal Simulation of Drift Emplacement".* 2003. GRS-194.

Stickney, R.G. and L.L. Van Sambeek. *Summary of the Avery Island Field Testing Program.* 1984. ONWI.

Molecke, M.A., and R.V. Matalucci. *Preliminary Requirements for the Emplacement and Retrieval of Defense High-Level Waste Tests in the Waste Isolation Pilot Plant.* 1984. SAND84-1444.

Final Thoughts

- No amount of laboratory testing and modeling have ever or will ever be adequate to inform and reassure the public or to solely prove performance and license a nuclear waste repository. A field test is an essential component of such a program.
- WIPP is the right place for this work.
- New test results, augmented by extensive geomechanics experience and data at the WIPP site, should enable us to make confident predictions of the long-term evolution of the repository environment in the period up to and after repository closure.
- It is critical to validate these TMHC models so that it they be used with confidence to represent the coupled processes in a repository PA analysis.
- This SDDI thermal test would set the foundation for additional higher heat field studies relevant to the disposal of civilian used nuclear fuel (e.g. SDI), should the nation decide to consider a repository for civilian waste in bedded salt.

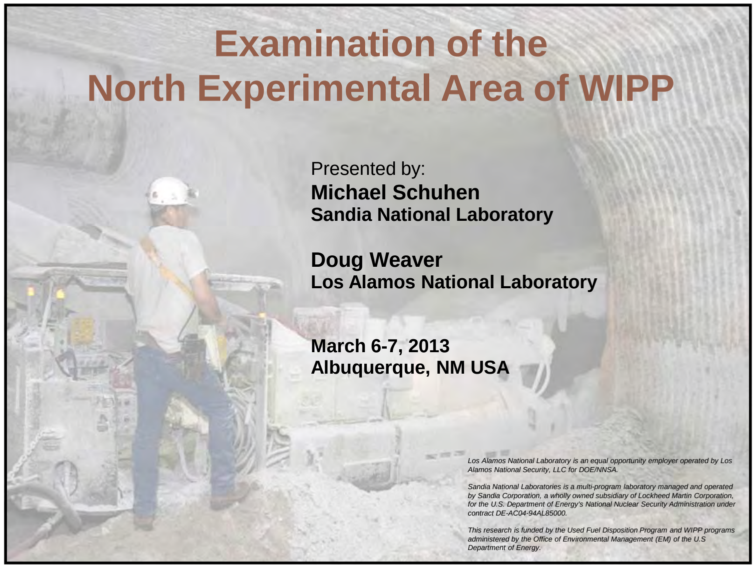
Questions?

Open Discussion

Thermal Field Testing at WIPP 37

Thermal Field Testing at WIPP 38

Thermal Field Testing at WIPP 39



Examination of the North Experimental Area of WIPP

Presented by:
Michael Schuhen
Sandia National Laboratory

Doug Weaver
Los Alamos National Laboratory

March 6-7, 2013
Albuquerque, NM USA

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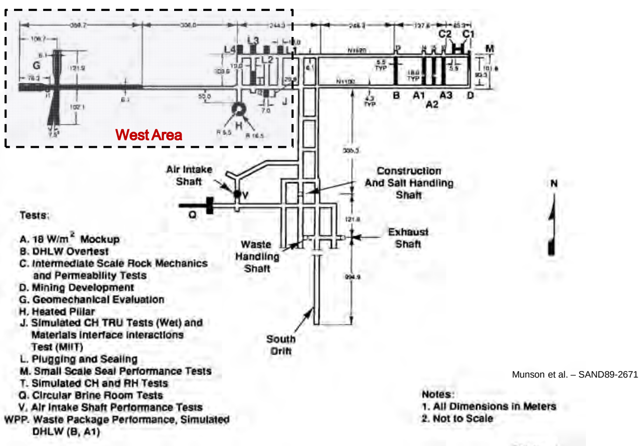
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

This research is funded by the Used Fuel Disposition Program and WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.

