Test Proposal Document for Phased Field Thermal Testing in Salt

Fuel Cycle Research & Development

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ACRONYMS

ADDIGAS	ADvective and DIffuse GAS transport in rock salt formations (Asse test)
BAMBUS	Backfill And Material Behavior in Underground Salt (Asse test program)
BPC	Borehole Pressure Cell
CMH	Chilled Mirror Hygrometer
DAS	Distributed Acoustic Sensing
DHLW	Defense High-Level Waste
DEBORA	Development of Borehole seals for High-Level Radioactive Waste
DOE	U.S. Department of Energy
DOE-CBFO	DOE – Carlsbad Field Office
DOE-EM	U.S. Department of Energy Office of Environmental Management
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
DCS	Distributed Control System
DPC	Dual Purpose Canister
DRZ	Disturbed Rock Zone
DTS	Distributed Temperature Sensing
EBS	Enhanced Barrier System
FBG	Fiber Bragg Grating
FEPs	Features, Events, and Processes
FFB	Fluid Flow Brine
FFG	Fluid Flow Gas
FIMT	Fiber In Metal Tube
FY	U.S. federal Fiscal Year
GPR	Ground Penetrating Radar
HGNW	Heat-Generating Nuclear Waste
HDP	Heat Dissipation Probe
HLW	High-Level Waste
LANL	Los Alamos National Laboratory
LNBL	Lawrence Berkeley National Laboratory
LVDT	Linear Variable Displacement Transducer
MODURN	Model-Driven Uncertainty Reduction
NAS	National Academy of Sciences
NEA	Nuclear Energy Agency (Paris, France)
NMR	Nuclear Magnetic Resonance
NV	Nevada
OECD/NEA	Organization for Economic Co-operation and Development /NEA
OSTI	Office of Scientific and Technical Information
PA	Performance Assessment
PSP	Plugging and Sealing Program
PZT	Lead Zirconium Titanate Piezo-Electric Sensors
RD&D	Research Development and Development
RDO	Repository Design and Operation
RH	Remote Handled (Figure 7) and Relative Humidity (Figure 14 and Section 9.4))
RoM	Run of Mine
ROV	Remotely Operated Vehicle
RTD	Resistance Temperature Detectors

SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories (Albuquerque, NM)
TDR	Time Domain Reflectometry
TH	Thermal and Hydrological
THC	Thermal, Hydrological, and Chemical
THM	Thermal, Hydrological, Mechanical
THMC	Thermal, Hydrological, Mechanical, and Chemical
TRU	Trans-Uranic waste
TSDE	Thermal Simulation of Drift Emplacement (Asse test)
TSI	Thermal/Structural Interactions (WIPP in situ testing program)
TSPA	Total System Performance Assessment
UQ	Uncertainty Quantification
URL	Underground Research Laboratory
UFD	Used Fuel Disposition (DOE-NE research program)
UFDC	UFD Campaign
UHF	Ultra High Frequency
U.S.	United States
VHF	Very High Frequency
WIPP	Waste Isolation Pilot Plant (Carlsbad, NM)
WPP	Waste Package Performance (WIPP in situ testing program)
XRD	X-Ray Diffraction

FCT Quality Assurance Program Document

Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone	**Test Proposal Document for Phased Field Thermal Testing in Salt**
Work Package Title and Number	FT-15LA081901 DR Salt Field Testing - LANL
Work Package WBS Number	1.02.08.19 - DR Salt Field Testing
Responsible Work Package Manager	Philip H. Stauffer P. Stauffer (Name/Signature)
Date Submitted	

Quality Rigor Level for Deliverable/Milestone	☒ QRL-3	☐ QRL-2	☐ QRL-1 ☐ Nuclear Data	☐ N/A*

This deliverable was prepared in accordance with Los Alamos National Laboratory
(Participant/National Laboratory Name)

QA program which meets the requirements of
☒ DOE Order 414.1 ☐ NQA-1-2000

This Deliverable was subjected to:

☒ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below
Name and Signature of Reviewers	
Hari Viswanathan H. Viswanathan	

*Note: In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity along with the Document Cover Sheet is sufficient to demonstrate achieving the milestone. QRL for such milestones may be also be marked N/A in the work package provided the work package clearly specifies the requirement to use the Document Cover Sheet and provide supporting documentation.

Executive Summary

The Used Fuel Disposition (UFD) campaign is conducting generic research, development, and demonstration (RD&D) activities to explore geologic disposal in salt, granite, clay/shale, and deep boreholes. The work described in this report applies UFD campaign objectives to the generic salt repository concept.

In this document, we summarize how a new round of staged thermal field testing will help to augment the safety case for disposal of HGNW in salt. The objectives of the proposed test plan are to: (1) address features, events, and processes (FEPs), (2) build scientific and public confidence, (3) foster international collaboration, (4) evaluate disposal concepts, and (5) validate coupled process models. Each stage of testing is tied to remaining uncertainties and knowledge gaps related to the safety case determined during expert panel discussions. Finally, a set of underground research laboratory (URL) experiments are described in more detail, starting with smaller, process-level borehole tests, progressing to the scale of a single 3 m canister, and culminating in multiple-heater drift-scale tests.

Small-diameter borehole thermal testing (Figure ES-1) is proposed as a first step to restarting US field testing in salt. These tests can be used to isolate phenomena in a simplified, more directed, and generic test configuration. Borehole tests are useful for (1) assessing damage related to mining and disturbance, (2) simulating a post-closure environment, (3) confirming salt material properties, and (4) model validation. The test will also (5) provide ramp-up opportunities for testing new equipment and sensors in the field, and develop modern best practices for in-situ experimentation to use during the larger tests in this staged testing plan.

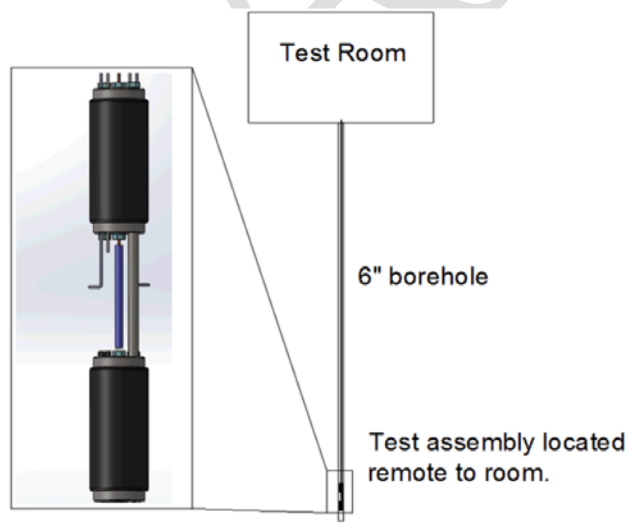


Figure ES-1. Schematic of a Standardized Vertical Borehole Heater Test in Salt.

The next scale of experiment will involve a single full-size heated canister to be emplaced in a larger borehole (Figure ES-2). A 2 ft diameter x 3 m long heated canister will be placed on the floor of a 3 ft by 16-20 ft horizontal borehole. The borehole will then be backfilled with screened (small grain size) run-of-mine salt and blocked from the drift by a series of seals. This test is an intermediate step forward in complexity from the small-diameter borehole tests, yet does not require the complexity associated with a dedicated drift and multiple heaters. Experiments performed in this configuration will provide valuable information on RoM backfill in the presence of in-situ temperatures, pressures, and fluid fluxes with a full-size heated canister.

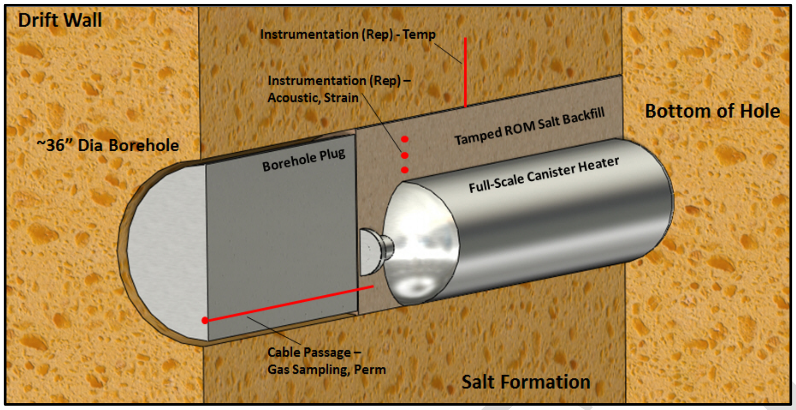


Figure ES-2. Schematic of the Borehole Emplacement Experiment.

Drift-scale testing refers to a spatial scale that includes many of the operational complexities of a repository, including mining full sized drifts and moving large quantities of RoM salt. FEPs that are missing from the small-scale and single-canister experiments and combinations of individual processes will be tested in this phase of testing. Two configurations for a generic salt repository are described for drift-scale in-situ testing: in-drift (Figure ES-3) and alcove emplacement. Relevant historical tests at this scale are presented followed by discussion of instrumentation and data acquisition techniques likely to be used in either drift-scale test configuration.

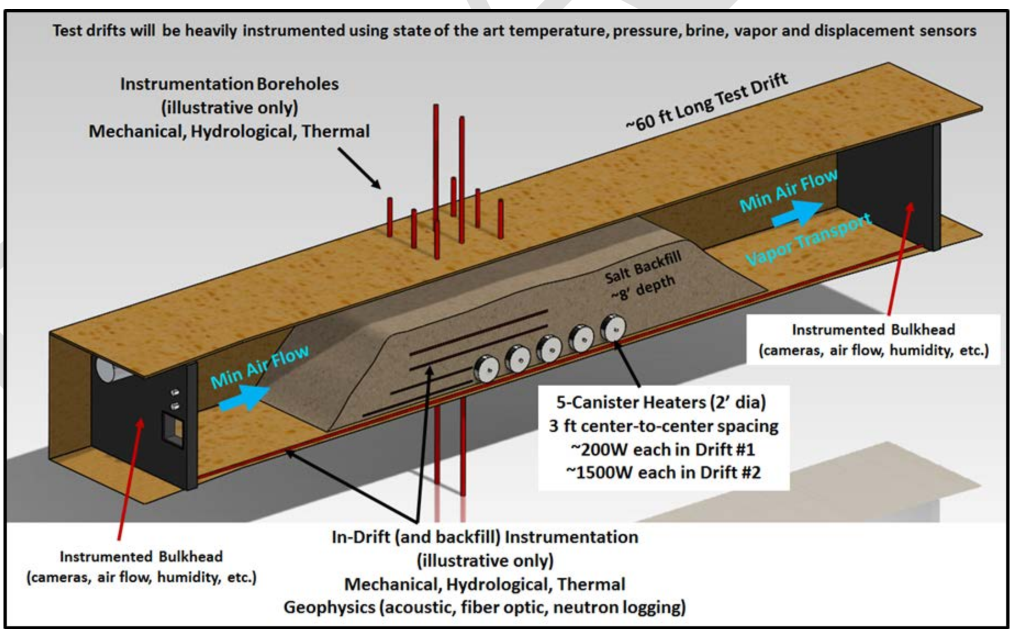


Figure ES-3. Schematic of the In-Drift Field-Scale Thermal Test and Disposal Demonstration.

Examples of questions to be addressed in the field testing program include:

- Does heat substantially change rock characteristics and evolution of the brine (distribution, movement, and chemistry) within intact host rock, the damaged rock zone, and/or salt backfill in such a way that post-closure performance would be impacted?

- Do uncertainties and inherent variability in salt formation mineralogy and brine composition lead to cases where acid gas formation becomes an important consideration?
- How does the ventilation air in the mine (i.e., active/direct during emplacement operations or passive/indirect ventilation after drift closure) affect vapor removal from a loaded drift in both open and closed drift configurations?
- How closely do models simulate the thermally-driven behavior of the mechanical, hydrological and chemical changes in the system, as well as the pre-heating processes in the system?

These tests are designed to address both long term performance assessment (PA) and shorter term operational uncertainties. This staged testing process will result in a systematic reduction of uncertainty and provide increasing confidence in the adequacy of our understanding of the thermal response of salt in a generic repository setting. Each test description includes rationale and justification, how the test builds on prior salt investigations, how the test is integrated with laboratory experiments and associated modeling, and how the test relates to the long-term safety case for heat generating nuclear waste disposal in salt.

TEST PROPOSAL DOCUMENT FOR PHASED FIELD THERMAL TESTING IN SALT

1. Introduction and Purpose

Ongoing research into generic geologic repository science related to creating a safety case for deep geological disposal is the responsibility of the Used Fuel Disposition (UFD) Campaign within the DOE Office of Nuclear Energy Office of Fuel Cycle Technologies (DOE, 2013). The UFD campaign is pursuing such supporting research, development, and demonstration (RD&D) activities to explore disposal in salt, granite, clay/shale, and deep boreholes, four of the most likely disposal concepts outlined in the UFD Campaign Disposal and Research Roadmap (DOE, 2012). The roadmap highlights that knowledge gaps and reduction of uncertainty in our understanding of deep geological storage are key concerns of the UFD program.

Specific objectives related to disposal system performance are defined in an update to the UFD Campaign Implementation Plan (McMahon, 2012). For 2013-2015 the focus is on using theory, experiments, and modeling in combination with existing underground research laboratory (URL) data to assess disposal system performance, including reduction of uncertainty associated with heat-generating nuclear waste (HGNW). HGNW is defined herein as the combination of both heat generating defense high level waste (DHLW) and civilian spent nuclear fuel (SNF). Thermal, hydrological, mechanical, and chemical (THMC) coupling and related modeling, as well as development of a field testing plan are called out in this objective. For the years 2015-2025, the UFD campaign goals shift to focus on "*…continued development of the capability for understanding of disposal system performance through modeling and simulation and focused experimentation in the laboratory and field (i.e. URLs). The URLs used will either be existing or constructed in the United States or those that could be accessed through international collaborations…*" (McMahon, 2012). All of these goals help to enhance the technical basis for disposal of HGNW and will lead to the development of science and engineering tools to facilitate future work.

1.1 Purpose

The purpose of this document is to define field thermal testing activities to augment a safety case for generic salt disposal of HGNW. SNF can include both commercial and defense components, while DHLW is strictly generated from U.S. defense activities. These waste forms are indicated in Table 1, along with the activities to support the safety case, validate long term performance assessment and/or demonstrate waste isolation. As SNF and DHLW age, the thermal load is decreased due to decay of heat generating isotopes, leading to differentiation of SNF in column 2 of Table 1 based on the time since removal from the reactor. In Row IV, DPC (Dual Purpose Canister) represents a unique configuration of an already existing container design that may be directly disposed in a salt repository. Examples of features Events and Processes (FEPs) that relate to the safety case, such as the damaged rock zone (DRZ), are also highlighted in Table 1. More information on HGNW waste streams and thermal loads is included in Section 2.3 and Appendix A.

Table 1. Salt RD&D Program Based on Existing Inventory and Large Cask Configuration (Nair, 2015).

Classification Levels	Representative Inventory/Cask Configuration	Nature of RD&D Activities		
		Pre-closure/ Operational period	Post-closure/ Long-term	Performance Confirmation-Demonstration
I	Low temperature (< 100 C) wastes, including most defense HLW, older DOE SNF, and other old commercial SNF.	System integration issues related to design, mining/construction, handling/operations and maintenance	Nominal: address unresolved, prioritized and applicable FEPs supporting safety case Disruptive: conduct critical assessment of assumptions	Validate long term performance assessment by lab/repository demonstration tests
II (proposed base case for salt safety assessment of HGNW)	Intermediate temperature (100–200°C) wastes, including DOE SNF not in Level I, commercial SNF out-of-reactor > 15years and low burnup (<45 GWd)	Thermal considerations on design, mining/construction, handling/operations and maintenance	Nominal: assess impact of thermally driven FEPs on safety case Disruptive: develop information to support potential stylized requirements	Construct lab/repository tests to evaluate assumptions employed in developing safety case
III	High Temperature (>Level II) wastes, including commercial SNF < 15 yr out-of-reactor and/or burnup of 45-60 GWd	Thermal-mechanical-chemical interaction considerations on design, mining/construction, handling/operations and maintenance	Nominal: evaluate DRZ and near field behavior on the performance of applicable FEPs Disruptive: conduct critical assessment of impact to safety case	Perform thermally accelerated tests in lab/repository to demonstrate confidence in waste isolation
IV	Thermo-mechanical tests for large waste packages with high heat loads, i.e., DPCs	Thermal-mechanical considerations on design, mining/construction, handling/operations and maintenance	Nominal: address thermo-mechanical effects on applicable FEPs Disruptive: conduct critical assessment of assumptions	Monitor in situ (repository) placement of a DPC over a long period of time

Figure 1 illustrates the role of field tests in the context of a broader set of investigations that facilitate a science-based safety case for disposal, under model-driven uncertainty reduction. The core concept is the systematic reduction of uncertainty in models through an iterative process of model development, experimental studies, and repository modeling to assess geologic disposal viability. Separate-effects tests examining individual processes under controlled laboratory conditions are reexamined in an integrated fashion in a URL, and models of the field test are developed. Because even a field test is of limited duration and spatial extent compared to an operating repository, additional modeling is used to quantify how residual uncertainties propagate through a generic model of a hypothetical repository, bringing in other relevant considerations and processes (e.g., scenario development, regulatory criteria, and subsystem models) in order to fully define a performance assessment analysis. These results, vetted at regular intervals with stakeholders, are used to inform modification of the science program as new knowledge is incorporated. Models are central to this approach because they drive the process of systematic learning, adaptation, and communication, which facilitates success in a repository program.

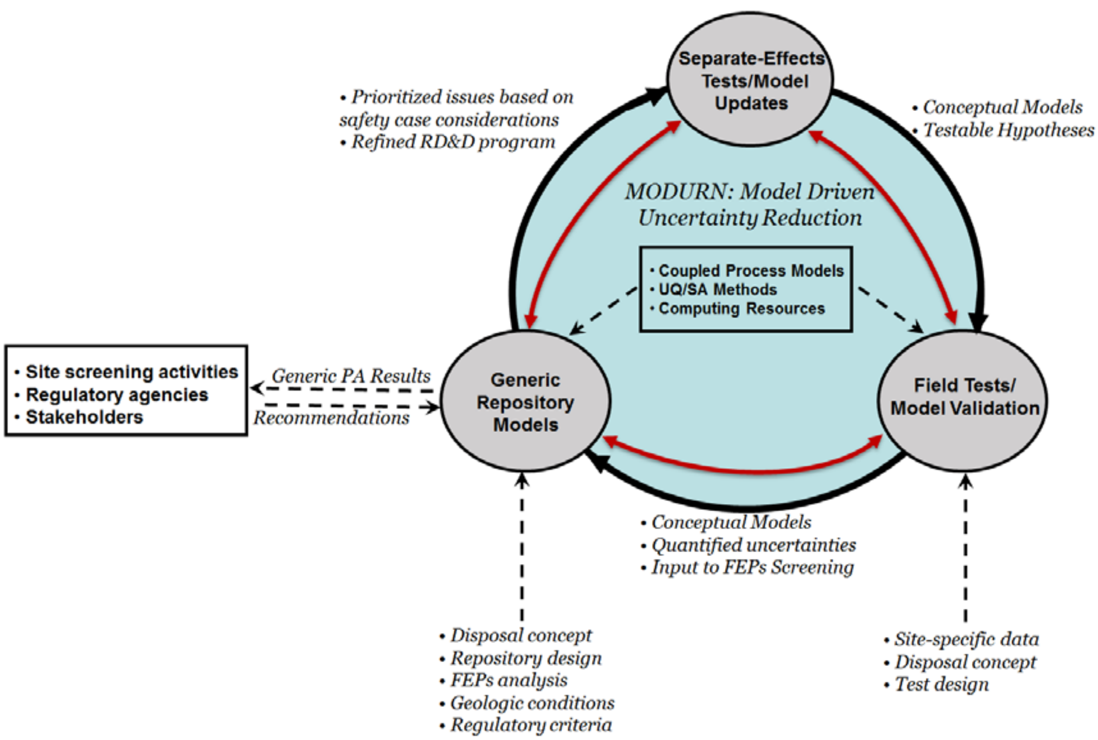


Figure 1. Conceptual Schematic of Iterative, Adaptive, Model-Driven Process for Repository Investigations (after Figure 2, Robinson et al., 2012).

Results from this work will support a safety case for a generic salt repository; see Section 2.2.2 of the "*UFD Campaign Disposal Research and Development Roadmap" (DOE,* *2012). OECD/NEA (NEA, 2004) defines a safety case as "synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied on." This definition posits the safety case is more inclusive than the post-closure performance assessment safety analysis and may include evidence such as understanding of physical processes related to the pre-closure repository operations safety, FEPs exploration and exclusion of processes that could impact the time evolution of the repository but not affect safety performance, and pre-closure operational issues related to backfill and waste packages. Further, the UFD Campaign Research Roadmap (DOE, 2012) states "An aspect of the UFDC's considerations associated with implementing a geologic repository in different geologic media is the marked differences between the U.S. and other nations, in the regulatory bases for assessing suitability and safety of a repository. Because the probability based – risk informed nature of U.S. regulations is sufficiently different from other regulations, <u>information gained in previous studies, while useful, likely needs to be supplemented to enable more convincing communication with the public, better defense of the scientific basis, and stronger safety cases</u>*" (DOE, 2012; emphasis added here).