Introduction

- As presented in the SDI Proposal (2011), an activity was added to the UFD Salt R&D work package to conduct test planning activities necessary for the acquisition of data from the existing north experimental area of WIPP.
- LANL, SNL, and WIPP M&O have been provided the resources necessary to develop a plan to examine the north WIPP experimental area that was shut down when heater tests were terminated in the early to mid 1990's. This scope includes:
  - the development of initial planning documents that define the information needs and scientific objectives (e.g. sampling plan, coring plan, forensics)
  - Planning by the WIPP M&O personnel to perform the physical activities associated with gaining access to the selected north experimental area.
- Milestones/Deliverables:
  - Forensic Studies of Material Recovered from the WIPP Experimental Area (3/29/2013)
  - Test Plan for Forensic Analysis in the North Experimental Area of WIPP (9/27/2013)
  - Re-entry Plan for Mining into the North Experimental Area of WIPP (9/27/2013)

North Experimental Area - West

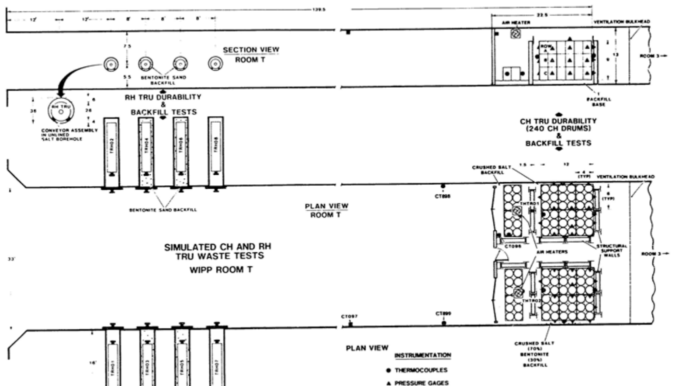


Munson et al. – SAND89-2671

North Experimental Area – West Side

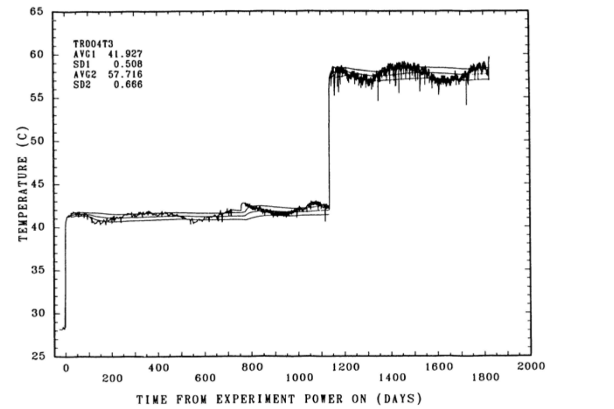
- Geo-mechanical Experiments in Room G and Room H
  - Room G - Never Implemented the Wedge Pillar Test and Access Drift Backfilled
  - Room H – No Waste Packages or Heater Canisters and Access Drift Backfilled
- Simulated Waste and Corrosion Experiments Room J and Room T
  - Room T Remains Intact – Access Drift Backfilled
  - Room J Completely Decommissioned
- Small Scale Seals & Plugging Program in L Rooms
  - Most of the seals were cored during testing and the access drift is backfilled