The field thermal testing activities recommended in this document are intended to support the generic salt safety case and are based on prioritized rankings produced during recent workshops and panels, technical publications, and proposals (Hansen and Leigh, 2011; Robinson et al., 2012; DOE/CBFO, 2012), which are discussed in section 2 of this document. Proposed activities were evaluated and their rankings are summarized at the March 6-7, 2013 workshop titled: Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt (Sevougian et al., 2013). This workshop had the goals of (1) formulating an expert consensus on the relative priority of technical issues related to disposal of heat generating waste in salt and (2) recommending ranked RD&D activities to address these issues, including modeling studies, laboratory studies, and field testing.

1.2 Salt Repository Background

Disposal of HGNW in salt is attractive because (1) salt can be easily mined, (2) salt has a relatively high thermal conductivity, (3) bedded salt has a wide geographic distribution, (4) salt is viscoplastic, (5) intact salt is essentially impermeable, (6) fractures in salt are self-sealing, and (7) bedded salt formations have been geologically stable for millions of years (NAS, 1957; Hansen and Leigh, 2011).

Several historical summaries have recently synthesized the wide range of field and large laboratory tests conducted in salt over the last 60 years. Hansen and Leigh (2011) provided a high-level summary of relevant testing and the technical state-of-the art related to disposal of heat-generating waste in salt. Kuhlman et al. (2012) summarized U.S. salt testing and created an online database of salt-based research (https://sited.sandia.gov/sited). Callahan et al. (2012) briefly discussed some historic testing performed outside the Delaware Basin (limited to discussion of Project Salt Vault, Avery Island, and a few tests at the Asse facility in Germany). Kuhlman and Malama (2013) recently conducted a more specialized summary of historic testing specific to the movement of brine in heated geologic salt.

Prior in-situ thermal testing in salt at URLs worldwide is discussed throughout this document where relevant to outstanding issues, questions, and data gaps; historical tests are further described in Appendix B. Bedded salt may contain upwards of an order of magnitude more water than domal salt (Hansen and Leigh, 2011); therefore, prior testing in domal salt may not cover effects of all water-sensitive processes, including understanding the full behavior of water in generic salt systems that are subjected to heating. Other information that factors into the proposed testing includes: (1) recent research results (FY13 through FY15; Section 9.4; e.g., Stauffer et al., 2014a,b), (2) focused discussions from a January 20, 2015 DOE-NE meeting concerning test planning, and (3) ongoing studies and associated reports (both US and international recommendations) related to the safety case and engineering performance (e.g., Hansen et al., 2014; Rundqvist, 2015).

1.3 Document Preview

Following the statement of objectives, we describe a phased testing plan that starts with smaller-scale tests that are independent of repository configuration (i.e., lower cost activities) and progresses to larger-scale tests that include more specific aspects of a repository configuration, all of which would address uncertainties related to the safety case. This phased approach would address expected ranges of thermal loading and aspects of test implementation for both measurement techniques and control of variables at the various scales. The phased approach leads methodically to more complex and higher cost URL tests that tie to the ultimate goal of performance confirmation and demonstration shown on the last column of **Table 1** and described in UFD planning documents (DOE, 2012; McMahon, 2012). This process will also allow development of advanced modeling capabilities (Appendix C), testing of a range of existing and proposed monitoring equipment in a salt environment (Appendix D), and training of the next generation of personnel. Related laboratory and small-scale in-situ experiments are discussed in Appendix E.

2. Objectives of a Generic Thermal Testing Program

Generic salt disposal research issues were evaluated within the context of the safety case at the 2013 workshop using a methodology for rating importance of issues relative to their impact on post-closure safety, pre-closure safety and design. Demonstration of confidence in performance of safety/design aspects used for models and testing data was also considered (Sevougian et al., 2013, Section 5). The general objectives of field-scale testing within the context of a safety case are given in Table 2.

Table 2. Objectives of Field-Scale Testing.

	Objective	**Description**
1.	Address features, events, and processes (FEPs)	Confirm our understanding and ability to model FEPs that affect the performance of a deep geologic salt repository for disposal HGNW
2.	Build confidence	Build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods
3.	Foster international collaboration	Enhance technical credibility through engagement with the international community
4.	Evaluate disposal concepts	Evaluate designs and operational practices
5.	Validate coupled process models	Predict and confirm evolution of processes at scales and times beyond those possible in lab or field testing

Subsequent to the 2013 SNL workshop, Sevougian and MacKinnon (2014) further delineated how any field scale study would support the safety case for a generic salt repository. An objectives "hierarchy" developed in that study is shown in Table 3. Work related to these objectives has significant benefit to support the safety case for a generic bedded salt formation repository at this time (Sevougian and MacKinnon, 2014).

Table 3. Safety Case Objectives Hierarchy (from Figure 4, Sevougian and MacKinnon, 2014).

Level 1	***Level 2***
Support Repository Design, Construction, and Operations	Support design of: underground layout and drifts; ventilation and drainage systems; access shafts/drifts; backfill; seal system; ground support; power supply; and waste canisters
	Support operations
Support Repository System Technical Bases	Support enhanced barrier system (EBS) technical basis
	Support geosphere technical basis (including site characterization)
	Support biosphere technical basis
Support Pre-closure Safety Evaluation	-
Support Post-closure Safety Evaluation	Support 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, and traceability

2.1 Historical Salt Testing Related to the Safety Case

Because past U.S. investigations have not focused on a high-temperature SNF disposal scenario, it is recognized that additional in-situ and laboratory activities will help build confidence and confirm the existing safety case based on current knowledge and understanding of a generic salt repository system (Kuhlman and Sevougian 2013; Sevougian and MacKinnon, 2014). A summary of brine flow in heated salt (Kuhlman and Malama, 2013) describes both laboratory and in-situ tests of high-heat experiments at U.S. and German sites. The Asse II site in Germany hosted several tests concerning HGNW spanning from the 1960s to the present (with a hiatus from 2000 to 2010). The most recent major research at Asse II was the BAMBUS II project (described in Appendix B and Bechthold et al., 2004), which covered the post-test forensic analysis performed on the Thermal Simulation of Drift Emplacement Experiment (TSDE) drift, backfill, and canisters. Significant DRZ characterization and permeability testing was performed as part of BAMBUS II (Bechthold et al., 2004).

Tying together the existing work on HGNW in salt, Kuhlman and Sevougian (2013) relate test results to the matrix of FEPs used in development of the safety case for HGNW disposal in salt. This work notes that "*A strong safety case for disposal of heat generating waste at a generic salt site can be initiated from the existing technical basis (e.g., MacKinnon et al. 2012). Though the basis for a salt safety case is strong and has been made by the German repository program, RD&D programs continue (Sevougian et al. 2013), in order to help reduce uncertainty, to improve understanding of certain* *complex processes, to demonstrate operational concepts, to confirm performance expectations, and to improve modeling capabilities utilizing the latest software platforms."* Some prior thermal tests in salt are summarized in Appendix B. Results from prior testing helped to delineate the information gap/uncertainty analysis that informs the following discussion of outstanding uncertainties of importance to the safety case.

2.2 Link between the Test Proposal and the Safety Case

Outstanding technical issues related to the generic salt repository concept were prioritized using a consistent methodology for decision analysis and expert opinion (Sevougian and MacKinnon, 2014). The participants ranked issues based on their relevance to the repository safety case. The post-closure safety case is built on quantitative metrics related to isolation, stability, and containment. During the ranking process at the workshop, the importance to post-closure safety (long-term performance assessment) was given primary consideration, with support for the following other first-level considerations also included: repository design, construction, and operations; pre-closure safety; technical bases for understanding the repository system (including site characterization); and confidence-building. The field thermal testing activities proposed in this report are designed to address the high-priority issues identified at the workshop.

Of the highly-ranked issues from the workshop, the field thermal tests proposed here were prioritized to address issues where prior research was limited or where uncertainties remain. This contributes to the ability to demonstrate the long-term post-closure safety case for HGNW through the regulatory period, which requires an understanding of evolutionary processes and the associated field parameters (some of which are site-specific). The progression from small-scale process experiments evaluating the range of possible thermal loads to a full-scale in-situ demonstration test more representative of a repository configuration allows development of a robust approach to successfully execute a large-scale, configurationally complex field test. Full-scale tests will provide data to validate and build confidence in the predictive capability of models and the current conceptual understanding, and to demonstrate that heated waste emplacement produces no adverse or unforeseen effects (Sevougian and MacKinnon, 2014).

shows the link between the proposed field test activities and the ranked issues from the workshop (Sevougian et al., 2013), as well as the relevant safety case elements–e.g., confidence building, pre-closure, post-closure, or repository design and operation (RDO). Additional benefits to these activities would be the application and testing of modern instrumentation and sensor technologies in the generic salt repository environment; use of these new technologies will help with confidence-building, will support potential future repository design and potential future monitoring, and will provide data to present the current state-of-the-art understanding of all issues to stakeholders, regulators, and the public. Table 5 lists the safety case issues referenced in , as numbered in Sevougian et al., 2013**,** from their Tables G-2 and G-3, and updated after the workshop.

Table 4. Safety Case Issues Addressed by the Proposed Field Tests.

Field test:	Elements addressed	Safety case issues addressed by test (see Table 2)
Small-Diameter Borehole Field Thermal Tests (section 3.1)	Confidence-building, Post-closure, Pre-closure	2, 3, 5, 6, 7, 9, 11, 14, 15, 16, 17, 18, 23, 28, 31, 32, 33, 34, 37, 39, 40, 43, 46, 47
Single Canister Test (section 3.2)	Post-closure, Confidence-building, RDO, Pre-closure	2, 3, 5, 6, 7, 14, 15, 16, 17, 18, 23, 28, 31, 32, 33, 34, 37, 38, 40, 41, 42, 43, 46, 47
Drift-Scale Tests (section 3.3)	Confidence-building, RDO, Pre-closure, Post-closure	2, 3, 5, 7, 14, 15, 16, 17, 18, 23, 28, 31, 32, 33, 34, 37, 39, 40, 41, 42, 43, 46, 47

Table 5. All High-Priority Safety Case Issues as Numbered in Sevougian et al. Asterisk (*) indicates pre-closure only cases.

*2. Physical-chemical properties of crushed salt backfill at emplacement
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement
5. Mechanical response of backfill
6. Impact of mechanical loading on performance of the waste package
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation
9. Mechanical and chemical degradation of the waste forms
11. Changes in chemical characteristics of brine in the waste package
12. Radionuclide solubility in the waste package and EBS
14. Stratigraphy and physical-chemical properties of host rock
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 DRZ
18. Brine and vapor movement through the host rock and DRZ, including evaporation and condensation
23. Thermal response of EBS and geosphere (heat transfer from waste and waste packages into the EBS and geosphere)
*25. Gas generation and potential physical impacts to backfill, DRZ, and host rock
27. Colloid formation and transport in the waste package, EBS, and host rock (including DRZ)
28. Performance of seal system
31. Appropriate constitutive models (e.g., darcy flow, effective stress)
32. Appropriate representation of coupled processes in process models
33. Appropriate representation of coupled processes in total system performance assessment (TSPA) models
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models
37. (Modeling) verification and validation
38. (Modeling) data and results management
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 impact on the host rock and the ability to comply with pre-closure and post-closure 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
43. (Confidence-building) Develop generic safety case
44. (Confidence-building) Comparisons to natural and anthropogenic analogs
*45. (Confidence-building) International collaboration
46. (Confidence-building) In-situ testing and demonstrations
47. (Confidence-building) Verification, validation, transparency, and traceability

Numerical models play an important role in the support and development of the safety case (Figure 1). Such models facilitate evaluating scenarios and hypotheses, and demonstrate our understanding of the physical-chemical system. Development and application of THMC models to support test planning is an integral part of development of field-scale testing and allows the rapid analysis of alternative test designs including scale effects, heating and cooling rates, boundary conditions, and coupled effects. The current suite of models being used and developed to include processes applicable to bedded salt repositories are discussed in Appendix C.

Multiple numerical models will be used to predict and design small-scale experiments. Next, the models will be validated against the results of the experiments. Before large-scale experiments can be performed, a consensus of modeling results must exist to adequately predict what will be expected to happen during the test and optimize test design and instrument placement.

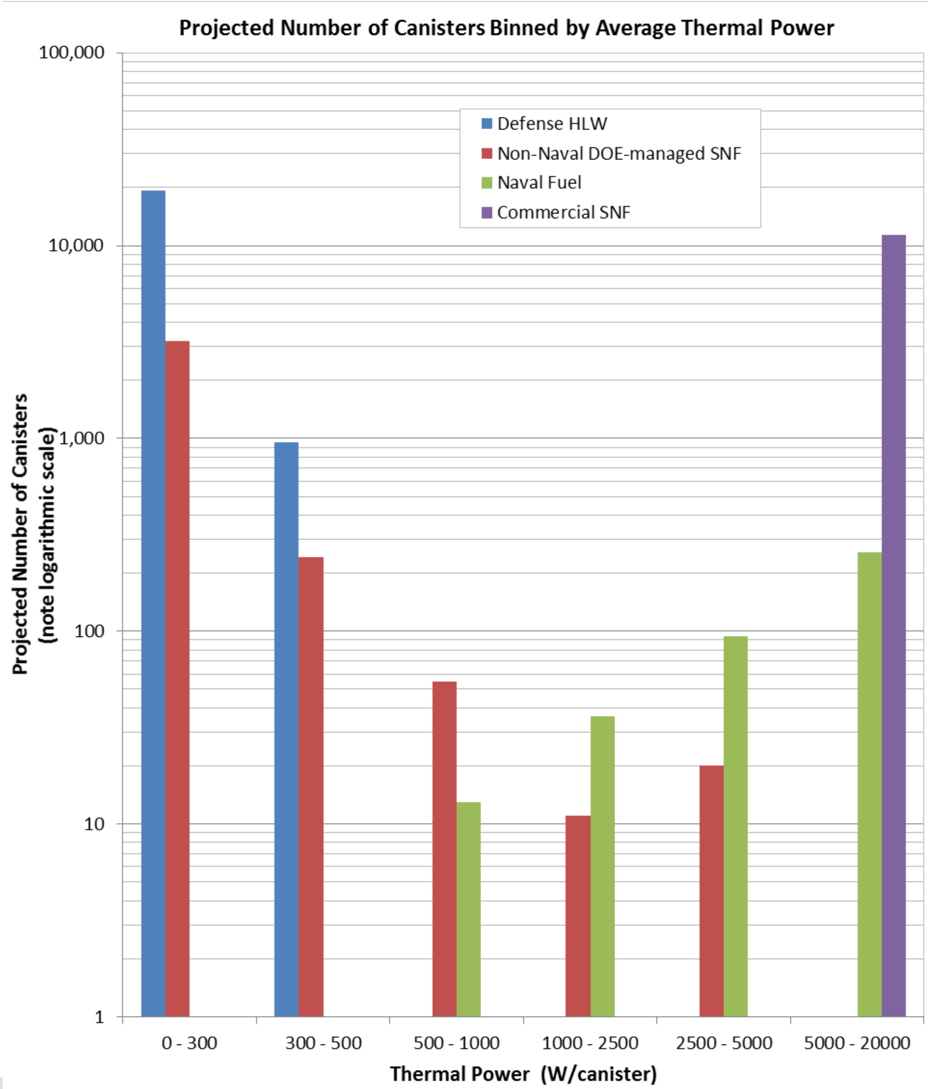
Studies such as Hansen and Leigh (2011), Sevougian et al. (2013), Hansen et al. (2014) and the Jan 20, 2015 DOE NV meeting indicated that carefully planned and executed investigations (both experiments and model refinement) at smaller scales (laboratory scale, small scale in-situ testing, and intermediate scale in-situ testing) can resolve technical uncertainties and enhance the safety case and will provide a more robust basis for executing a full-scale thermal field test. The associated laboratory experimental work and model development will help reduce uncertainties in fundamental processes and resolve equipment issues in a more controlled environment but are not the focus of this document. Therefore, we note that laboratory, in-situ small-scale testing results, and coupled process models will be used to help guide further development of the proposed field-scale underground tests; furthermore, model development and validation would be done in an iterative process using bench scale lab data and smaller experiments in-situ before conducting large scale tests in a URL. (See Appendix E for a summary of the relevant laboratory activities).

2.3 Proposed Field Thermal Testing Approach

A program of field testing of thermally-driven processes generally would consist of tests occurring over a range of spatial scales to directly address aspects of process scaling. For a generic salt site, a phased approach to field testing would involve staging both the scale and level of configuration complexity of the field tests. Starting with a more idealized, smaller-scale borehole test to constrain specific field properties and processes, field tests could progress to larger in-drift configurations that represent more realistic emplacement schemes all the way up to full-scale demonstration testing.

Given the generic nature of repository investigations within the UFD Campaign, the primary rationale and objectives for any field-scale thermal testing in salt should be generic in nature and not wedded to a specific site. For example, a bedded salt deposit may be targeted by the planning of a generic thermal test; however, the test objectives and justification should not be dominated by geologic units specific to one particular deposit. This is more easily accomplished in smaller, more isolated field tests that can be located remote from site specific features. At larger scales that implement configuration characteristics, test results incorporate more site specific behavior such that those aspects would also be evaluated directly (see example below). However, any in-situ test will necessarily involve the specific chemistry of water contained in local brine associated with the most pristine halite layers identified for testing. Once a robust rationale and a set of objectives are detailed for such generic salt testing, there may be additional site-specific considerations that could be added when fielding such a program of investigations.

A fundamental consideration of any field-scale thermal investigations is the range of thermal load from the waste forms that are candidates for disposal within a generic salt repository. For DHLW, thermal outputs per package are fractions of a kilowatt (generally less than about 0.5 kW, see Figure 2). For DOE-managed SNF and naval SNF canisters, the thermal load can be multiple kW (with naval SNF canisters having thermal loads ≥10 kW at disposal). This upper end of canister thermal load is defined primarily by commercial SNF canisters that represent the majority of the DOE-NE UFD Campaign focus for disposal (about 85% by volume and almost all the activity projected out to 2048; SNL 2014). Defining the full range of expected thermal perturbation, volume of rock affected, and duration of perturbation to be investigated depends directly on expected waste form thermal output, and specific properties of the disposal concept such as repository layout and operations.



Note: Projections assume completion of currently planned treatment of all HLW at DOE-managed sites.
DOE-managed SNF (including naval SNF) is projected to 2035. Commercial SNF is projected to 2048
and is assumed to be packaged in dual-purpose storage and transportation canisters of existing designs.

Figure 2. Number of Projected SNF and DHLW Canisters Binned by Average Thermal Power (from DOE, 2014, Figure 3; data sources: Carter and Leduc, 2013; SNL, 2014).

Any field test will be evaluating post-closure thermally-driven processes over a much shorter time scale (generally less than a decade) than the duration of major thermal perturbation within any repository system. Therefore, processes must be considered to possibly be effected by both heating or cooling rates and peak temperature. Cooling rates will be very gradual in a post-closure salt repository due to the gradual decay of heat generating radionuclides and the large thermal mass of the host rock. A fast cooling rate (i.e., shutting off an electric heater) may induce mechanical stress of a very different nature than would be expected for long slow cooling. In addition, slowly occurring processes and that change over long times (hundreds to thousands of years) are difficult to observe in short-term testing. These considerations would be included in both the pre-test planning/analyses and post-test analyses, and are central to delineating clear objectives for post-closure studies in a generic salt repository.

Pre-closure investigations must consider the duration of waste emplacement within drifts prior to backfilling and sealing those drifts. Processes occurring within this pre-closure period will modify the initial conditions of the post-closure period. Representing post-closure evolution accurately is facilitated by a robust understanding of the effects of heating and ventilation during pre-closure. Pre-closure conditions are likewise dependent on and tied to the development of the distributed rock zone during initial excavation of mined openings in the repository.

Thermal, mechanical, hydrological, and chemical (THMC) processes are strongly coupled in salt. Measuring the movement of water and water vapor is an important goal of the field testing. Techniques used in the 1980s were able to measure some aspects of water movement (Krumhansl et al., 1991), while the German program has explored novel technologies. However, the proposed field testing will likely require implementation of new technologies to allow more detailed measurements of water migration (Appendix D).

The duration of a test will be related to whether pre-closure aspects, post-closure aspects, or both are investigated. A longer test is more expensive than a shorter test, but may be required if the processes of interest do not manifest over very short time scales. Slowly occurring processes would be more of a challenge to observe and constrain in shorter-term tests. Such considerations should be handled in both the pre-test planning/analyses and post-test analyses, but ultimately constraints on test duration would stem from clearly defined objectives for a test for a generic salt repository.

The THMC properties of salt are strongly temperature-dependent. An isothermal test would allow isolating hydrological, mechanical, and chemical processes, but would not elucidate potentially important non-linear thermal coupled processes. As discussed above, the range of thermal loads relevant to disposal would be considered directly, and although heating rate may be accurately represented, cooling rates are likely to be much faster than for any repository system that will cool over hundreds to thousands of years. Additionally, the full range of thermal perturbation should be evaluated to assess processes that occ-ur predominantly at the higher expected temperatures. For example, thermally driven changes for common minerals in salt deposits that may be relevant to the safety case are: (1) generation of HCl vapors (Krumhansl et al., 1991) from reaction of magnesium chloride salts (e.g., $MgCl_2{\cdot}4H_2O$), and (2) dehydration of clays (and other phases), which begins at temperatures as low as 75^{o}C (Caporuscio et al., 2013). Although these minerals tend to be minor in salt deposits, their variable distribution may have effects on geochemical conditions potentially relevant to repository performance. Detailed field testing would be designed to answer specific questions related to safety case objectives.

Examples of questions to be addressed in the field testing program include:

- Does heat substantially change rock characteristics and evolution of the brine distribution/chemistry within intact host rock, the DRZ, and/or salt backfill in such a way that post-closure performance would be impacted?
- Are the heating/cooling rates imposed on the salt backfill, disturbed rock zone, and/or intact host rock directly responsible for generating qualitatively different (or new) processes?

- How closely do THMC models simulate the thermally-driven behavior of the mechanical, hydrological and chemical changes in the system, as well as the pre-heating HMC processes in the system?
- How important are hydrological initial conditions (i.e., pressure and saturation) and parameter fields (i.e., permeability and porosity) in non-mechanical THC models of excavations? How sensitive are these models to the mechanically derived conditions developed during initial excavation of the drift?
- Do uncertainties and inherent variability in salt formation mineralogy and brine composition lead to cases where acid gas formation becomes an important consideration?
- How well do coupled process models account for free convection and thermal radiation in the air spaces around HGNW, and is this an important process to include in the safety case?
- How does the ventilation air in the mine (i.e., active/direct during emplacement operations or passive/indirect ventilation post drift closure) affect vapor removal from a loaded drift in both open and closed drift configurations?

  What configurations of backfill and bulkhead/seals are effective at mitigating any deleterious effects of ventilation that may affect post-closure behavior of the system?

3. Proposed Staged Testing Program

The following sections describe the proposed staged testing program. Three primary scales of in-situ experiments are presented, progressing from smaller, more generic tests to more complex, disposal-design-specific tests representing operational and post-closure scenarios in a generic salt repository. In section 3.1, small-diameter borehole heater tests are proposed. Section 3.2 describes a full-size canister borehole heater test. Section 3.3 considers full-scale, design-specific tests, beginning with overall objectives for tests of such configuration in Section 3.3.1. The in-drift emplacement concept considered below includes both moderate and higher thermal loads in two drifts (described in section 3.3.2). Experiments with an alcove emplacement concept are described with higher thermal load in section 3.3.3.

Each test description includes rationale and justification, how the test builds on prior salt investigations, how the test is integrated with laboratory experiments and associated modeling, and how the test relates to the long-term safety case for HGNW disposal in salt.

The field thermal testing will inform, guide, and ultimately validate capabilities for the next generation of coupled multiphysics modeling for HGNW disposal in salt (Table 2, goal 5). Model validation under in-situ conditions is a key component for building confidence in predictive capabilities. Simulation tools currently in use, and those requiring further development to accurately simulate the field tests before deployment, are described in Appendix C. Specific pre-test modeling activities, such as simulations of the experiment to be performed in advance to guide sensor placement and sensitivity requirements, will be developed as the in-situ experiments are designed.

Each of the field tests discussed in this document will have associated laboratory tests; these investigations will be a continuous, integral part of planning the in-situ tests to ensure their success and relevance. Laboratory tests can be quickly designed and run to provide support by isolating individual processes; they can be controlled for temperature, moisture, and airflow more readily than the in-situ tests; and are more easily focused on individual processes. Integrated laboratory testing allows parameterization and validation of numerical models at various spatial scales to analyze the field tests. Ongoing and planned laboratory efforts that will be directly associated with the in-situ tests are discussed in Appendix E.

3.1 Standardized Small-Diameter Borehole Field Thermal Tests

Small-diameter borehole thermal testing is proposed as a first step to restarting US field testing in salt. These tests can be used to isolate phenomena in a simplified, more directed, and generic test configuration. Borehole tests are useful for (1) assessing damage related to mining and disturbance, (2) simulating a post-closure environment, (3) confirming salt material properties, and (4) model validation. The test will also (5) provide ramp-up opportunities for testing new equipment and sensors in the field, and develop modern best practices for in-situ experimentation to use during the larger tests in this staged testing plan.

3.1.1 Test Objectives and Description

Multiple small, standardized heater tests fielded in vertical and horizontal boreholes (both in the DRZ and away from the mechanical influence of mined openings) would address generic open issues from previous tests, provide fundamental data for the salt system of interest, and would be low cost and efficient to deploy as a standard modular test. The tests would be designed with long-lived components and simple instrumentation so they can be economically operated for years. The small scale and the heating methodology will facilitate observation of time-varying brine evolution in the shortest overall time possible. Modularity and compact size will help to ensure tests would be readily repeatable with different thermal and mechanical loading conditions, and across different geologic layers in different salt formations. This standardized test design could involve international collaboration.

The test configuration will consist of an electrical heater and co-located instrumented sample package with a packer/plug system to isolate the test interval. One proposed design is shown in Figure 3. Depending on desired configuration or local lithology, the test may be implemented vertically or horizontally. The basic configuration will include heaters, temperature sensors, dry-gas moisture collection, borehole closure measurements, seismo/acoustic sensors, and capability for visual inspection of the borehole wall. Desiccated salts on the borehole wall will be inspected and sampled in real time (to avoid effects from deliquescence) and after conclusion of the test. The test would be conducted under both heated and unheated conditions across different geologic layers to compare HMC with THMC responses of various evaporate minerals. Because of the flexibility of this test configuration, it could be used to evaluate a range of possible thermal loads, as well as effects of varying heating and cooling *rates* on intact salt and various types of run-of-mine (RoM) salts (if RoM packing is used around some of the small borehole tests; e.g., differing water and impurity content).

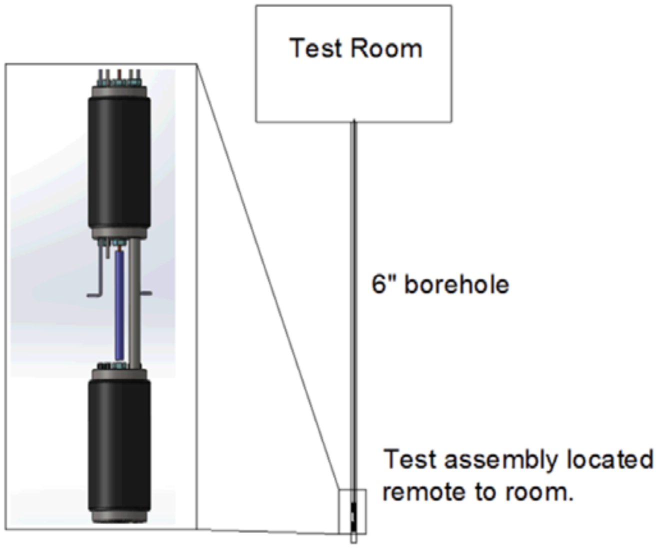


Figure 3. Schematic of a Standardized Vertical Borehole Heater Test in Salt.

Small borehole tests will also permit exploration of new instrumentation and techniques to detect and better track changes in water saturation, humidity, and gas formation at locations drilled away from the disturbed zone. Acoustic/microseismic events will be observed as indicators for changes within the borehole and potential long term changes in the mechanical integrity of the formation around the borehole (i.e., microcracking, creep noise, settling, etc.) (Becker, 2014). Additionally, one or more of the small diameter isothermal borehole tests could involve emplacement of a long-term permanent seismic monitoring geophone at the base of the hole.

One test configuration being considered involves an over-core slot drilled around the test borehole, prior to drilling of the actual test borehole. Due to physical constraints on core barrel size, this test would be limited to the DRZ surrounding a drift. The over-cored slot would be filled immediately with impermeable bonding material that forms a zero-migration boundary – similar to the corejacking tests conducted at Avery Island (Stickney, 1987a; Stickney, 1987b). Seismo/acoustic sensors would be installed concurrently. This test would be used to evaluate range-of-influence features of the salt system using coupled predictive models. After installation of monitoring instrumentation in a pilot borehole to characterize the state of near-field stress for different locations and configurations within the test location, the test borehole itself would be over-cored. The test configuration would also have peripheral, small-diameter boreholes for monitoring the responses away from the borehole during the test, such as temperature, bulk deformation of the salt, and to allow easy recording and potential imaging of acoustic emissions after the drilling and during the test. Such a test would best be done concurrently with at least one non-overcored test borehole to evaluate the influence (disturbed zone effects) in the overcored test borehole.

In a previous workshop (Sevougian et al. 2013) this small-borehole heater test was found to have first-order influence on mechanical and hydrologic research questions, and THM coupling (Table 2), issues 15, 16, and 17). It was also considered to have high relevance for new instrumentation development and methods for in situ testing and characterization (Table 2), issues 39 and 40). A standard modular borehole heater test design is an efficient approach to probing high-temperature mechanical, hydrological, and chemical conditions and processes at interfaces in a salt repository system. Because of its low cost and portability, a standard modular borehole test design provides a robust initial test in a staged approach to field testing for generic salt repository R&D. This type of test can likely be simulated using existing THMC tools before detailed test design begins. These tests would address issues across all phases of repository operation, including pre-emplacement, pre-closure, and post-closure. One note of caution, the gasses created by heating local brines may be caustic enough to impact the packer and/or instrument assembly (Molecke, 1986). Care should be taken to ensure that all URL equipment is robust and impervious to possible chemical attack in the harsh, heated salt environment.

The specific safety case issues addressed by this test are given in Section 2.2, . More broadly, this small-diameter borehole testing meets the following objectives:

- Table 2, Goal 1 (address FEPs):
    - Validate our conceptual understanding of large-scale thermal, mechanical, and brine migration/chemistry processes and responses due to heat input in intact host rock, the DRZ, and possibly in any included RoM salt.
- Table 2, Goal 2 (build confidence):
    - Build confidence for the *generic* salt repository safety case
    - Develop technology and methodology needed for underground monitoring/measurement of THMC processes
    - Enhance communication with stakeholders
- Table 2, Goal 3 (foster international collaboration):
    - Promote international collaboration on salt R&D and salt repository operations
- Table 2, Goal 5 (validate coupled process models):
    - Begin developing a framework for pre-test modeling, post-test model evaluation, and inter-model comparison. This framework would be developed for the small-scale tests and carried forward into the design and execution of larger scale tests.
    - Coupled process THMC model validation

3.1.2 Relevant Historical Tests

Past field heater tests performed at the Waste Isolation Pilot Plant (WIPP) and other salt sites worldwide have provided significant basis for our current understanding of salt behavior (Callahan et al., 2012; Kuhlman et al., 2012; Kuhlman, 2014; Kuhlman and Sevougian, 2013). Additional discussion of prior testing in salt formations relevant to all proposed field tests is provided in Appendix B.

For a borehole emplacement layout in bedded salt, Project Salt Vault in the 1960s (Bradshaw and McClain, 1971), the WIPP DHLW tests in the 1980s (Tyler et al., 1988), and the French Amélie potash mine in the 1990s (Kazan & Ghoreychi, 1997) placed heater(s) into vertical boreholes in the floor of bedded salt facilities, monitoring temperature, closure, brine inflow and corrosion. For borehole emplacement in domal salt, Avery Island in the 1970s and 1980s (Stickney & Van Sambeek, 1984), and several tests at Asse in Germany from the 1960s to 1990s (see summary in Kuhlman & Sevougian, 2013) similarly monitored effects from heating boreholes adjacent to mined drifts.

In vertical borehole heater tests at WIPP (Krumhansl, 1991), a low-porosity salt deposit was observed to contain residue from boiling away brine which flowed to the borehole through clay layers. This salt precipitation, along with compaction and creep of salt surrounding the borehole filled the initially empty annular space around the heater with salt. In addition, Krumhansl (1991)—as well as ongoing investigations at LANL—have produced evidence of strong acid vapor generation from heated RoM salt. Safety implications could be addressed by more small-diameter borehole experiments.

3.1.3 Instrumentation and Data Collection

Table 6 shows an abbreviated list of potential monitoring tools that may be used to make measurements for the small diameter borehole tests. A larger list with detailed descriptions of the anticipated monitoring technologies and measurement techniques can be found in Appendix D.

Table 6. Example Measurements and Monitoring Methods for the Small Diameter Borehole Tests.

Measurement	Monitoring Methods
Borehole closure	Temperature-compensated load cells or pressure plates between heater and borehole, linear variable displacement transformer (LVDT), strain gages on borehole wall
Temperature	Thermocouples, resistance temperature detectors (RTD)s
Heat flux to salt	Heat-flux meter mats with thermocouples
Microseismics/Acoustics	PZT sensors (accelerometers) buried in fill salt and in surrounding over cored slot
Water vapor and water movement	Electrical resistance tomography (ERT) probes, PZT sensors for sound speed changes, air volume and humidity sensors, time domain reflectometry (TDR), potentially low field nuclear magnetic resonance (NMR), circulation of dry N_2 gas through humidity sensors or periodically weighed desiccant canisters

3.2 Single canister test

The next scale of experiment will involve a single full-size heated canister to be emplaced in a larger borehole. The following sections describe the test layout and objectives, relevance to the safety case, and associated modeling and laboratory investigations.

3.2.1 Test Description and Objectives

A 2 ft diameter heated canister (Figure 4) will be placed on the floor of a 3 ft by 16-20 ft horizontal borehole. The borehole will then be backfilled with screened (small grain size) RoM salt and blocked from the drift by a series of seals. Laboratory scale tests on grain size effects will dictate appropriate grain sizing. This test is an intermediate step forward in complexity from the small-diameter borehole tests, yet does not require the complexity associated with a dedicated drift and multiple heaters. Experiments performed in this configuration will provide valuable information on RoM backfill in the presence of in-situ temperatures, pressures, and fluid fluxes with a full-size heated canister.

Seals/bulkheads in the test should serve to isolate the drift so the primary gas pathway is the DRZ. Isolating an excavated borehole/drift from active mine ventilation remains a challenge, due to significant gas flow through micro- and macro-fractures in the DRZ. Quantifying such effect during a thermal test may entail using a series of bulkheads that facilitate control and quantification of gas fluxes from the test drift to the external ventilated drifts. Relatively complete isolation may only be achieved if carefully-installed bulkheads penetrate the DRZ and cut off connected DRZ pathways to the external drifts. These intermediate-scale tests can be used to evaluate methods of sealing such openings and quantifying gas movement through and around such seals. Larger (drift-scale) seals are more difficult to construct and monitor, justifying careful investigation of bulkhead and drift-sealing options at this intermediate scale.

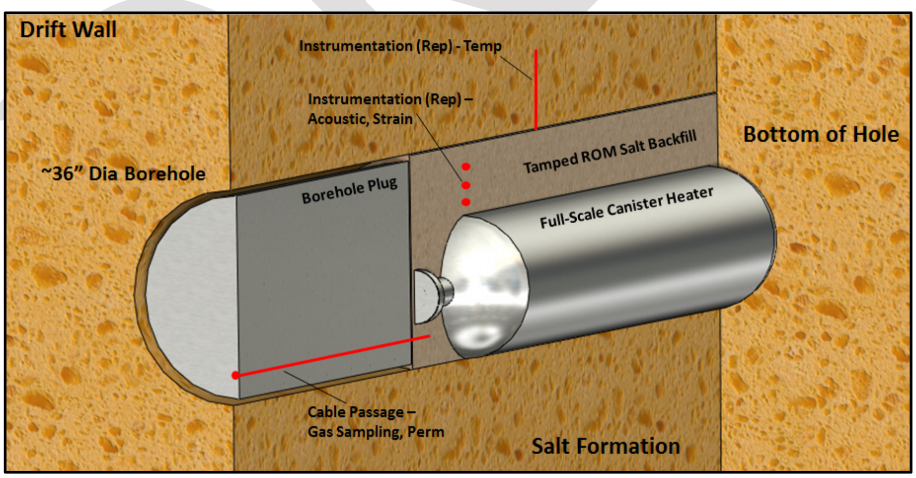


Figure 4. Schematic of the Borehole Emplacement Concept for this Test, including Representative Suggestions for Instrumentation.

A full-scale prototype heater canister was designed and fabricated in FY2014 through the DOE Environmental Management (EM) program. Laboratory tests of the prototype canister heater are underway to test for robustness, reliability, and investigation of heating characteristics while in an open air environment. Associated numerical modeling of canister heat production and thermal transport accompanied the laboratory investigation (Figure 6).

Figure 5. Prototype Heater Canister in the Laboratory.

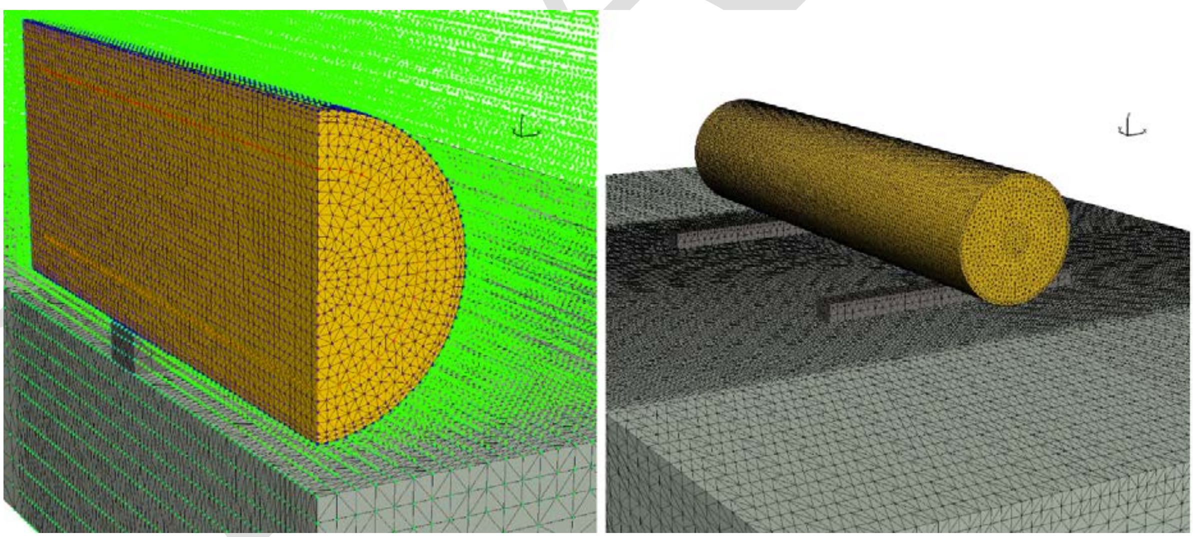


Figure 6. Computational Mesh Developed for Simulations of the Heated Prototype Canisters in the Laboratory.

Additionally, further single-canister tests could be implemented over a range of thermal loads to evaluate effects of various cooling rates on the drift configuration and host rock at scales that would be relevant to emplacement drifts. Comparison of two same-scale borehole emplacements with thermal loads representing high-level waste (~500 W per canister) and representing spent nuclear fuel (~5 kW per canister) would be facilitated by the single heater test layout. Beyond the flexibility and efficiency of fielding such borehole tests, the testing would also provide valuable *in-situ* experience for designing and implementing a larger-scale field test that would include more of the specific layout elements of a potential repository configuration in a site-specific setting as discussed in the next section (3.3). Further instrumentation testing and development will occur simultaneously.

This experiment will include measurements of evaporation and water vapor migration through the porous RoM backfill under 2-phase conditions and through or around seals and bulkheads, processes that are not yet completely parameterized. The intermediate-scale test will be designed to help understand the level of passive ventilation around bulkheads of various designs. Water is expected to be mobile in this experiment; water sources include intergranular porewater, intragranular brine inclusions, mineral dehydration water, and water flowing into the test area from the DRZ.

The safety case issues addressed by this test are given in Section 2.2, . More broadly, the single canister test meets the following objectives:

- Table 2, Goal 1 (address FEPs):
    - Validate our conceptual understanding of large-scale thermal, mechanical, and brine migration/chemistry processes and responses due to heat input in intact host rock, backfill salt, and the DRZ
- Table 2, Goal 2 (build confidence):
    - Build confidence for the *generic* salt repository safety case
    - Develop technology and methodology needed for underground monitoring/measurement of THMC processes
    - Enhance communications with stakeholders
- Table 2, Goal 3 (foster international collaboration):
    - Promote international collaboration on salt R&D and salt repository operations
- Table 2, Goal 4 (evaluate disposal concepts):
    - Demonstration of design and operations concept(s) for generic salt repositories including a range of heat-generating waste forms
- Table 2, Goal 5 (validate coupled process models):
    - Coupled process THMC model validation
    - Model parameter estimation for heterogeneous in-situ properties in bedded salt formations

3.2.2 Relevant Historical Tests

Numerous historical tests have been done at this scale (Appendix B; Kuhlman and Sevougian, 2014; Kuhlman and Malama, 2013). The testing discussion in 3.1.2 is also largly applicable to this discussion. New efforts in this proposal will focus on issues that the historical tests did not fully explore. Additional discussion of prior testing in salt formations that is relevant to all proposed field tests is provided in Appendix B.

Brine inflow into both mined and bored drifts under isothermal conditions has been monitored in the WIPP brine sampling and evaluation program (Deal et al., 1995) and Room Q (Jensen et al., 1993) experiments.