Room T Test Layout



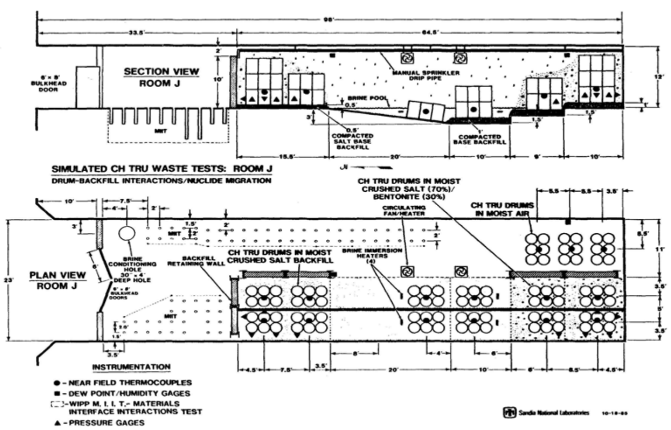
Molecke et al. SAND88-1314

Highest Temperature for Room T WPs at 120 Watt & 300 Watt Outputs



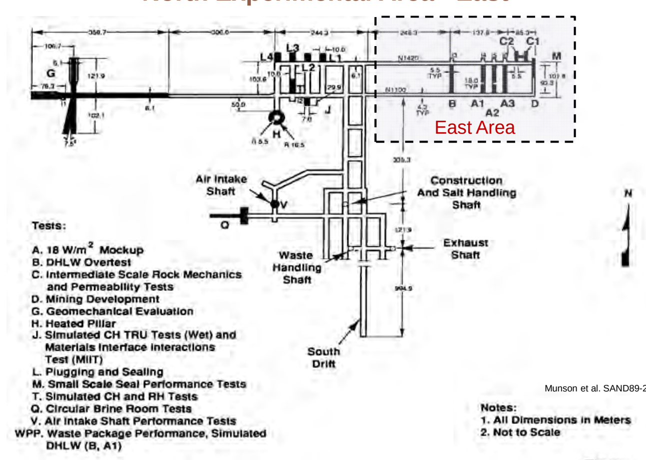
Molecke et al. SAND88-1314

Room J Test Layout



Molecke 1985

North Experimental Area - East



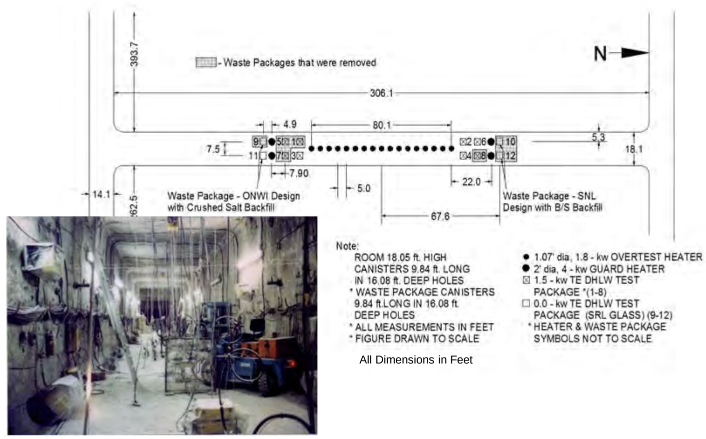
Munson et al. SAND89-2671

North Experimental Area - East Site

- **Thermo/Structural Interaction Tests Rooms A1-A3, Room B and Room D**
  - **TSI heaters and equipment abandoned in place, roof collapsed in test rooms in 1990's**
- **Waste Package Performance Tests in Room B and Room A1**
  - **Room A1 waste packages remain in place, damage from roof collapse to test room**
  - **Room B had 7 waste packages removed in ≈ 1989, 5 waste packages remain**
- **Plugging and Sealing Program in Room M**
  - **Majority of Seals Remain intact, a limited number were cored**

Re-Entry Test Planning 9

Room B Heater & Waste Package Layout



Re-Entry Test Planning 10

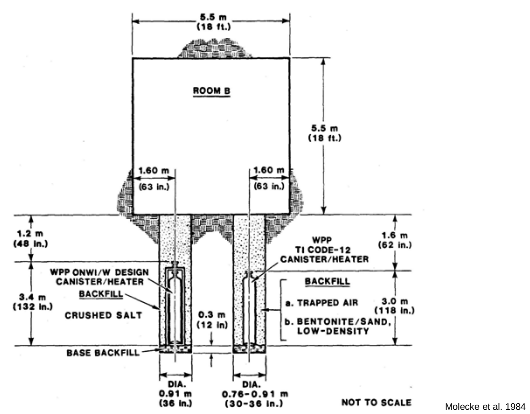
Room B Heater Listing

WP/Heater ID	Test	Heater*	Qty	Heat (Watts)	Canister Size (in.)	Description	Backfill Material	Objective
B061-B064	TSI	Guard	4	4,000	24 x 120	Schedule 40 Mild Steel Pipe	Table Salt and Vermiculite	Thermal Load
B020-B027 B030-B038	TSI	Canister	17	1,800	12.8 x 120	Schedule 80 Mild Steel Pipe	Table Salt and Vermiculite	Thermal Load
WB1	WPP	Canister Removed	1	1,500	31.5 x 132	ONWI Mild Steel Overpack	Trapped Air	Nondegraded, Brine Migr., Fluid Vol. Prod.
WB5	WPP	Canister Removed	1	1,500	31.5 x 132	ONWI Mild Steel Overpack	Crushed Salt	Degraded, Long-Term Brine Intrusion
WB9	WPP	Canister	1	None	31.5 x 132	ONWI Mild Steel Overpack	Crushed Salt	Degraded, Long-Term Brine Intrusion
WB11	WPP	Canister	1	None	31.5 x 132	ONWI Mild Steel Overpack	Crushed Salt	Transportation & Handling Effects on SRL Glass
WB3,WB6, WB7,WB8	WPP	Canister Removed	4	1,500	24 x 118	All TiCode-12	Bentonite/Sand Low Density	Degraded & Nondegraded Canisters, Tailored backfill
WB10, WB12	WPP	Canister	2	None	24 x 118	All TiCode-12	Bentonite/Sand Low Density	Handling Effects on SRL Glass, Long-Term Brine
WB2	WPP	Canister Removed	1	1,500	24 x 118	Schedule 60 Steel Pipe,	Trapped Air	Non-degraded, Brine Migration., Fluid Vol. Prod.
WB4	WPP	Canister Removed	1	1,500	24 x 118	Schedule 60 Steel Pipe, TiCode Overpack	Bentonite/Sand Low Density	Non-degraded, Tailored backfill