The Thermal Drift-Scale Emplacement (TSDE) full-scale thermal test in domal salt at Asse, Germany used longitudinally emplaced canister heaters covered with crushed salt backfill. It was found the crushed salt backfill dried out relatively rapidly during the heating period (about 9 years total; Bechthold et al., 1999). In that test, humidity measurements in the gas phase of the heated drift indicated that levels rose to saturation in about 3 months (for about 40°C) and then fell. It was noted that the total amount of gases lost could not be constrained accurately because the high-permeability of the backfill and unsealed nature of the testing drift allowed ready dilution of water vapor from the heated area with mine ventilation from the access drift. Estimates of water remaining (from humidity measurements) in the crushed salt backfill at the end of the heating test indicated the crushed salt water content had been reduced by over two orders-of-magnitude. Although fundamental data were collected and key processes were observed in this test, investigation of evolution of vapor within the system was only partially answered due to insufficient control/measurement of gas fluxes in/out of the test drifts.

Experimental data on evaporation in natural systems (e.g., soil to the atmosphere) are plentiful, but not for the saturated brine/granular salt system under conditions of a ventilated repository environment. Currently, data gaps exist in parameterization of the following physical processes: evaporation rate as a function of temperature, relative humidity, saturation, air flow, and changes in pore structure of the RoM salt; effective diffusion properties of water vapor through salt, including hygroscopic effects; heat transfer models in RoM salt and air, with parameters such as emissivity for radiation considered highly uncertain; moisture availability, relative permeability, and capillary suction as a function of saturation in reconsolidating crushed and damaged intact salt; and deformation magnitude and rate caused by porosity and water content changes.

3.2.3 Instrumentation and Data Collection

Table 7 describes potential monitoring tools that may be used to make measurements for the single canister test. Detailed descriptions of the anticipated monitoring technologies and measurement techniques can be found in Appendix D.

Table 7. Example Measurements and Monitoring Methods for the Single Canister Test.

Measurement	Monitoring Methods
Borehole closure, RoM salt settling with temperature	Temperature-compensated load cells or pressure plates between heater and borehole, LVDT, strain gages on borehole wall
Temperature	Thermocouples, RTDs
Heat flux to salt	Heat-flux meter mats with thermocouples
Microseismics/Acoustics	PZT sensors (accelerometers) buried in backfill salt
Water vapor and water movement	ERT probes, PZT sensors for sound speed changes, air volume and humidity sensors, TDR, low field NMR, nonlinear acousto-elastic measurements

3.3 Drift-Scale Tests

Drift-scale testing refers to a scale that includes many of the operational complexities of a repository, including mining full sized drifts and moving large quantities of RoM salt. Effects and processes that are missing from the small-scale and single-canister experiments and combinations of individual processes will be tested in this phase of testing, as described in section 3.3.1 (introduction and objectives). Two configurations for a generic salt repository are described here for consideration for drift-scale in-situ testing: in-drift (section 3.3.2) and alcove (section 3.3.3) emplacement. Relevant historical tests at this scale are presented in section 3.3.4, and section 3.3.5 discusses instrumentation and data acquisition techniques likely to be used in either drift-scale test configuration.

3.3.1 Introduction and Objectives

Larger scale, layout-specific disposal demonstrations will facilitate gathering data for large-scale model benchmarking and improve understanding of the following concepts: (1) THM aspects of room closure, (2) the quantity and nature of inflow of brine into the emplacement drifts and the associated DRZ, (3) the effects of mine ventilation on the emplacement drift, and (4) the behavior of the RoM salt emplaced around HGNW. Large-scale thermal field testing provides demonstrative and confirmatory results of the technical bases for large-scale coupled THMC processes occurring within a potential repository configuration that can supply additional confidence in the safety case for disposal in salt.

This testing concept is a full-scale demonstration of a generic salt repository design configuration, which will assess the operational efficiency of the concept and allow confirmatory observations and measurements of temperature changes, salt deformation, vapor generation and flow, water condensation and salt dissolution, and pressure changes. The in-drift disposal concept to be tested will lead to the movement of water as vapor within and potentially out of the test area, at least during the time period when the mine-run salt has sufficient permeability to support gas flow by forced or natural convection processes. Thus, a primary objective is to quantify this vapor movement, and to demonstrate a quantitative understanding through predictive (i.e., prior to test execution) modeling of the moisture and gas flow data. This would provide confirmation of our numerical models of these processes for a large-scale configuration of a potential repository.

Although these tests are not planned to be longer than a few years, we expected some brine migration from the host-rock salt under pressure and temperature gradients, or from the backfill salt. Brine migration is expected to be highest at earlier times and then diminish with time. Experience indicates that the permeability of the backfill salt will be very high throughout the short duration of this field demonstration test, such that the backfill design may be a key aspect to control the degree to which flow occurs in this period. Thus, another primary objective of this full-scale field test is to quantify the brine movement in the backfill salt and to demonstrate a quantitative understanding through predictive modeling of the brine flow data. Instrumentation for measuring brine migration will be developed specifically for the test; generic hydrologic and moisture monitoring techniques are discussed in Appendix D.

The movement of water and water vapor will be affected by the heat transport from the heater canisters through the crushed salt, and into the intact salt. The vaporization and condensation of water may in turn lead to salt precipitation/dissolution processes. The hydrologic initial conditions of the test in the DRZ and intact salt are derived from mechanical deformation and damage associated with the room excavation and geomechanical effects are anticipated to be small during the period of testing. However, these effects will also be monitored, as they are known to play a role in the ultimate reconsolidation of the crushed salt and the healing of the fractures in the DRZ.

Isolating an excavated drift from active mine ventilation remains a challenge (Jensen et al., 1993), due to significant gas flow through micro- and macro-fractions in the DRZ. The effect ventilation has on the heated emplacement drift during test or disposal operations may be significant. Quantifying ventilation effects during a thermal test may entail using a series of bulkheads that facilitate control and quantification of gas fluxes from the test drift to the external ventilated drifts. Significant isolation may only be achieved if carefully-installed bulkheads penetrate the DRZ and cut off connected DRZ pathways to the external drifts. Gas tracers injected into the volume of the test cavity will be useful in determining drift air exchange rates.

RoM salt has distinctly different THMC behavior from intact salt. This large-scale test would allow evaluation of the evolution of RoM salt properties under repository-relevant stress and temperature conditions, potentially both for pre-closure ventilation conditions and relatively “sealed” ventilation conditions that may be more relevant to post-closure behavior. For example, monitoring the evolution of the RoM salt porosity and permeability resulting from both mechanical compaction and brine migration under the thermal/mechanical conditions of the test would provide enhanced understanding of the hydrologic properties expected in the salt surrounding waste packages in the post-closure period.

Not only would data from a large-scale thermal test serve to validate our conceptual models of how heat-generating wastes may affect the mechanical, hydrological, and chemical behaviors in such a system, it would also provide a data set for testing the accuracy of our constitutive and numerical models.

The safety case issues addressed by this test are given in Section 2.2, . More broadly, the following key objectives are relevant to both field-scale thermal tests of the in-drift (section 3.3.2) and alcove (section 3.3.3) disposal concepts:

- Table 2, Goal 1 (address FEPs):
    - Validate our conceptual understanding of large-scale thermal, mechanical, and brine migration/chemistry processes and responses due to heat input using observations in intact host rock, the DRZ, RoM backfill, and open drift air
- Table 2, Goal 2 (build confidence):
    - Build confidence for the *generic* salt repository safety case
    - Develop technology and methodology needed for underground monitoring/measurement of THMC processes
    - Enhance communications with stakeholders
- Table 2, Goal 3 (foster international collaboration):
    - Promote international collaboration on salt R&D and salt repository operations
- Table 2, Goal 4 (evaluate disposal concepts):
    - Demonstration of design and operations concept(s) for generic salt repositories including a range of heat-generating waste forms
- Table 2, Goal 5 (validate coupled process models):
    - Coupled process THMC model validation
    - Model parameter estimation for heterogeneous in-situ properties in bedded salt formations

A principal technical uncertainty to be addressed by these large-scale tests is the behavior of the small amounts of water and water vapor contained in the salt upon heating. Because bedded salt may contain upwards of an order of magnitude more water than domal salt (Hansen and Leigh, 2011), either in the form of fluid inclusions, intergranular brine, or hydrous minerals, testing of disposal concepts in domal salt may not cover effects of all water-sensitive processes, including understanding the full behavior of water in bedded salt systems that are subjected to heating.

The current state-of-the-art models (Appendix C) will be instrumental for defining and optimizing the layout of the large-scale in situ field tests and will continue to provide bases for performance assessment in the future. Next-generation coupled THMC codes developed concurrently with the planning phase of the field tests would then be benchmarked against current codes and validated using the smaller-scale field test data. The validated conceptual and numerical models resulting from the effort can then be used in future design calculations or performance assessment analyses. Modeling needs particular to the high thermal load field tests include extremely high-temperature processes, such as water release and physical/mechanical changes from salt decrepitation and hydrous mineral dehydration (Caporuscio et al., 2014; Clayton and Gable, 2009). Appendix A discusses expected thermal regimes for high thermal load HGNW.

Laboratory experiments discussed in Appendix E are also directly relevant to these large-scale field tests. Thermomechanical testing should include experiments at high temperatures relevant to SNF, and high pressures, because understanding the physics under these conditions is vital to operational concepts, design, safety, and long-term isolation.

Test planning requires considering the following factors to efficiently address the objectives of a field thermal test in a generic salt system, and collect appropriate data to answer the specific questions posed for those objectives. A test would be designed to maximize the general applicability of data collected during testing using careful choice of test location and instrument locations in the testing horizon. For example, care would be taken such that unique site-specific features (e.g., anhydrite and clay layers) do not dominate the mechanical and hydrologic response of a test, unless the point of the test is to investigate these features in particular. The design of the drift-scale tests will also be based on the test objectives as they relate to addressing different periods of drift use: e.g., (1) pre-closure, including (a) active operational/waste emplacement time, (b) drift "isolation" by bulkhead while other parts of the repository are still in the operational phase, and (2) post-closure. For example, during pre-closure phase (a) the drift is actively ventilated; after bulkhead emplacement, the drift undergoes passive ventilation. The large-scale testing will be designed to further understand the level of passive ventilation around bulkheads of various designs. The tests will be designed to reflect the appropriate configuration for the relevant phase of operation depending on clearly selected objectives.

3.3.2 In-Drift Test Description

The in-drift emplacement design concept is based on a disposal strategy in which a series of repository panels, each of which is a subsurface cell consisting of individual drifts, are constructed underground (Figure 7). Retreat waste emplacement is conducted in the open disposal drift by bringing in one canister at a time using a remotely operated vehicle and placing it perpendicular to the drift, on the floor. The single canister (or multiple canisters) is covered with RoM salt backfill, which would act as shielding during pre-closure operations in addition to its post-closure functions. The backfill strategy and the target areal heat loading desired will dictate the location of the next canister (typically 1–5 foot spacing). The process is repeated until the entire drift is filled and the backfill is emplaced. From the time a drift is mined to the closure of the drift to active ventilation (blocked by backfill or bulkhead) is expected to take ~5 months to 1 year (Carter et al., 2012). The total operational period may last ~40 years, with an additional 9-12 years for closure (Carter et al., 2012, Table 7-1).

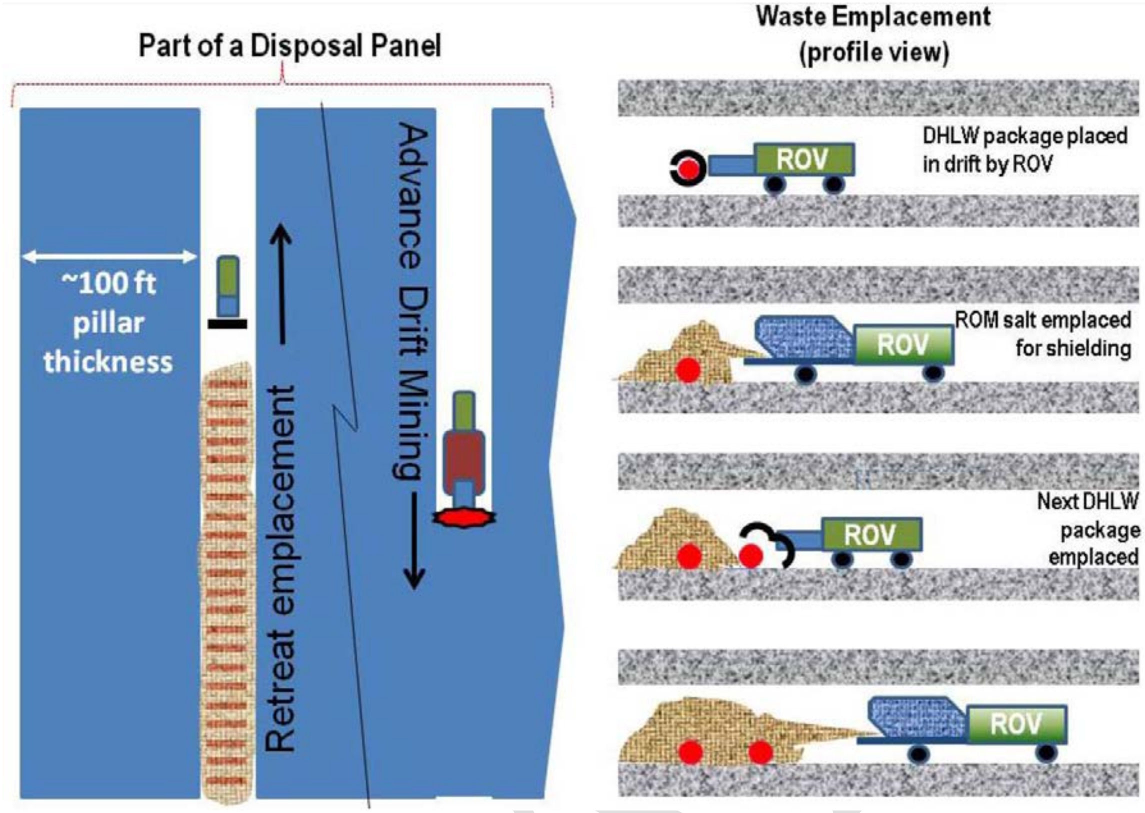


Figure 7. In-Drift Disposal Waste Emplacement Strategy. From Carter et al., 2012.

Drifts will creep closed and surround the backfilled waste packages, with the rate depending on the physical dimensions and the temperature of the emplacement drift. The RoM backfill will also reconsolidate, at rates that depend on the amount of moisture in the material, among other factors (Hansen et al., 2014). Eventually, the backfill will be in contact with the drift roof, and any forced ventilation provided during the pre-closure period will pass through the backfill salt and the DRZ. This disposal concept allows drying of the salt backfill and drift during the pre-closure ventilated period; despite many years of operational experience, remaining data gaps in our understanding of in-situ RoM salt dry-out make the amount of drying highly uncertain. The amount of moisture removed from the test system and any accumulation along the drift or near the canisters are phenomena to be quantified in a field demonstration test.

Repository design may require the waste packages not be subject to a large quantity of brine (limiting the potential for corrosion) during pre-closure, to retrieve the waste packages.

An in-drift experiment concept has been developed (DOE, 2012) in which two drifts (~60 ft long each) of minimal cross-sectional dimensions (approximately 16 ft wide by 10 ft high) would be mined. Figure 8 provides a general overview of the test drifts and the test layout. The dimensions and testing horizon are tentative and will be defined in detailed test planning and functional and operational requirements development.

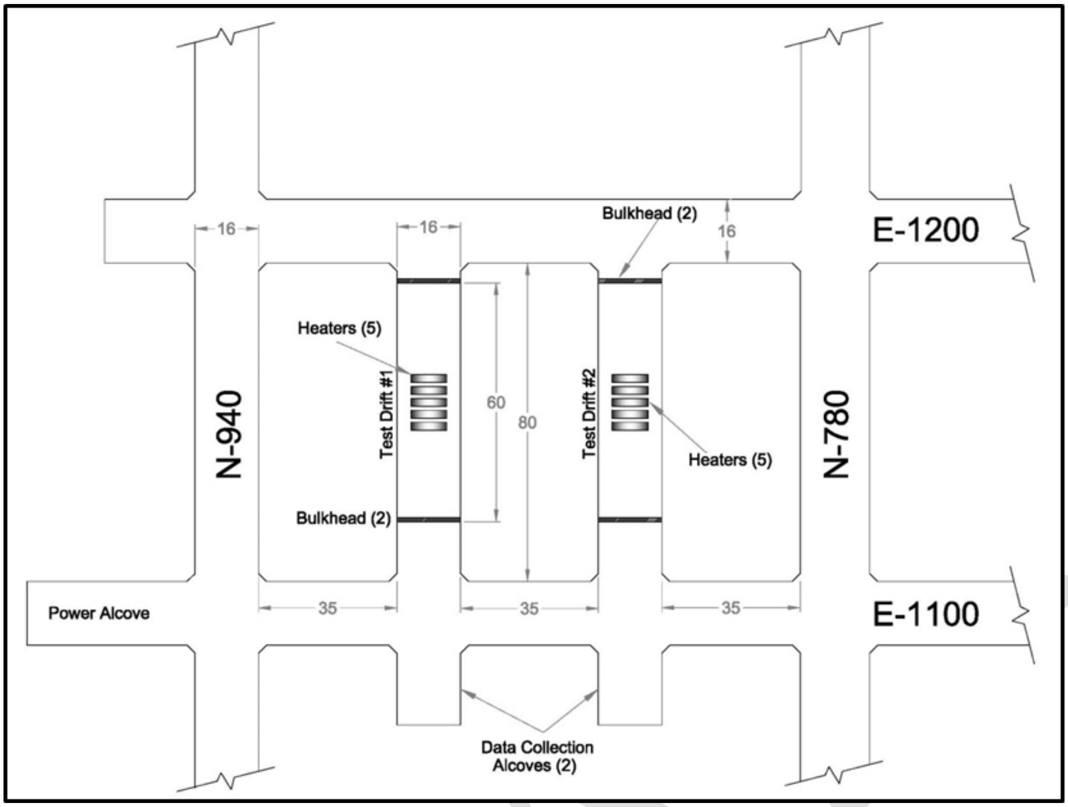


Figure 8: Plan view of the layout of the proposed in-drift emplacement thermal test and disposal demonstration.

For this in-drift experiment, 5 canister heaters, each approximately 9 ft long and 2 ft in diameter, are to be placed on the floor of each test drift. The canister heaters are planned to be spaced approximately 1-3 ft apart, center-to-center (Figure 9). The planned heater power in test drift #1 is intended to simulate the majority of the DOE DHLW inventory (<200 W per canister). The planned heater power in test drift #2, (750-1500W) is intended to simulate hotter wastes and create higher temperatures in the salt, leading to more coupled processes (thermal-mechanical-hydrological-chemical) including sufficient energy to stimulate boiling of salt water in the near-field to the heater. With this heating strategy, thermal data will be collected relevant to defense waste plus the cooler portion of the civilian spent nuclear fuel inventory.

In the test layout, both test drifts would be set up identically, and RoM salt backfill would be placed on top of the five canister heaters to a yet to be determined height, without compaction. The height of the backfill in the test drift would be chosen based on the specific objectives selected for the test. For example, short-term processes during the first few months or the operational period might be examined with a lower-height backfill pile and larger air gap. On the other hand, long-term processes might be possible to isolate in order to mimic the post-closure period by packing the RoM salt all the way to the ceiling and looking at interactions between the host rock and backfill. However, the settling of the RoM salt may be faster than the DRZ closure resulting in the creation of an air gap as the test progresses. One concept for the in-drift test could involve placing the salt with an air gap at first for thermal testing, then returning to the same drift later to stack RoM to the ceiling for longer-term monitoring of mechanical effects.

A bulkhead (or series of bulkheads) would be located at both ends of the drift to help control air flow through the drift and allow for measurement of the air characteristics (humidity, temperature, pressure, flow). Ventilation around bulkheads and through the DRZ will need to be quantified to assist model development and interpretation of test results. The heating and ventilation of the test will also be designed to meet specific objectives (to be determined) related to different periods of operation of the repository, e.g., pre-closure and post-closure periods. The drifts will be heated for approximately one year before a decision is made to either continue the heating or allowing the drift to cool and post-test forensics conducted, if enough of the key phenomena, such as the movement and fate of water have been observed and understood. The cooling rates in this case may be faster than expected in a repository setting, which will be gradual due to radioactive decay and the thermal inertia of the system. It may be desired to handle cooling of the in-situ test in a manner that does not create process artifacts that would interfere with realistic post-test forensics.

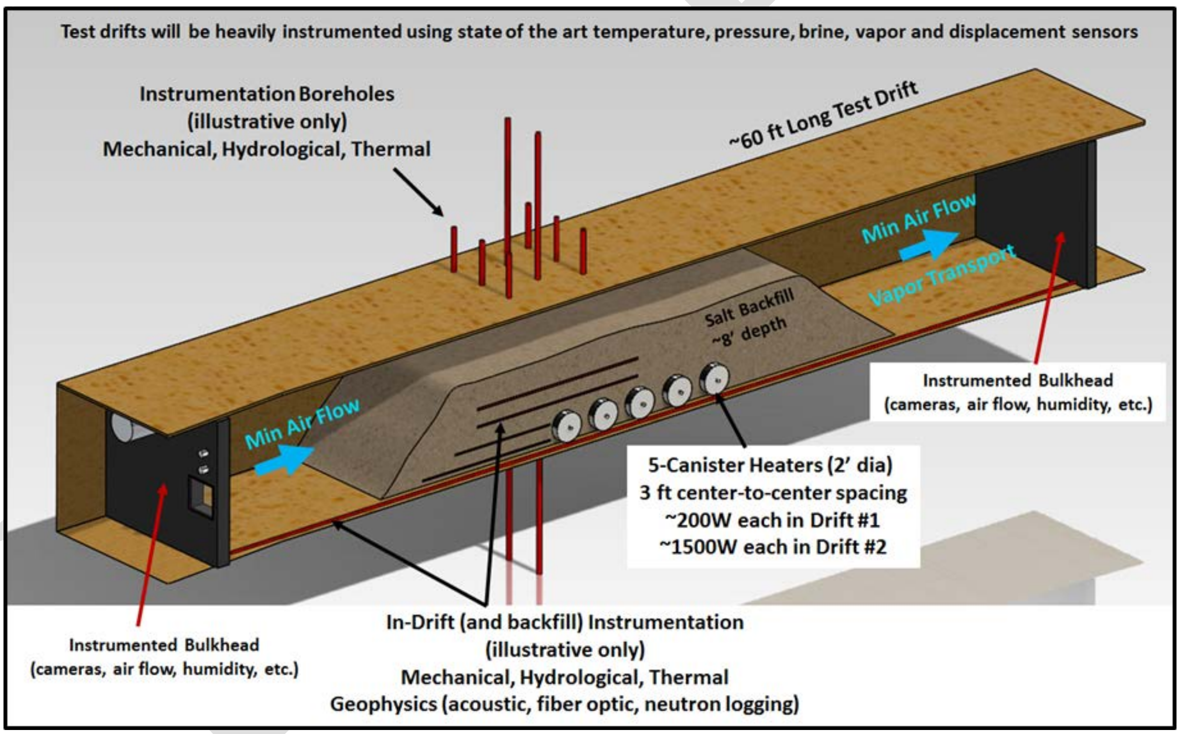


Figure 9: Isometric view of the layout of the proposed in-drift field-scale thermal test and disposal demonstration.

3.3.3 Alcove Test Description

This section provides a brief description of a thermal test for an alcove emplacement concept for higher heat loads than proposed previously; additional details may be found in DOE (2011) and subsequent published papers describing the proposed test (Nelson and Buschman, 2012; Robinson et al., 2012). In the present study, this test serves as the starting point for the design of a full-scale thermal test for alcove disposal of high-heat generating wastes.

The thermal loads for the test are on the order of 8500 W/alcove locally and 39 W/m^2 in a repository-average sense, which are reasonable upper bounds for civilian SNF (See Figure 2 and discussion of waste inventory thermal loads in Appendix A). This is the highest thermal load end of the waste inventory, considerably hotter than DHLW. This test would be used to provide demonstrative and confirmatory observations and measurements for a disposal concept that optimizes the management of heat by adequately spacing the waste packages, while economizing on underground space and linear feet of drifts to be mined.

Under these heating conditions, test temperatures well in excess of 100°C would be expected in the intact salt mass after two years of heating (Clayton and Gable, 2009). Closer to the heat source, within the alcove, temperatures in the 200–300°C range would be expected (see Appendix A). As with the in-drift test, there will be a focus on quantifying the effects on thermal properties, brine liberation and transport, and evolution of the intact and crushed salt properties. The basic model validation data sets would include transient temperature measurements, deformation of the intact salt and backfill, and the movement of moisture/brines in the salt.

As envisioned in DOE (2011), the proposed field test consists of seven alcoves, five of which contain an electrical heater to simulate a disposal package (Figure 10). Each electrical heater would be placed on the floor near the back of the alcove and covered with crushed salt (Figure 11), the alcove disposal concept. Waste package spacing would bound thermal conditions for disposal operations, thereby ensuring that the field test would produce data directly applicable to a generic alcove salt repository. Timing of this emplacement concept may be somewhat different from the above in-drift concept, and should be considered to assess time constraints on the test and to address specific objectives related to different periods of repository operation (e.g., pre-closure/operational, pre-closure/passive ventilated, post-closure).

Thermal, mechanical, and other geophysical techniques would be used to measure the response, and the data set would be used for validation of numerical models. For less-well-understood high-temperature processes, the basic observations would test the conceptual models for those aspects of the system. These observations will important to improving the scientific basis for the disposal concept and increasing confidence in the safety case.

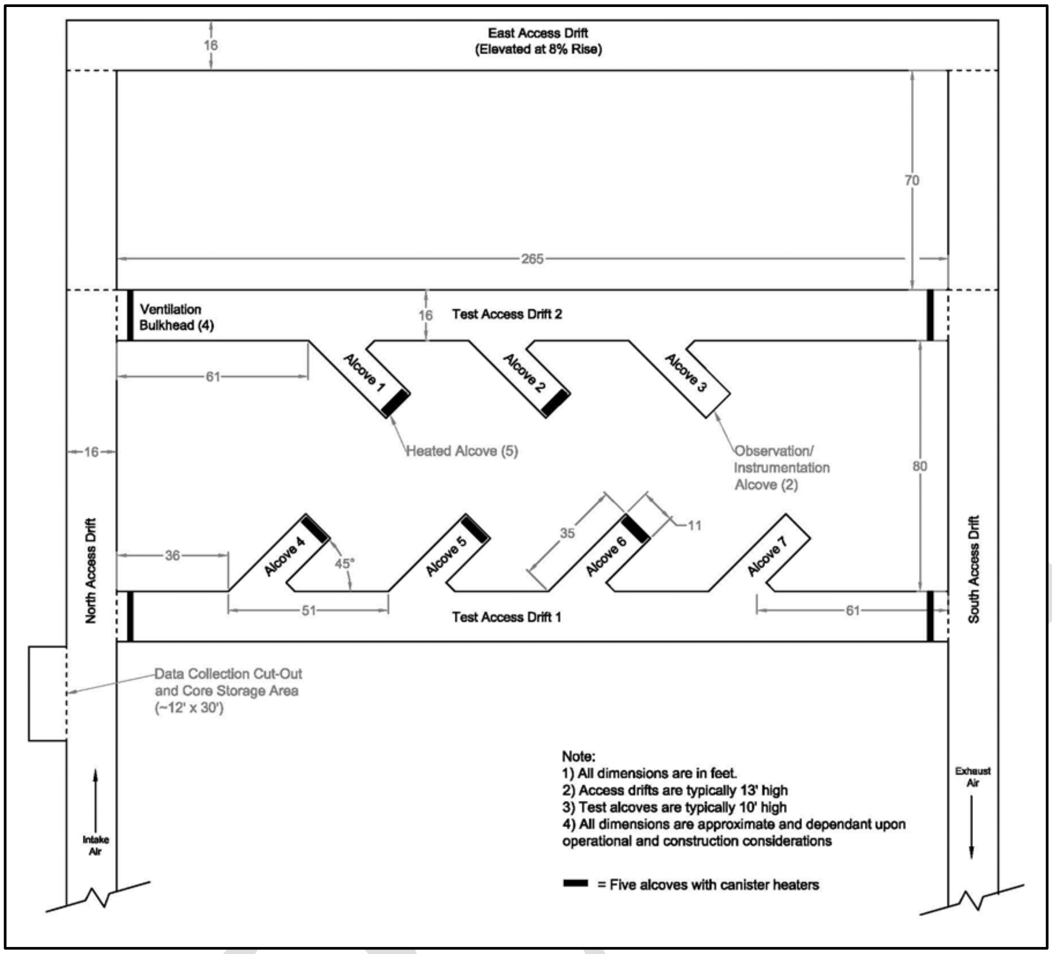


Figure 10: Plan view of the mining layout for an in-situ thermal test of the alcove disposal concept.

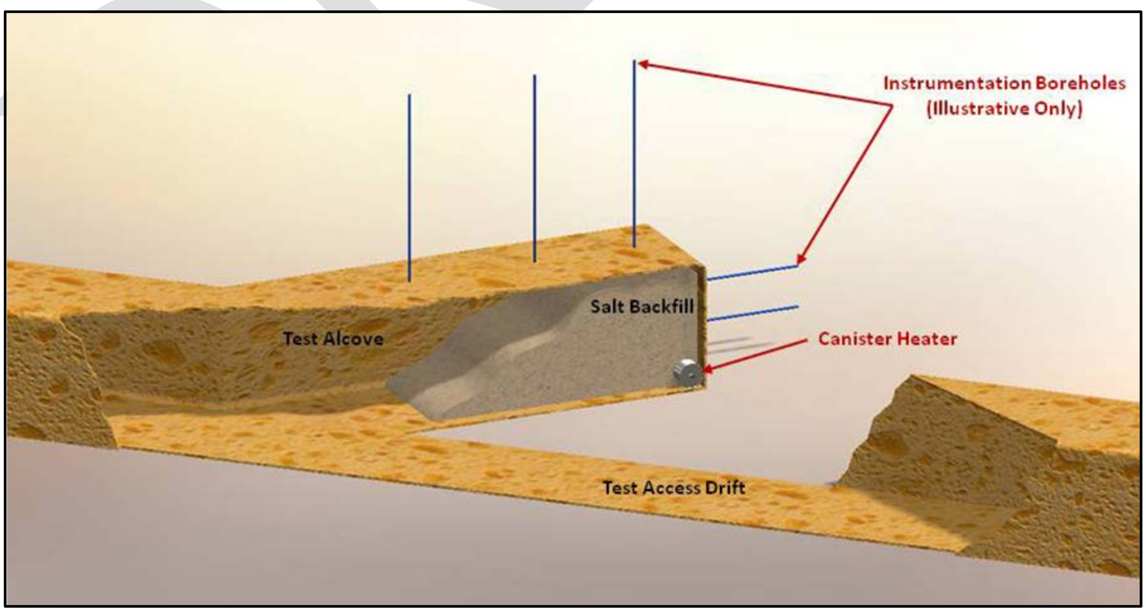


Figure 11: Perspective view of a test alcove, with a canister heater buried in crushed salt.

Figure 12 illustrates, in perspective view, the general layout and architecture of the field test, including a view of the instrumentation boreholes. The test would incorporate measurements of temperature changes imposed on the intact salt surrounding the alcove (roof, floor, and pillars) and crushed salt backfill over the waste.

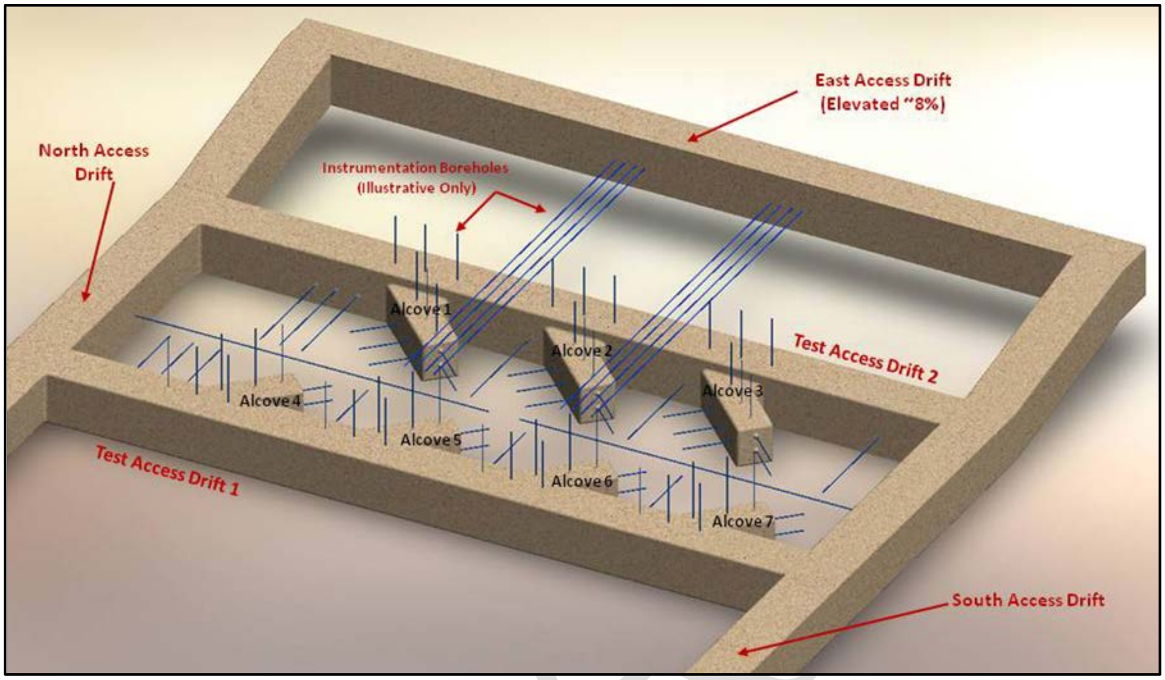


Figure 12: Perspective view of the mining layout and instrumentation borehole configuration for an in situ thermal test of the alcove disposal concept.

The proposed research, development, and demonstration of salt efficacy for the safe and efficient disposal of thermally hot waste proposed here would augment the basis for a single repository that can readily isolate large quantities of SNF, a key component of a safe and secure nuclear future for the nation. The narrative provided previously for an in-drift disposal thermal test concept is also substantially applicable to this alcove emplacement concept as well. A large-scale thermal test serves to test our conceptual models of how heat-generating wastes at SNF temperatures may affect the mechanical, hydrological, and chemical behaviors in such a system, will provide a comprehensive new data set for testing the accuracy of our quantitative models, and confirm the safety case for long-term disposal.

3.3.4 Historical Tests Relevant to Drift Scale Testing

As described in Appendix B, laboratory and field studies of intact salt and crushed salt and the chemical interactions of salt with waste packaging, waste forms, and waste constituents received a considerable amount of attention in the 1980s. However, the upper temperature limit for the thermomechanical intact salt tests has been about 200°C, and crushed salt and chemical interaction tests have been conducted predominantly at room temperature. Past TSPA studies for WIPP have been more than adequate to demonstrate that disposal of non-heat generating waste in salt is safe (DOE, 1996).

However, for thermally hot waste there are gaps in the experimental data that are addressed in this testing concept.

There have been several drift-scale heated tests in both bedded and domal salt since 1950 (Kuhlman et al., 2012; Kuhlman & Malama, 2013; Kuhlman & Sevougian, 2013), but compared to borehole heater tests in salt, there have been fewer in-drift heater tests. At WIPP (bedded salt), isothermal emplacement tests in Room T monitored stacked steel drums backfilled with either salt or salt and bentonite (Tyler et al., 1998; §4.3.3.1.2). As described in section 3.2.2, in a thermal test in domal salt at Asse, Germany during the 1990s, a number of 5.5-m long heated Pollux casks were placed longitudinally into drifts and backfilled, followed by extensive monitoring of the system in a test with 9 years of heating (Bechthold et al., 2004).

Table 1 from Callahan et al. (2012) shows that despite the fact that thermal testing has been conducted in both bedded and domal salts both in the U.S. and Germany, there is a gap in our experience base regarding the way in which bedded salt for a generic site would behave for the in-drift disposal concept. Testing has been conducted for the borehole disposal concept in both bedded and domal salt, and the in-drift concept has been tested in domal salt at Asse, but knowledge of the behavior of bedded salt for the in-drift and alcove disposal concepts is a gap that still exists.

3.3.5 Instrumentation and Data Collection for Drift Scale Testing

Instrumentation of these test concepts will focus on the behavior of the crushed salt in the drift/alcove and the surrounding DRZ, measuring processes and parameters in the drift/alcove that provide evidence of water vapor and brine migration and physical and chemical property changes with time. Descriptions of specific monitoring and measurement tools that may be employed during these large-scale field tests are provided in Appendix D. Initially, the backfill properties will be those of a permeable, granular medium, making the backfilled test drifts more accessible to measurements of a variety of parameters than the DRZ or intact salt.

The heaters will have sealed (welded) ends with high-temperature potted electrical leads, and the electrical controller will use a variable step-down transformer to regulate heater power. Engineering specifications for the heater and canister design require that each heating element be redundant, have additional capacity, and be designed to operate in a wet saline environment. The need for redundant or back-up power systems to maintain heating during power outages will be explored during detailed test planning.

It will be important to understand the temperature regimes in and around the drifts, especially in the salt backfill. Each heating element will be independently controllable and monitored by the data collection system. Mechanical measurements, although not dominant in this test due to the relative short time period of the test, will be made in the salt and from within the backfill.

The presence, movement, and ultimate fate of water in this test are of primary importance, so hydrologic instrumentation will also be installed within the test drift, salt backfill, and in the adjacent salt mass. Inlet and outlet air characteristics (e.g., relative humidity, flow rate, volume, and temperature) will be measured. Brine and vapor migration measurements are generally not as straightforward as monitoring for temperature or ground movement; field experimental challenges must be tackled to make detailed measurements of brine and water vapor processes. With a higher thermal load, the thermally driven processes would occur over a broader spatial extent and perhaps to involve water in a wider variety of forms in the host salt. Therefore, development of suitable techniques for observing the spatial and temporal distribution of water in real time is a key intermediate technical goal of the research program. By sequencing the field testing program with a low to intermediate heat load test first, significant technological development of such instrumentation will have been accomplished by the time the high-heat test is conducted.

The hydrologic behavior of the DRZ surrounding a drift is often dominated by a few large-scale open fractures (e.g., en-echelon fracturing found in the roof or floor of excavations; Hansen, 2003). Brine flow in large-scale discrete fractures is challenging to predict with continuum-scale porous-medium flow models. Large scale testing would be conducted to quantify the role such DRZ fractures have as pathways for brine or water vapor movement within the system. Open fractures would be instrumented for these in-situ tests to determine if those fractures represent significant sources and/or reservoirs for brine around the excavation. Instrumentation of open fracture flow is recognized as a challenge and the development and demonstration of techniques and instrumentation will be necessary prior to final field deployment. A combination of techniques including direct instrumentation embedded in fractures, geophysics, observation and instrumentation of boreholes, and environmental monitoring of in-drift conditions will likely be investigated.

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.

Creep closure would be measured directly by differential displacement gauges, as well as post mortem forensic reconnaissance. Chemical effects on various metal coupons and radionuclide analog elements would be assessed during the forensics stage. Finally, geophysical measurements, including active and passive seismic monitoring and imaging using electrical resistivity, are envisioned to probe the physical configuration of the three-dimensional space impacted by the heating, to track the movement of the thermal and moisture fronts with time, and to monitor the salt rock mass for evidence of fracturing and decrepitation as a result of heating.

The configuration of the proposed large-scale thermal tests described above also provides an opportunity to characterize the test bed before, during, and after excavation of the rooms. The test drifts will be instrumented from within, as well as from the adjacent access drifts (Figure 13) (Howard, 2014; Hansen et al., 2015). Characterization of the test bed will allow for interpretation of structural deformation including formation and evolution of the DRZ, measurement of first-order effects on the poroelastic evolution of the salt from impermeable to more transmissive, and provide initial and boundary conditions as well as hydraulic property distributions needed to simulate the in-drift test. Temperature gauges will be placed together with deformation gauging; fluid flow measurements would be made in additional mine-by boreholes (Figure 14).

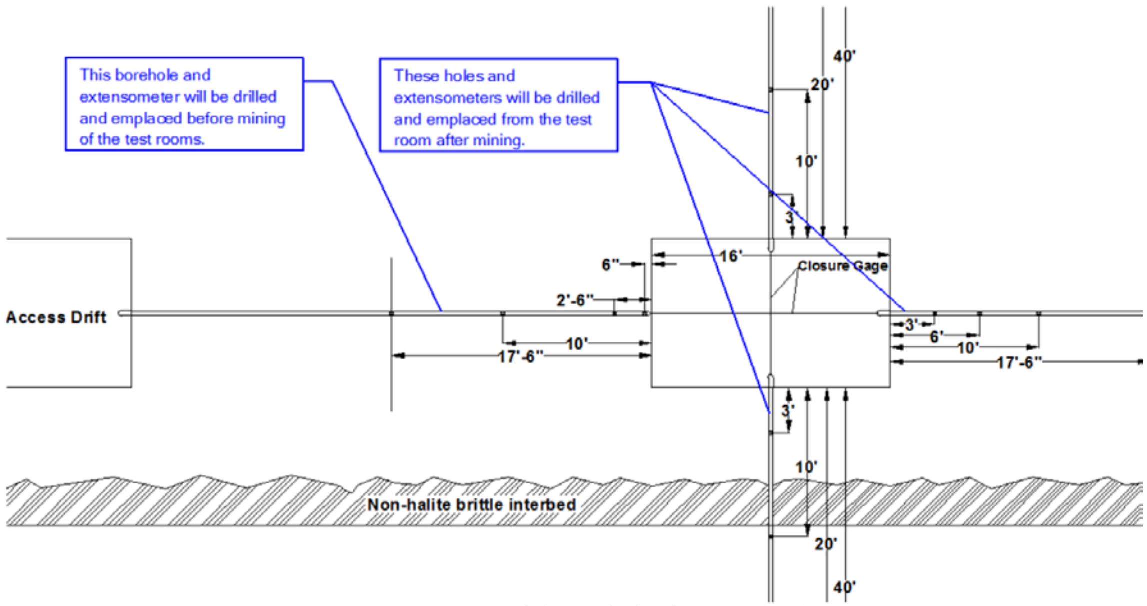


Figure 13: General Layout Suggested for Deformation Borehole and Gauges for Mechanical Characterization Boreholes. From Howard (2014).