Red Text Represents Waste Packages that Have Been Removed

Re-Entry Test Planning 11

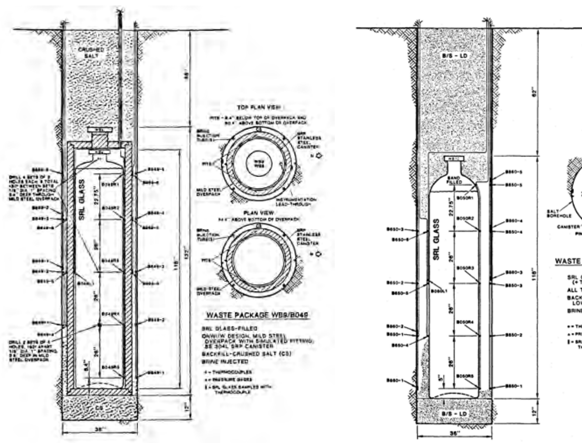
Room B Waste Package Installation



Molecke et al. 1984

Re-Entry Test Planning 12

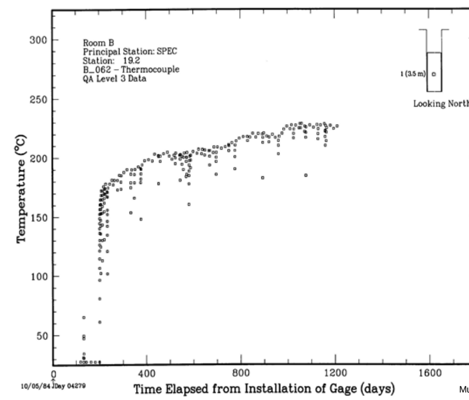
Room B Waste Package Configuration



Molecke et al. 1984

Re-Entry Test Planning 13

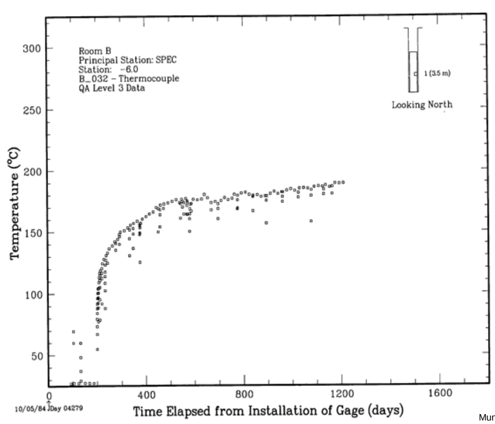
Typical 4 kW Guard Heater Temperature Data