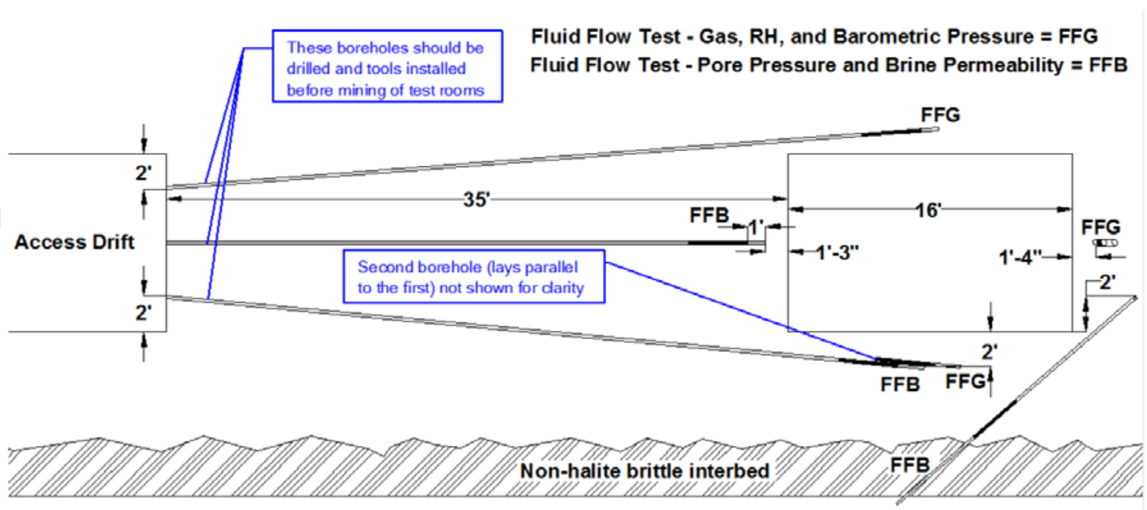


Figure 14: General layout of brine and gas testing borehole relative to the thermal test drifts. From Howard (2014).

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. 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; Munson et al., 1997b).

In the alcove emplacement test, measurements would be made of temperature changes in the intact salt surrounding the alcove (roof, floor, and pillars) and the mine-run salt placed as backfill over the waste. Creep closure will be measured directly by differential displacement gauges, as well as evaluated by post facto forensic reconnaissance. The experiment would measure the imposed transient temperature field, the accelerated deformation in the intact salt and backfill, and the movement of moisture/brines in the salt.

Instrumentation and equipment planned for the in-drift and alcove emplacement concept test program are provided in Table 8. Additional details on specific instrumentation methods are provided in Appendix D.

Table 8. Example Measurements and Monitoring Methods for the large-scale field tests.

Measurement	**Monitoring Methods**
Roof/floor closure	1 m range spring-loaded pull-wire potentiometer, temperature-compensated
Salt displacement and deformation	Multiple Point Borehole Extensometer (MPBX) with invar rods; displacement transducers
RoM backfill pressure on heaters	Temperature-compensated load cells between buried loading plates
Temperature	Thermocouples, RTDs
Heat flux to salt	Heat-flux meter mats with thermocouples
Microseismics/Acoustics	PZT sensors (accelerometers) buried in fill salt and in surrounding over cored slot
Water vapor and water movement	ERT probes, PZT sensors for sound speed changes, air volume and humidity sensors, TDR, potentially low field NMR, circulation of dry N_2 gas through humidity sensors, periodically weighed desiccant canisters
Equipment and Hardware	**Description**
Heaters with controller	Rod heaters (redundant leads and elements, 10 kW capacity in 24-inch diameter casing, sealed ends, potted high-temperature leads
Data acquisition	Multi-channel Distributed Control System (DCS)
Fiber optic communication system	Communications cable data hub and system to communicated data to the DCS and the surface
Cameras and recording	Digital video cameras and video station

4. Summary

Carefully-considered science and engineering field studies can reinforce the technical basis for geologic disposal of heat-generating radioactive waste in salt. Generic URL/field testing will focus on addressing issues that will contribute additional confidence in the safety of disposing heat-generating waste in a generic salt repository. Emphasis on this central purpose for generic field-based testing facilitates efficiency of resources because such large-scale testing tends to be personnel intensive, multi-year in nature, and relatively expensive. Full implementation of thermal field studies in salt could entail a substantial portion of current UFD Disposal RD&D program resources over a number of years. A clearly defined rationale with specific objectives delineated within the context of the safety case for a generic salt repository facilitates justification, planning, and decision making for such an undertaking.

The phased approach to field testing outlined in this document represents progression from low-complexity, repeatable, relatively inexpensive small-diameter borehole experiments through an intermediate stage (full-size, single-canister testing in an oversized borehole) to field-scale, design-specific tests for both the in-drift and alcove emplacement concepts, which focus on different thermal loads to target different parts of the HGNW inventory. A large-scale disposal configuration demonstration and thermal test would address thermal, mechanical, chemical and hydrological evolution within the host rock, the DRZ, and within the drift to provide data to validate THMC models, to inform future repository design, and to enhance the safety case for a generic salt repository. Additional investigation of brine inflow via the DRZ and brine inflow into heated drifts in a large-scale test for a generic repository configuration would elucidate the contribution and fate of brine related to the heated.

5. Appendix A : Summary of HGNW thermal loads

This section describes the heat loads of the various defense and civilian waste streams in the U.S. inventory, and summarizes past work performed to identify the expected thermal conditions and scientific uncertainties for a salt repository hosting these wastes.

5.1 Heat Loads

A fundamental consideration of any field-scale thermal investigation is the range of thermal loads from the waste forms that are candidates for disposal within a generic salt repository. Defining the full range of expected thermal perturbation, volume of rock affected, and duration of perturbation to be investigated depends directly on waste form thermal output, and specific properties of disposal concept such as repository layout and operations. For DHLW, thermal outputs per package are fractions of a kilowatt (generally less than about 0.5 kW, (see Figure 2). For DOE-managed SNF and naval SNF canisters, the thermal load can be multiple kW (with naval SNF canisters having higher upper thermal loads on the order of 10 kW, or greater, at disposal). This upper end of canister thermal load is defined primarily by commercial SNF canisters (about 85% by volume and almost all the activity projected out to 2048: SNL, 2014), and is a steadily growing inventory.

On the other hand, the DHLW inventory is approximately fixed (about 15% by volume of waste projected out to 2048), and can be characterized as a high-volume waste stream with much more modest heat loads and activity, but consisting of a very large number of disposal canisters (SNL, 2014). These canisters would be much smaller than DPCs, and most could, if desired, be transported over the roadways using the existing transportation system (e.g. Robinson et al., 2014). Disposal would be operationally straightforward, using technologies presently used at WIPP to convey the waste to the underground, as opposed to requiring new technological developments to handle very large, heavy packages (SNL, 2014). The large number of HLW and DOE-managed SNF packages dictates that a large area of underground space is required, even if the canisters are densely packed[a]. Finally, disposal of very hot waste packages may require special underground configurations such as alcove disposal in order to optimally distribute heat to the surrounding rock mass (Carter et al., 2011; DOE, 2011).

These factors suggest that in a staged repository program, an early emphasis on the defense waste portion of the inventory would be sensible[b], through the development of a safety case relevant to either a standalone repository for defense waste, or one section of a combined repository for all waste. A staged approach beginning with disposal of low-to-intermediate-heat defense waste, building upon the safety case and operational experience of the WIPP TRU

[a] *Carter and McCabe (2014) estimate a total of 224,000 linear m of drift covering about 2.6 square km to dispose all of the defense wastes in the inventory using an in-drift disposal design.*

[b] *Other potential benefits to the U.S. DOE cleanup mission have also been identified related to "front-end" waste processing costs enabled by availability of a salt repository for defense wastes: see Robinson et al. (2014) for details.*

(transuranic) waste repository, would build confidence through the modest, yet important intermediate step of developing a safety case for defense waste.

With respect to thermal testing, the response of salt can be usefully divided into categories in a manner consistent with a staged approach in which repository domains with wastes of different heat loads would be developed, with lower-heat wastes disposed first. Recognizing the large number of low-heat canisters in the DHLW and DOE-managed SNF inventories, a salt disposal system for DOE wastes with a limit of on the order of 1500 W/canister would cover virtually all wastes except for ~30 DOE-managed SNF canisters and the roughly 400 canisters of naval SNF, which in this scenario would be assumed to be co-disposed with commercial SNF. The rationale for this disposition path for naval SNF is based on its similar characteristics in terms of package size and heat loads (SNL, 2014).

5.2 Expected Thermal Regimes and Behavior

Assuming a division of waste into low- and high-heat categories, the expected thermal response based on this categorization can be understood from past repository heat modeling studies. Specifically, heat management for low-to-intermediate-heat defense wastes has been investigated by Harp et al. (2014), whereas salt response for high heat loads was studied by Clayton and Gable (2009). Although the thermal behavior modeled in these studies depends to some degree on the assumptions of waste content, repository design, and time period of interest, the results can be used as a guide to understand the thermal regimes expected for the various waste streams. The key results of the two studies are described below.

Low-to-Intermediate-Heat Waste (Harp et al., 2014): This study examined the disposal of defense wastes (borosilicate glass HLW and DOE-managed SNF) in a salt repository employing the in-drift disposal concept with RoM salt backfill. The purpose of the study was to examine heat management issues associated with a defense waste repository in salt to identify any thermal constraints that might be associated with this disposal method. The model configuration, shown in Figure 15, uses a fixed geometry for the drift dimensions and spacings. Thermal conduction calculations were performed as a function of waste package spacing, heat load per canister, and thickness of RoM salt backfill.

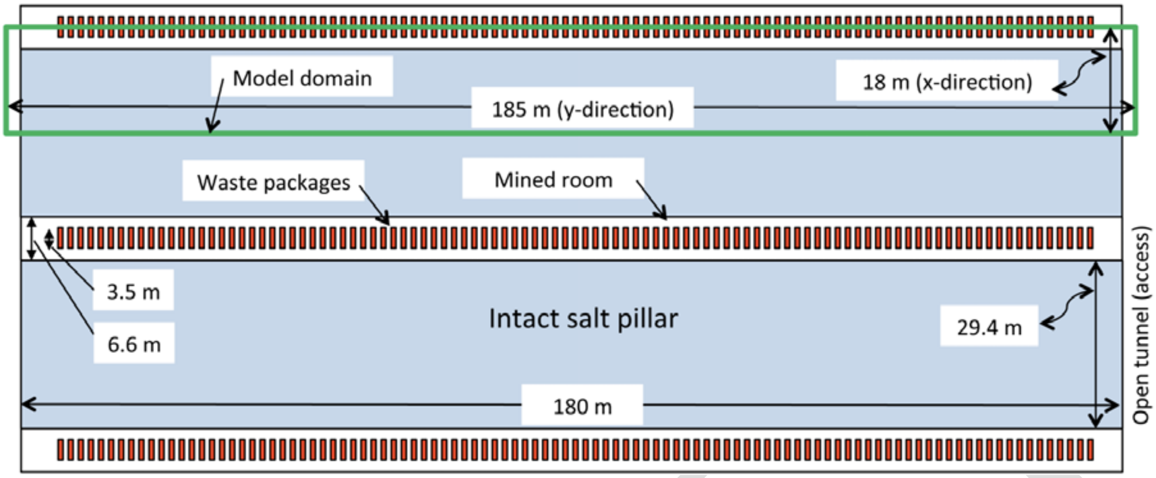


Figure 15. Plan view of repository heat transfer model for low-heat defense waste (from Harp et al., 2014).

A representative result is presented in Figure 16, showing steady-state horizontal temperature profiles[c] through a canister to the centerline in the salt pillar (top), and vertical profiles through the canister, drift, and intact rock above and below (bottom). The key result from this model is that nowhere in the model domain does the temperature exceed the boiling point of water for canister heat loads of 220W or less (i.e. the vast majority of the DHLW inventory). Even at the canister-salt interface, where temperatures are hottest, temperatures reach only 95^{o}C for the 220W case, and are controlled by the canister heat flux. Average temperatures within the rock mass, which are controlled by the areal heat load, are even lower. For reference, the areal heat loads for the 55W, 110W, and 220W cases are 1.7W/m^2, 3.3W/m^2, and 6.6 W/m^2, respectively, which is considered to be a modest areal heat load for salt[d].

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[c] *The heat load was assumed to be constant, rather than a more realistic decline with time, to enable long-time, steady-state behavior to be examined without the complicating effect of a decreasing heat source with time. The approach used tends to overestimate the peak temperature.*

[d] *More densely packing the waste is not possible without stacking the canisters because they are already as close as possible to one another along the drift, and geomechanical constraints limit how closely spaced the drifts can be to one another.*

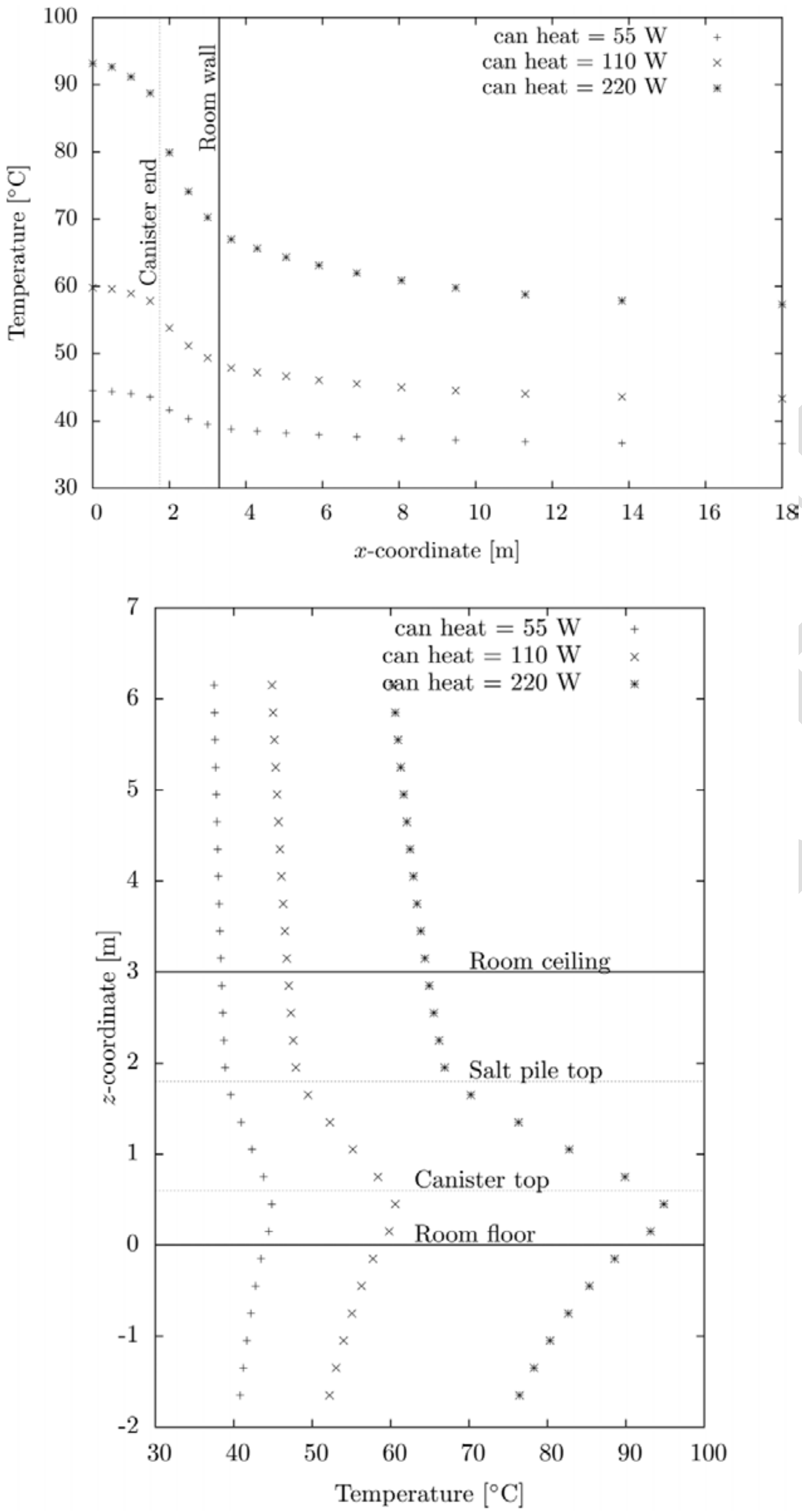

Figure 16. Steady-state horizontal (top) and vertical (bottom) temperature profiles for closely spaced canisters (0.9 m or 3 ft center-to-center spacing) in the defense waste repository model (from Harp et al., 2014)

Thermal-hydrologic (TH) behavior is expected to play a relatively minor role in affecting the heat transfer away from the canisters in this regime. With respect to geomechanical effects, available information suggests that processes such as salt creep, compaction, and fracture healing will be accelerated at higher temperature. For example, Figure 17, from DOE (2011), shows the strain versus time measured in creep tests at various temperatures. The magnitude of this enhancement for low-heat waste will be relatively small, especially for the 55W and 110W cases, where maximum temperature increases above background of only a few tens of ^{o}C are expected. Thus, drift closure rates are expected to be somewhat enhanced by the increased temperatures, but the effects should be relatively modest.

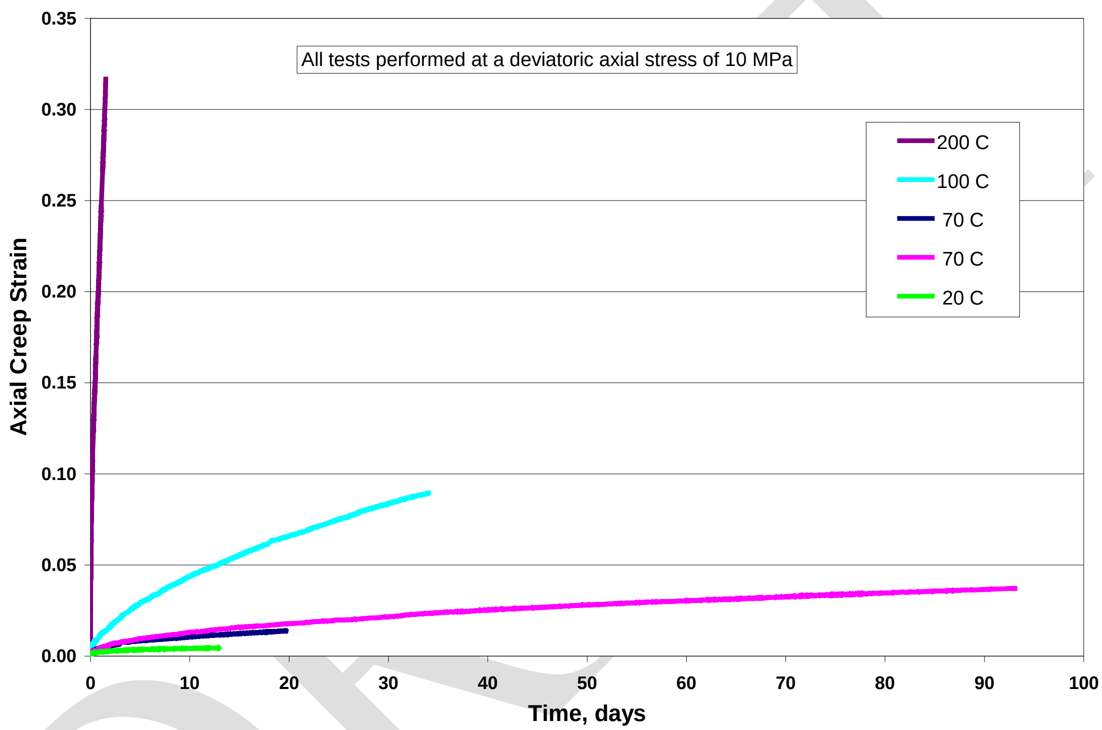

Figure 17. Impact of temperature on creep of salt (from DOE, 2011).

Harp et al. (2014) also performed numerous sensitivity analyses, including examining the temperature response for heat loads extending up to 2000W per canister, which covers the majority of the DOE-managed SNF, as well as some aged, low-burnup commercial SNF, and some of the naval SNF inventory[e]. Figure 18 shows the vertical temperature profiles for 3 and 6

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[e] *The portion of the naval and commercial SNF inventory covered in this range of thermal loads depends on whether the SNF would be repackaged prior to disposal. A large fraction of these used fuels could fall in this range if repackaged into smaller units, say, 4- or 9-assembly units, as has been studied within the UFD campaign. This approach would, of course, come at the expense of creating many more disposal packages, as well as the worker exposure risks associated with the fuel repackaging operation.*

m canister spacings, for the range of heat loads from 1000W to 2000W. Temperatures above the boiling point are predicted in this range of heat loads, and the average temperatures are higher, due to the higher areal heat loads. For example, for the 3 m spacing cases, the areal heat loads are 9 W/m^2, 13.5 W/m^2, and 18 W/m^2 for the 1000W, 1500W, and 2000W cases, respectively, and a factor of two lower for the 6 m spacing cases. Note that these spacings are larger than for the DHLW due to the restriction assumed in Harp et al. (2014) to limit the maximum temperature to values less than 200^{o}C.