Munson et al. SAND89-2671

Re-Entry Test Planning 14

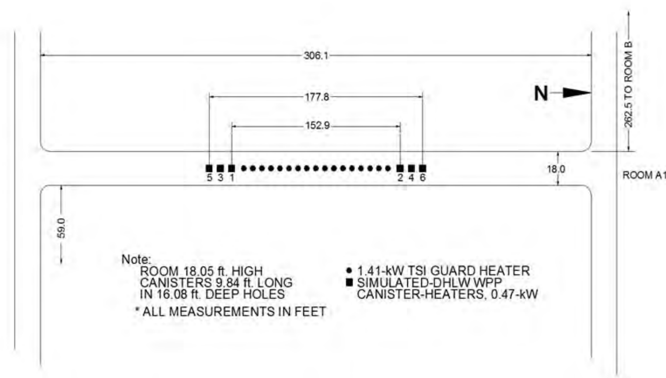
Typical 1.8 kW Heater Temperature Data



Munson et al. SAND89-2671

Re-Entry Test Planning 15

Room A1 Canister & Waste Package Layout

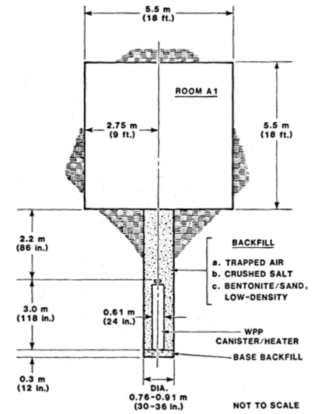


Re-Entry Test Planning 16

A-Room Canister and Waste Package Listing

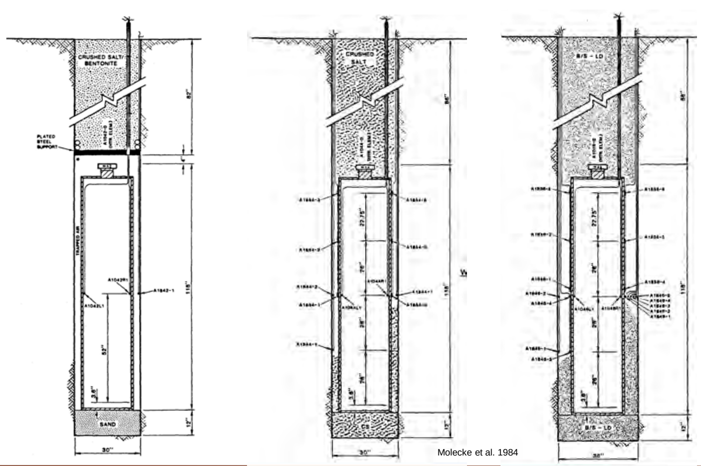
Room	Test	Heater*	Quantity	Heat Load (Watts)	Canister Size	Description	Backfill Material	Objective
A1	TSI	Guard	13	1,410	12.8 in x 118 in.	Mild Steel	Crushed Salt	Thermal Load
A1 WA3, WA4	WPP	Canister	2	470	24 in. x 118 in.	Mild Steel	Crushed Salt	WPP
A1 WA5, WA6	WPP	Canister	2	470	24 in. x 118 in.	Mild Steel With TiCode Overpack	Bentonite/Sand Low Density	WPP, Tailored Backfill
A1 WA1	WPP	Canister	1	470	24 in. x 118 in.	Mild Steel	Trapped Air	Brine Migr., Fluid Vol. Prod.,
A1 WA2	WPP	Canister	1	470	24 in. x 118 in.	Mild Steel With TiCode Overpack	Trapped Air	Brine Migr., Fluid Vol. Prod.,

Typical Room A1 Waste Package Installation



Molecke et al. 1984

Three Types of Room A1 Waste Packages



Molecke et al. 1984

Why Room B and A1

- DHLW Overtest & DHLW Mockup Test generated the highest heat loads. Temperatures > 200° C measured at some of the heater / salt interface.
- Availability of undisturbed heaters and waste packages that had power outputs ranging from 0.47kW to 4kW.
- Wide range of backfill materials around the heaters – Crushed Salt, Table Salt, Bentonite/Salt, Air, Vermiculite and Bentonite/Sand.
- Accurate and detailed As-Built documentation exists for these test locations.
- Proximity to the newly mined SDI/SDDI areas.

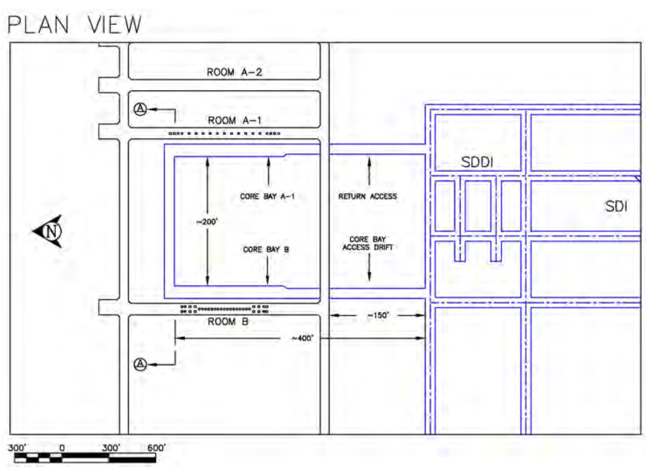
Proposed Forensic Activities

- **Investigate the Brine and Formation Permeability through laboratory testing of core and in-situ testing of boreholes drilled up to the heaters**
- **Evaluate the performance of Waste Package and Heater Materials in place for > 30 years (Ticode & Steel)**
- **Assess performance of crushed salt and crushed salt/bentonite backfill materials through laboratory testing of core samples**
- **Perform in-situ tests to assess the Disturbed Rock Zone (DRZ) surrounding the heaters and test rooms**

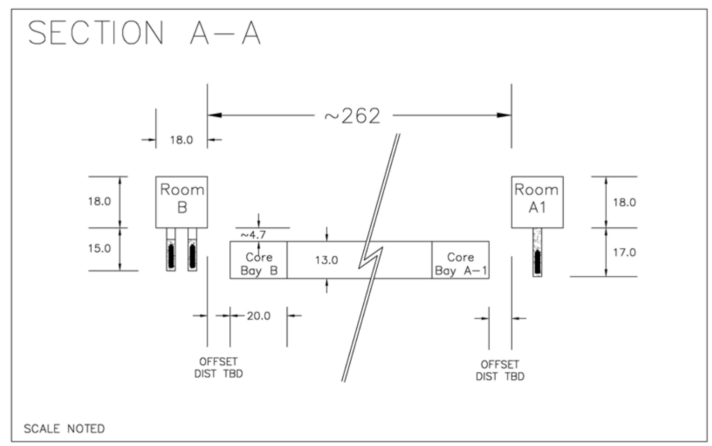
Access to A-1 and B Room Heaters

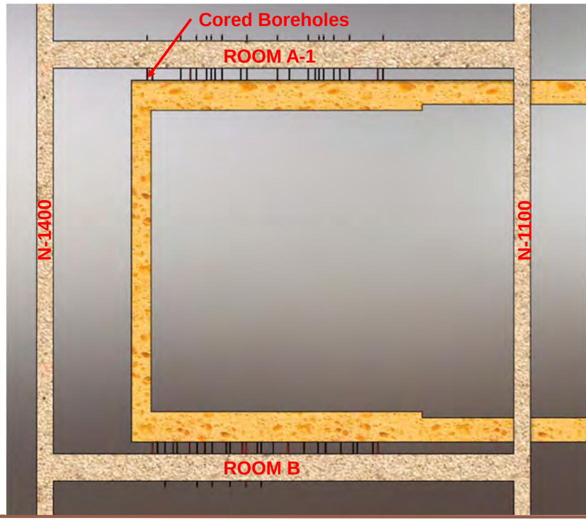
- **Safe access to areas of interest will be planned and engineered by the M&O.**
- **Planning is in process and will culminate in a plan to be delivered in September, 2013.**
- **Access will allow for core collection, sampling, and in-situ testing of the properties outlined previously.**
- **The following are flat file and 3-D conceptual illustrations of access drifts that will meet the program objectives.**

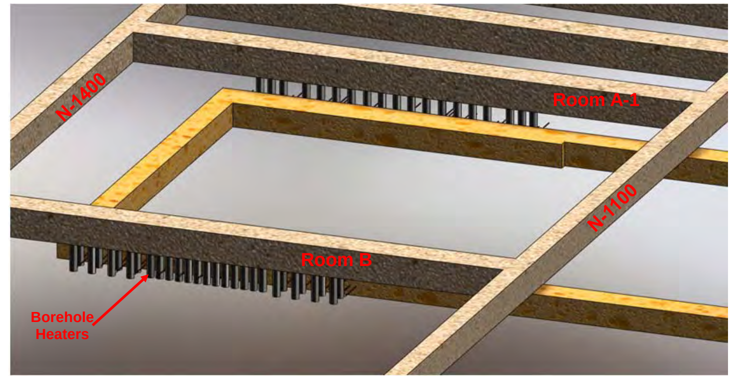
Access to A-1 and B Room Heaters



Access to A-1 and B Room Heaters







Summary

- As an extension of the SDI Research Area, this new area will provide opportunity for a wide range of additional forensic type investigations by multiple organizations.
- ROM cost of initial construction and testing is ≈ $2.25 million.
- Initial phase will take 2-3 years to construct and perform testing (both in-situ and laboratory).
- Excellent opportunity to gather insight into long term conditions for areas that have been heated and cooled and remain undisturbed for ≈ 30 plus years.
- Other Potential Benefits?