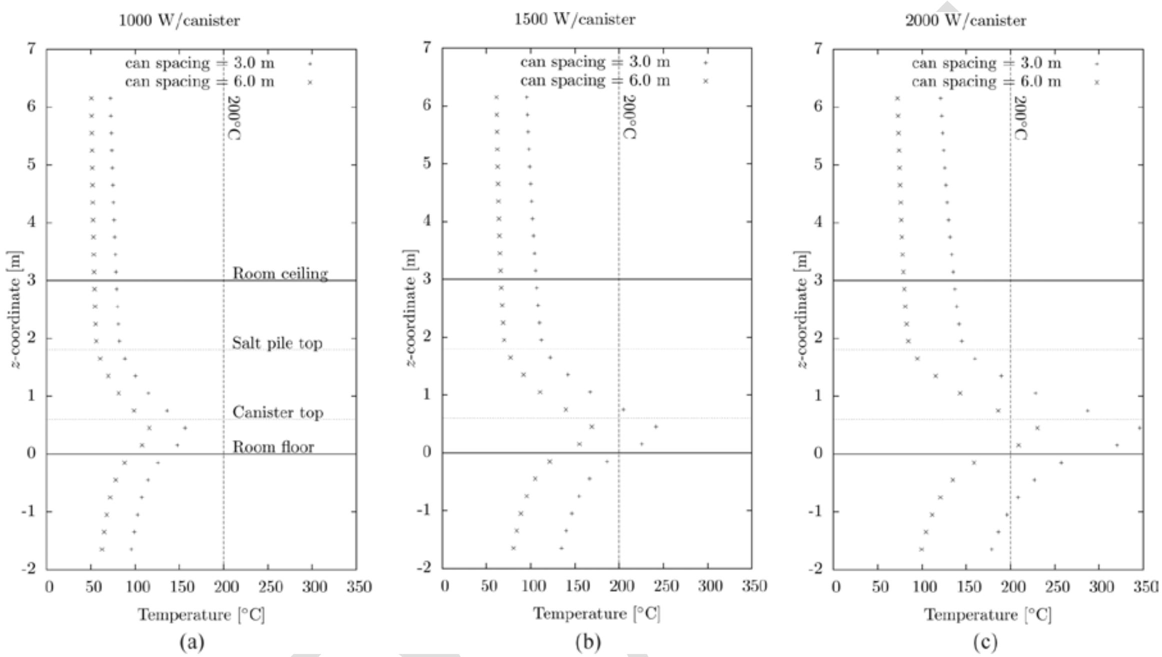

Figure 18. Steady state vertical temperature profiles for 1000W, 1500W, and 2000W canisters at 3 m and 6 m spacings (from Harp et al., 2014). Note: Temperatures far in excess of 200^{o}C would probably not be considered in an actual design but are included here to illustrate the sensitivity of maximum temperature to the combination of spacing and thermal load.

Under these conditions, qualitatively different thermal, hydrological, and geomechanical behavior is expected. Stauffer et al. (2012, 2013, 2014a) have demonstrated through numerical modeling the possibility of coupled TH and THC processes impacting the macroscopic heat transfer behavior through the development of heat pipes in the RoM salt.Figure 19, a plot of simulated temperature difference between a coupled TH model and a pure conduction model, illustrates this phenomenon for a simulation of a heater test consisting of five 1500W heaters. If heat pipes form, they would enhance the heat transfer from the canisters compared to a conduction-only case, flattening the temperature gradient and resulting in lower temperatures near the canister. Accompanying this behavior is the redistribution of salt through a process of dissolution at locations where condensation occurs, and precipitation at the boiling front. These processes have been demonstrated in small-scale laboratory experiments under controlled conditions (Olivella et al., 2011). Observable effects of this phenomenon, if it occurs, would be in the form of a rind of low-porosity salt near the canisters, which would armor the canister from water intrusion. The time frame over which this would occur would be of order a year or two, in advance of crushed salt consolidation, which would require significantly longer times for closure to apply a mechanical load to the RoM salt.

Geomechanical effects would be somewhat more accelerated compared to isothermal conditions and the effects at the lowest heat loads, exhibiting sensitivity to temperature as shown previously inFigure 17.

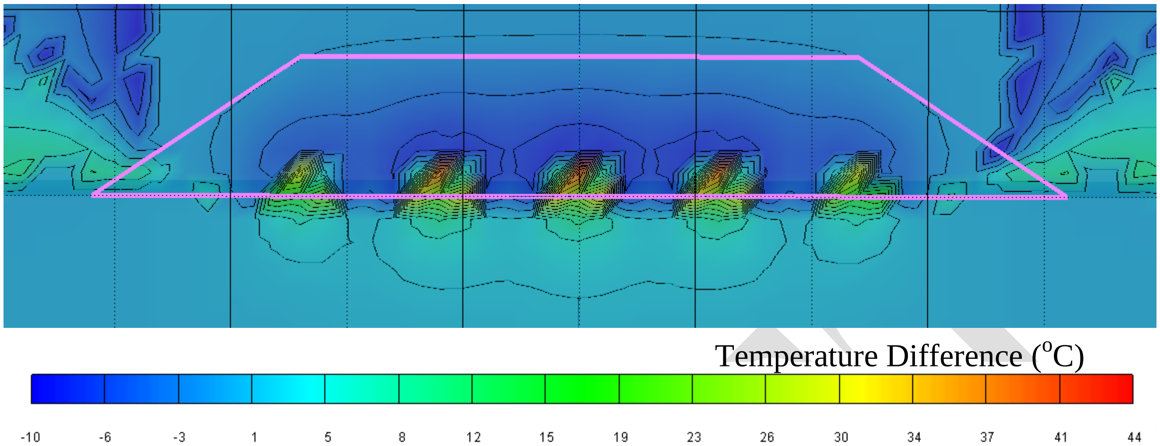

Figure 19. Temperature difference between a conduction-only and coupled TH simulation after 2 years (from Stauffer et al., 2012). This plot records the difference between the conduction-only temperature and the coupled TH temperature at each location. Red colors represent a higher (by as much as 44°C) temperature in the conduction-only model.

High-heat waste (Clayton and Gable, 2009): This study examined the thermal behavior of salt under higher per-canister and areal heat loads for a waste form assumed to be generated under a nuclear fuel reprocessing regime. The per-canister and areal heat loads for this study were as high as 8400W per canister and 39W/m^2, and thus are a useful benchmark for high-heat waste, including naval SNF and commercial SNF. The repository geometry and emplacement strategy was taken from studies being performed at that time, and subsequently published in Carter et al. (2011). The model assumed the high-heat waste canisters would be emplaced in alcoves mined at an angle off of a main drift, to optimally distribute the heat as uniformly as possible across the repository footprint (Figure 20). As with the in-drift disposal concept, RoM salt would cover the waste packages in this design. In addition to geometrical differences between the low-heat and high-heat models, the high-heat model assumed a waste form with major heat contributions from Cs-137 and Sr-90, each of which have a half-life of approximately 30 years. A three-dimensional, thermal conduction model representing a repeating unit consisting of one alcove and adjacent rock and drift were simulated, with appropriate boundary conditions to simulate the transient thermal response in and around an alcove near the center of the repository.

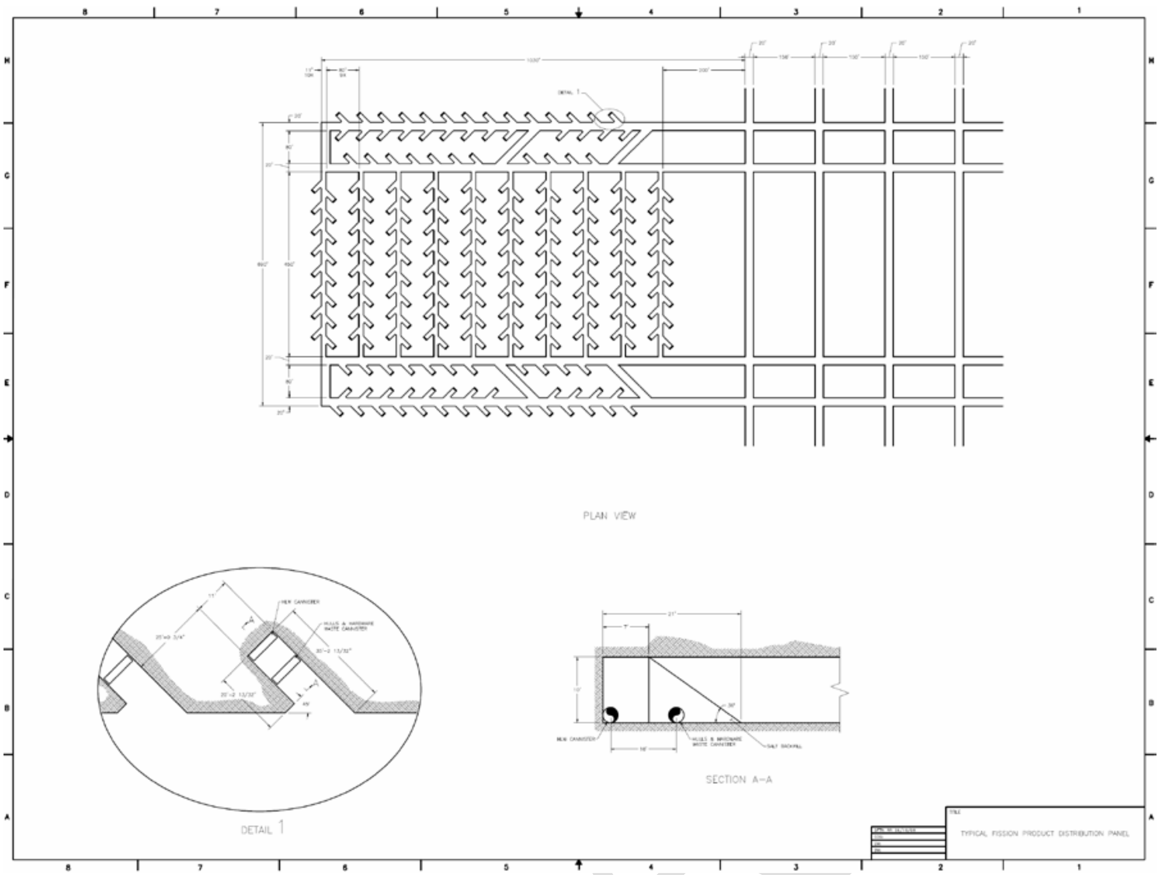

Figure 20. Layout for a portion of the repository for the high-heat disposal case (from Carter et al., 2011).

Although the differences in the two modeling studies preclude a direct, one-to-one comparison, the high-heat model provides an estimate of the projected thermal regime that extends to higher heat loads. Table 9(From Table 4.9 of Clayton and Gable, 2009) shows the maximum and average salt temperatures in the alcove as a function of canister heat load for a fixed alcove footprint (base case and sensitivity cases 9, 10, and 11), and temperatures as a function of canister heat load for the same areal heat load of $39W/m^2$ (base case and sensitivity cases 12, 13, and 14). The latter cases were obtained by reducing dimensions of the alcove footprint (i.e. reducing the spacing between alcoves) so that the same areal heat load is represented as a larger number of lower-heat, more closely spaced canisters.

The results in this table illustrate a basic point about repository heat management: the maximum temperature experienced in the salt, which occurs at the salt-canister interface, is controlled most strongly by the individual per-package heat loads, whereas the average temperature in the repository, especially at long times, is controlled by the areal heat load. This fact provides constraints on how densely the waste packages can be packed and how large the per-package heat load can be while still meeting repository thermal design criteria. Understanding these tradeoffs is important when determining the possible regimes that might be encountered in a salt repository.

The most obvious result of the high-heat calculations is the prediction of much higher temperatures, especially near the canisters. Temperatures in excess of 150°C are predicted in large regions, rather than only near the canister. Temperatures near the canister are even higher, often exceeding 200°C, a limit above which there are significantly greater process uncertainties. For example, other processes such as rock decrepitation may occur at about 270°C, and chemical transformations of non-halite minerals in the salt may be different, or more rapid, than those occurring at lower temperatures.

With respect to geomechanical behavior, salt creep would be expected to be perhaps an order of magnitude faster compared to isothermal conditions, leading to much more rapid alcove closure, fracture healing, and crushed salt reconsolidation. The migration of brine might be expected to be qualitatively similar to the low-heat case, but the high temperatures could lead to more extensive dryout in and around the alcove, which in turn could affect reconsolidation and fracture healing.

Table 9. Comparison of peak salt temperatures for the high-heat disposal case (Table 4.9 of Clayton and Gable, 2009).

Case	Salt Maximum		Salt Average	
	Temp. (C)	Time (years)	Temp. (C)	Time (years)
Base Case (8400W, 39 W/m^2)	377	8.0	162	37.0
Sensitivity Case 9 (7000W, 32.5 W/m^2)	296	8.5	137	37.0
Sensitivity Case 10 (4200W, 19.5 W/m^2)	165	9.0	89	36.5
Sensitivity Case 11 (2400W, 11.1 W/m^2)	98	9.0	61	36.5
Sensitivity Case 12 (7000W, 39 W/m^2)	322	10.5	162	37.0
Sensitivity Case 13 (4200W, 39 W/m^2)	238	17.0	162	37.0
Sensitivity Case 14 (2400W, 39 W/m^2)	199	24.0	162	37.0

5.3 Summary of Regimes

To understand the thermal regimes that could be encountered in a repository for U.S. wastes in salt, it is necessary to combine information on thermal load of the various waste streams in the inventory with modeling assessments describing the behavior under these heating conditions. Figure 21 captures this information as characteristic regimes on a plot of areal heat load versus per-package heat load, illustrating the thermal regimes within the range of practical combinations.. These axes are chosen since each play a role in the temperatures experienced near waste packages, or in an average sense within the repository. Approximate ranges of canister heat loads are shown below the x axis for the various defense and civilian waste streams. Furthermore, practical considerations will drive repository design away from the combinations of high areal heat load and small per-package heat load, or low areal heat load and large per-package heat load.

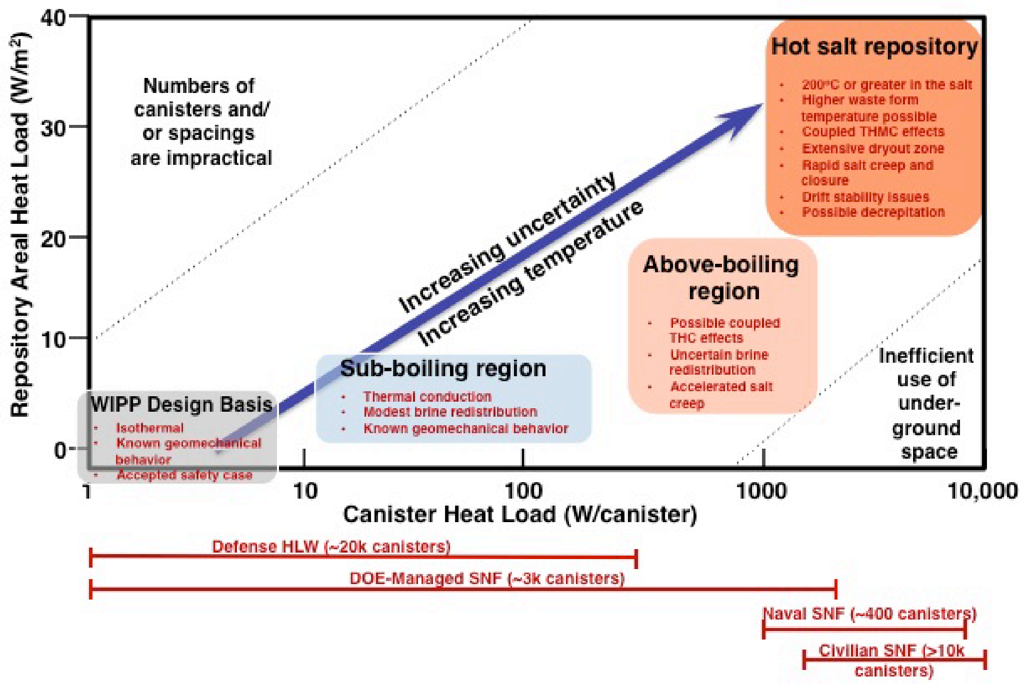

Figure 21. Schematic of Areal Heat Load versus Canister Heat Load

Within the practically acceptable region, the different regimes identified are based on the discussion provided in the previous section, and thus are somewhat dependent upon the disposal concepts on which the modeling studies were based. This is acceptable, given the qualitative nature of the discussion.

WIPP Design Basis: Conditions at very low areal and canister heat loads are characteristic of the WIPP repository, for which an accepted safety case has been formulated. A repository under these heat loads remains essentially isothermal. Significant fractions of the DHLW and SNF inventories fall into this category, having heat loads that would not present any unresolved issues with respect to heat management[f].

Sub-boiling Region: The next region extends up to about 250W/canister and leads to conditions under proposed disposal concepts in which temperatures increase above ambient, but remain below the boiling point of water. Brine evolution and migration effects, if they deviate from the response under ambient conditions, will be modest, and thermal response is likely to be conduction-dominated. Geomechanical processes are also likely to be only slightly more aggressive than under isothermal conditions. These conclusions represent expert judgment based on knowledge from the WIPP repository and results from historical experiments performed at

[f] *For these very low-heat wastes, the prohibition against disposal at WIPP is based on legal rather than technical considerations, and stems from the restrictions imposed in the WIPP LWA, which allows only TRU waste of defense origin to be disposed in the WIPP repository.*

higher thermal loads, making them provisional and subject to field confirmation. Virtually all the DHLW inventory and a large fraction of the DOE-managed SNF inventory falls in this regime (or in the previous category).

Above-boiling Region: This region, ranging from 250W to perhaps 1500W, leads to conditions exceeding the boiling point of water within the RoM salt backfill, and within the intact rock. The upper limit is approximately set so that temperatures do not exceed 200^{o}C anywhere in the system, although the ease with which this design objective could be achieved would be driven by details in the operational processes employed. Knowledge of the coupled processes acting in this regime is significantly more limited than for the regimes discussed previously. Hydrologic processes may impact the bulk heat transport behavior. Also, dissolution/precipitation processes lead to redistribution of salt near the waste packages, and geomechanical processes are accelerated due to thermal effects. This regime covers the remainder of the DOE-managed SNF, much of the naval SNF, the lowest burn-up commercial SNF, and commercial SNF were it to be repackaged into canisters holding a smaller number of fuel assemblies.

Hot Salt Repository: This region covers the remainder of the canister heat load range, from about 1500W to about 10000W. Temperatures could greatly exceed 200^{o}C near waste canisters, and temperatures would be between 150 and 200^{o}C across broad areas within the repository emplacement region. There are significant uncertainties in how this would impact pre-closure and post-closure performance. Drift and alcove closure would be vastly accelerated compared to the less aggressive thermal loading scenarios, leading to questions on how drift stability and large-scale discontinuities such as non-halite mineral seams are impacted. Hydrologic response is similarly uncertain, both within the DRZ and the RoM salt. Decrepitation processes may also occur, with unknown consequences to the properties of the rock mass. Finally, it may be more difficult to predict whether waste form/package thermal limits are met, since temperatures within the canister will be much higher, and the ability of the surrounding medium to reject the heat will be more uncertain. While none of these uncertainties are currently showstoppers, and in fact, high heat loads could improve rather than degrade performance in some aspects, the evolution of the system in a hot salt repository is much more uncertain than for the cooler regimes. This regime covers the remainder of the naval SNF not falling in the previous category, and all of the commercial SNF if disposed in DPC.

6. Appendix B : Summary of Previous Studies on Thermal Testing in Salt

Past field heater tests, performed at WIPP and other salt sites worldwide have provided significant basis to our current understanding of salt behavior. Previous reports (Callahan et al., 2012; Kuhlman et al., 2012; Kuhlman, 2014) have synthesized the information from these tests to evaluate the completeness of our understanding, so that an accurate assessment of the need for future field testing could be evaluated. Table 10, from Callahan et al. (2012), shows a gap in our experience base regarding the way in which bedded salt would behave for the in-drift disposal concept, either for low-to-intermediate or high heat loads. This is despite the fact that significant thermal testing has been conducted in both bedded and domal salts both in the U.S. and Germany. Testing has been conducted for the borehole disposal concept in both bedded and domal salt, and the in-drift concept has been tested in domal salt, but a knowledge gap still exists relative to the behavior of bedded salt for the in-drift and alcove disposal concepts is a gap that still exists.

A principle technical uncertainty that would be addressed is the behavior of the small amounts of water contained in the salt upon heating. Because bedded salt may contain upwards of an order of magnitude more water than domal salt (Hansen and Leigh, 2011), either in the form of fluid inclusions, intergranular brine, or hydrous minerals, testing of the in-drift concept in domal salt is insufficient for understanding the behavior of water when subjected to decay heat.

Thus, a demonstration of a proof-of-principle in-drift disposal concept, focusing on water movement, would help to clarify our state of knowledge, in particular improving our understanding of the thermal-hydrologic behavior of heat-generating waste in a bedded salt repository. There remains uncertainty in brine and vapor transport due to the complexity of predicting the interplay of multiple processes, as well as issues of scale (Robinson et al., 2012). A field testing campaign in a bedded salt URL, will provide valuable information on the suitability of bedded salt for a host of wastes in the U.S. inventory, including defense and civilian wastes. Field-scale studies and demonstrations, in contrast to laboratory-scale studies and computer generated models, provide the scientific and engineering base of information necessary to produce the scientific basis necessary for legislators, regulators, or public stakeholders to make informed, confident decisions. Field testing and full-scale demonstrations are essential components of such a program.

The next section establishes the conditions under which in situ thermal tests in salt could be performed in order to cover the range of behaviors expected for disposal of wastes in the U.S. inventory.

Table 10. Summary of historic and proposed thermal testing (Callahan et al., 2012)

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				
Salt Defense Disposal Investigations (SDDI)		X	Bedded salt	• Peak salt T ~80-150°C • 1-2 year heating duration • Power – 0.5-2 kW/heater
Salt Disposal Investigations (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.

6.1 Salt Vault Tests in Bedded Salt

The first significant tests in geologic salt relevant to disposal of radioactive waste were conducted in two existing Carey Salt mines in Kansas in the late 1950s and 1960s (Morgan, 1959; Empson, 1961), culminating in the "Project Salt Vault" borehole disposal demonstration (Bradshaw and McClain, 1971). Much of our current understanding on the mechanical behavior of salt was first formulated from data collected as part of the Salt Vault Project. Testing included heated boreholes that induced significant decrepitation (>350 °C), three concurrent vertical borehole heater tests (7 boreholes and 10.5 kW power each) with radioactive sources and brine collection, a heated room pillar test (33 kW), and numerous long-term room closure measurements.

6.2 Avery Island Tests in Domal Salt

In situ tests were performed on the uppermost (169 m) level at the Avery Island salt mine (near New Iberia, Louisiana). Tests were conducted mostly by RE/SPEC Incorporated (Stickney and Van Sambeek, 1984), with minor testing by SNL. There were four main tests and several smaller tests conducted at Avery Island beginning in 1977, including: Borehole heater tests (Ewing, 1981; Van Sambeek et al., 1983; Waldman and Stickney, 1984), brine migration tracer tests (Krause, 1983), corejacking mechanical tests (Stickney, 1987a; Stickney, 1987b), and heated gas permeability tests (Blankenship and Stickney, 1983).

The permeability data collected during heating and cooling of the brine inflow and heater tests presents a unique dataset illustrating the evolution of damage through during and after heater tests (Kuhlman and Malama, 2013).

6.3 WIPP Heated Tests in Bedded salt

A large number of in situ tests were conducted in the Permian Salado formation on the 655-m level at the Waste Isolation Pilot Plant (WIPP), some to improve the technical basis for disposal of heat-generating waste in salt, and directly related to the WIPP transuranic waste disposal mission. Three main high-level waste testing programs were developed (Tyler et al., 1988). Numerous Thermal/Structural Interactions (TSI), Waste Package Performance (WPP), and Plugging and Sealing Program (PSP) tests were conducted underground at WIPP from the early 1980s to the mid-1990s.

The WIPP Thermal/Structural Interactions (TSI) program consisted primarily of the Rooms A, B, G, and H in situ tests (Munson and Matalucci, 1986; Munson et al., 1997a; Munson et al., 1997b). The TSI tests were designed to provide information about long-term deformation in excavated rooms and overlying rock, which encapsulates the emplaced wastes. Rooms D, A, and B were similar in physical configuration, essentially representing cool, warm, and hot versions of the same room. The extensive in situ mechanical and thermal datasets collected during TSI testing are reported for Room H (Munson et al., 1987), Room D (Munson et al., 1988), Room B (Munson et al., 1990), and Room A (Munson et al., 1991 & 1992).

The WIPP Waste Package Performance (WPP) test program was designed to test the effects of the repository environment on containers for contact handled TRU waste, remote handled (RH) TRU waste, and DHLW (Molecke, 1984; Molecke and Matalucci, 1984). The program investigated the durability and reactions of various containers or container materials (including backfills) in the host rock.

The WIPP Plugging and Sealing Program (PSP) included nine in situ tests and was responsible for developing materials and emplacement techniques for use in plugging shafts, drifts, and nearby boreholes to limit groundwater flow in both the short and long term. The PSP tests were grouped into two major technical areas: (1) characterizing the mechanical and hydraulic properties of evaporite formations, and (2) developing seal materials and evaluating the seals.

6.4 Asse Tests in Domal Salt

The Backfill and Material Behavior in Underground Salt Repositories (BAMBUS) project was a multipart international collaboration that included two relevant major field tests in salt (Bechthold et al., 1999; Rothfuchs et al., 2003; Bechthold et al., 2004). The tests were conducted in domal salt at the 800-m level of the former Asse salt and potash mine in Germany. There were several other large-scale tests at Asse relevant to disposal of heat-generating waste in salt, including a heated deep borehole convergence test (Doeven et al., 1983), a series of six heated borehole tests conducted from 1968 to 1985 (Kessels et al., 1986), a heated brine migration test with gas collection and ^{60}Co sources (Rothfuchs et al., 1988), and a vertical borehole heater test with subsequent heater excavation (Rothfuchs et al., 1995). A summary of brine migration results associated with thermal testing at Asse is found in Coyle (1987).

The BAMBUS Thermal Simulation of Drift Emplacement (TSDE) test emplaced six heated (6.4 kW each) full-scale POLLUX®disposal canisters in a drift, backfilling the remaining space with RoM salt (Rothfuchs et al., 2003; Bechthold et al., 2004). Significant in situ data were recorded before, during, and after the 9-year heating phase. Significant laboratory testing was conducted on the canisters, reconsolidated backfill, and instruments during the post-mortem excavation phase.

Two BAMBUS Development of Borehole seals for High-Level Radioactive Waste (DEBORA) tests were conducted in vertical boreholes near the TSDE experiment (Bechthold et al., 1999). These tests involved heating crushed salt emplaced in boreholes over approximately a year, while monitoring reconsolidation.

The Proceedings of the 5th US/German Workshop on Salt Repository Research, Design and Operation (Hansen et al., 2015) indicate that there is little recent thermal testing in salt. The workshop (held September 8-10, 2014) focused on (1) operational safety, (2) geomechanical issues, (3) underground research laboratories, and (4) capturing early evolution of salt excavations. A certain effort was also allotted to updating FEPs with regard to high-heat flow salt repositories. In part, a pause in repository research in Germany concerning thermal testing in salt may be due to the 10 year hiatus (2000–2010) owing to political decisions and a formal moratorium in Germany (Hansen et al., 2015).

7. Appendix C : Modeling Tools

Field-validated coupled THMC models of salt behavior are a major objective of in-situ testing (Table 2, Goal 5). Within the UFD campaign, the generic repository studies would rely on such a validated model to assess and constrain the processes that would be included in a system-level performance assessment model as part of the safety assessment of generic salt repository concepts for HGNW.

Additionally, pre-test numerical model predictions, inverse modeling during the test, and final calibrated models and sensitivity analyses would help achieve the following technical objectives: (1) establish a quantitative understanding of the combined effects of the individual processes previously examined in isolation in laboratory studies; (2) compile a record of improved understanding as a result of this integrated test program; (3) quantify predictive uncertainties and document residual conceptual uncertainties; and (4) provide information relevant to a future design process for a generic repository in salt.

A recent summary of salt repository modeling results from multiple teams is provided in Kuhlman (2014). The following sections briefly describe several of the models that have been used for coupled processes around HGNW in salt formations.

7.1 CODE_BRIGHT

CODE_BRIGHT (https://www.etcg.upc.edu/recerca/webs/code_bright) is a two-phase, variably saturated, porous medium flow, finite-element model developed at Universitat Politècnic de Catalunya to solve the poroelastic air/brine flow problem in deforming salt (Olivella et al., 1994, 1995). CODE_BRIGHT has been used to simulate reconsolidation (Czaikowski et al., 2012) and dissolution/precipitation (Castagna et al., 2000; Olivella et al., 2011) of crushed salt.

CODE_BRIGHT can simulate large deformations, with thermal, mechanical, hydrological (gas and liquid phases), and transport processes in a tightly coupled manner. Chemical processes are generally limited to the dissolution and precipitation of NaCl. The numerical model executables are freely available (but it is not open source) and it is typically used with the commercial GiD pre- and post-processor (http://www.gidhome.com). CODE_BRIGHT is only available compiled for Windows and is limited to a single processor.

7.2 FEHM

The Finite Element Heat and Mass transfer code (FEHM) (https://fehm.lanl.gov) uses the control volume finite element method to find approximate solutions to the governing equations of mass and momentum conservation, assuming a multiphase form of Darcy’s Law is valid for all phases across the domain (Zyvoloski et al., 1999). Reactive transport is sequentially coupled following the tightly coupled energy and flow calculations. Many new capabilities have been added to FEHM to enable the tightly coupled THC processes of fluid transport in heated salt, including (Stauffer et al., 2013): porosity change from the precipitation/dissolution of salt, with salt solubility as a function of temperature; permeability as a function of variable porosity; thermal conductivity of salt as a function of porosity and temperature; vapor pressure of water as a function of concentration and temperature; water vapor diffusion coefficient as a function of saturation, porosity, pressure, and temperature; and dehydration of hydrous minerals in impure salt. Simulations have been tested against recent and historical experimental data to develop and improve the salt material model. FEHM executables are freely available (under a non-commercial LANL software license) for Linux, Macintosh OS X, and Windows. The software is limited to a single processor.

7.3 PFLOTRAN

PFLOTRAN (http://www.pflotran.org) is a multiphase flow and reactive multicomponent transport simulator (Hammond et al., 2014; Lichtner et al., 2014). In the context of subsurface simulation, PFLOTRAN simulates single and multiphase fluid flow (i.e., Richards' equation, airwater, CO_2-water), thermal conduction/convection, and biogeochemical transport (e.g., aqueous speciation, sorption, mineral precipitation-dissolution, microbial degradation, radioactive decay and ingrowth) on structured and unstructured finite-volume grids. The structure of the software allows general inclusion of processes (e.g., electrical geophysics); an infinitesimal-strain geomechanical process is currently under development.

Toolkit for Scientific Computation (PETSc) framework (Balay et al., 2014). PFLOTRAN is developed for high performance distributed memory parallel supercomputing, to simulate subsurface problems composed of billions of degrees of freedom utilizing hundreds of thousands of processor cores while still being applicable to serial batch systems or one-dimensional reactive transport using the identical executable and source code (Hammond and Lichtner, 2010). PFLOTRAN is open-source, developed under a GNU Lesser General Public License and freely available for download from https://bitbucket.org/pflotran/pflotran-dev.

7.4 SIERRA Mechanics

SIERRA Multimechanics is a general multi-physics finite-element suite of numerical models comprised of several independent but potentially interrelated modules (Stewart and Edwards, 2003). Aria is an energy (conduction, convection, and enclosure radiation) and incompressible Navier-Stokes/porous media flow module with electrostatics and transport capabilities (Notz et al., 2007). Adagio (SIERRA Solid Mechanics Team, 2011) is a quasistatic large-deformation mechanical module (i.e., including clay layer slipping, failure, and tearing) with salt-relevant constitutive models implemented (Munson and Dawson, 1979; Callahan, 1999). The Aria and Adagio modules typically solve their respective numerical problems on different finite element meshes, which must be externally interpolated and coupled through the Arpeggio module (Kostka and Templeton, 2010). The SIERRA Mechanics suite was developed for applications outside repository sciences, but it has been used to simulate large non-isothermal deformations under salt repository conditions (Clayton and Gable, 2009; Clayton et al., 2010; Stone et al., 2010; Argüello and Rath, 2012, 2013; Argüello, 2014) as well as other geoscience-related applications (Martinez et al., 2011). SIERRA Multimechanics is developed and used internally on Linux clusters at Sandia National Laboratories, and is not available for general distribution outside Sandia, Los Alamos, and Lawrence Livermore National Laboratories. It is configured to run in parallel on large-scale supercomputers.

7.5 TOUGH-FLAC/FLAC-TOUGH

TOUGH-FLAC is a set of iteratively coupled independent domain-specific models, which has been used in enhanced geothermal reservoir simulations, CO2 sequestration, and modeling earthquake swarms (Rutqvist and Tsang, 2003; Rutqvist, 2011; Blanco Martín et al., 2015). TOUGH-FLAC runs each program independently: it modifies the porosity, permeability, and capillary pressure inputs to TOUGH2 based on output from $FLAC^{3D}$, and modifies the pressure, temperature and saturation inputs for $FLAC^{3D}$ based on the output from TOUGH2 (EOS3). The coupling scheme between TOUGH2 and $FLAC^{3D}$ is based on the fixed stress-split method (Kim, 2010; Rutqvist et al., 2014). The flow problem is solved first, and the pore pressure and temperature are prescribed during the geomechanical calculation. Clausthal University of Technology has developed a related coupled model referred to as FLAC-TOUGH (Blanco Martín et al., 2015). It uses a different coupling strategy and first solves the mechanical problem. FLAC-TOUGH is compared to TOUGH-FLAC in Rutqvist et al. (2014).

TOUGH2 (http://esd.lbl.gov/research/projects/tough) solves the mass and energy balance equations in porous media, allowing different equations of state (EOS) modules to be used, each bringing different capabilities to TOUGH2 (e.g., precipitation and dissolution of saline porous media). TOUGH2 is freely available for download (under a non-commercial LBNL software license) for U.S. Government users and collaborators, but must be purchased for commercial use, and is limited to a single processor. The related TOUGH-MP simulator does allow parallel execution of TOUGH2 simulations on distributed-memory systems (Zhang et al., 2008). FLAC and FLAC^{3D} (http://www.itascacg.com) are two- and three-dimensional commercial explicit finite difference large-deformation geomechanical numerical models by Itasca Consulting Group. The models are primarily geomechanical models, with heat conduction and limited poroelastic flow capabilities. The software has the capability to implement new constitutive models not included in the main executable (i.e., the FISH language), which is used by some researchers to implement different salt creep constitutive models (Wieczorek et al., 2010; Wolters et al., 2012). All FLAC programs are only available for Windows, and only FLAC^{3D} (version 5.01) is available as a multi-threaded shared-memory program, although constitutive models or coupling routines implemented in FISH are executed serially (Rutqvist et al., 2014).

8. Appendix D : Monitoring Technologies

The following section discusses instrumentation anticipated to be candidates for a large-scale field 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. Final determination of instrumentation will be dependent upon detailed test planning and instrumentation design/development activities.

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 (Munson et al., 1997b; Callahan et al., 2012). In the initial phase of the project, various measurement systems and diagnostic methods were evaluated to assess their feasibility and likelihood of providing relevant information. A brief description of each method is provided below:

Thermal and mechanical measurements: spatially distributed measurements of temperature using resistance temperature detectors (RTDs) will be the primary method of monitoring temperature. Fiber optic methods to monitor temperature are also being evaluated as a potentially new approach to provide more widespread coverage within the test bed. Geomechanical monitoring systems such as multi-point borehole extensometers (MPBX) will be used to observe the response of the drift during heating.

Hydrologic and geochemical measurements: Hydrologic parameters to be measured include 1) local gas permeability within the test bed in the salt pile and the DRZ; 2) local water content within the salt pile, potentially using a combination of moisture probes adapted for use in a salt environment, such neutron probes and time domain reflectometry (TDR) methods; 3) gas and water vapor tracer methods to monitor vapor-phase transport within the salt pile and surrounding air gap and DRZ; 4) geochemical sampling to understand the evolution of chemical composition of the liquid and gas phases.

Geophysical Methods: Geophysical imaging methods with the potential to provide a three-dimensional, dynamic view of conditions within the test bed are being explored: 1) Electrical resistance tomography (ERT) with the potential to image the location of liquid water within the test bed; 2) passive seismic event monitoring and active time-lapse in situ seismic wave transmission measurements and monitoring are being considered that could be able to noninvasively detect thermal/mechanical changes and the presence of liquid water.

A summary of lessons learned for various types of instrumentation are discussed below. Additional information exists on each these measurement techniques and its application to the anticipated test environment; however, in the interest of brevity, only a summary is provided on each.

8.1 Temperature Measurements

Temperature measurements should be straightforward. Most of these sensors are commercially available, proven technology, and reliable under hot saline test conditions. A large quantity of these types of sensors will be installed to measure the temperature of heaters, salt backfill, intact salt, air, bulkheads, and for thermal compensation of other instrumentation (e.g., extensometers). Candidate instrumentation for obtaining thermal data is as follows:

- Thermocouples/Resistance Temperature Detectors – Used previously in WIPP thermal experiments, premium grade, Type-E thermocouples with ungrounded junctions, high purity magnesium oxide insulation, and Inconel 600 sheathing are selected due to the hot, humid, and salty environment. "Premium grade" denotes conductors made of high-purity alloys that ensure greater measurement accuracy, while "Type-E" denotes junctions of chromel and constantan conductors. It will be imperative that the thermocouples are well sealed to prevent brine from invading the insulation.
- Resistance Temperature Detectors (RTDs) measure temperature by correlating the resistance of the RTD element with temperature. RTDs are often more accurate temperature sensors than thermocouples and provide excellent stability and repeatability, but can be more fragile and come with fixed lead lengths, making their placement in the test bed more dependent on up-front test design.
- Fiber Optic Temperature Array – Fiber optic distributed temperature sensing involves sending laser light along a fiber-optic cable. Photons interact with the molecular structure of the fibers, and the incident light scatters. Analysis of backscatter for variation in optical power is used to estimate temperature. Commercially available detectors can achieve a continuous measurement over long distances (kilometers), with spatial

resolution of about a meter and thermal resolution of about 0.01 degrees Celsius. This technology might be considered for temperature measurements within the salt backfill as a mesh might be laid down as the backfill is emplaced.

8.2 Mechanical Measurements

Mechanical measurements will be made in the intact salt mass surrounding test drifts as well as within the test boreholes and drifts. Because of the relatively short time frames associated with these proposed field tests there is not expected to be significant drift closure during the testing period. Mechanical measurements will be conducted to confirm this hypothesis. Comparison of these measurements will be made to existing thermomechanical models as well as past observations and data.

- Multi-Point and Single-Point Borehole Extensometers – Used previously in Asse and WIPP thermal tests, extensometers monitor rock mass extension by measuring the relative displacement between an anchor set at some depth in a borehole and the borehole collar. This can be done with a single anchor or multiple anchors set at different lengths. These are often installed in an array around the room with anchors set at varying depths up to 50 feet.

- Room Closure Gages – Displacement transducers provide remotely monitored room closure data and were used extensively in past Asse, Salt Vault, Avery Island, and WIPP thermal tests. Typically, the closure gages are physically linked to extensometer heads at opposite sides of the test room. The transducer is attached to one extensometer, while a span wire is stretched across the room and attached to an eyebolt on the other. These can be installed in both the vertical and horizontal orientations at a station. If an extensometer is not co-located at this location, the gages can be anchored directly to the formation using a transducer bracket on one side.

- Active time-lapse in situ seismic wave transmission measurements and monitoring – Active seismic methods are the primary geophysical tool that could remotely, noninvasively detect subtle thermal/mechanical changes within the test area. The velocity at which seismic waves travel through solid material varies with density, temperature, and pressure. The density, wave scattering properties, and energy dissipation of the material also change with temperature. Thus, spatial variations in the travel time, scattering, and attenuation of seismic waves can be used to map changes in seismic wave velocities, material density, heterogeneity, and viscoelastic properties caused by temperature gradients in and around a heated region of salt and/or brine and vapor movement. One method that may be used is known as seismic tomography and is similar to techniques used in medical X-ray diagnostics. Full three-dimensional coverage of the region surrounding heated drifts with appropriate seismometers or accelerometers would allow detailed tomograms to be obtained using active seismic data acquired at different times, which would illustrate how the spatial temperature profile around the heaters evolves.

- Pressure Cells – Borehole pressure cells (BPC) have been used to measure stress change in a wide variety of rock types. A BPC typically consists of a flat metal chamber filled with a fluid that has a transducer connected by a tube; the transducer converts force into a measurable electrical output. The cell is inserted into the media (borehole or crushed salt backfill), and pumped up to create contact with material to be measured. The BPC responds primarily to stresses acting perpendicular to the plane of the flexible plates, but also has a small sensitivity to stress changes in the plane of the flexible plates. Two cells installed in a borehole at right angles to each other will provide orientations of the principal stresses in the plane perpendicular to the axis of a borehole.

- Passive Seismic Event Monitoring – The deformation induced by heating the salt will likely result in multiple scales and degrees of brittle failure of the alcove structure and surrounding formation. During initial heating, small-scale deformation might occur along cracks or fracture planes, either by crack growth or by slippage along pre-existing planes of weakness. These discrete events will result in very small microseismic or acoustic emissions. As heating progresses, large-scale fracturing can occur in the salt alcove walls, ceiling, and floor. Data from these events can be used to determine the location, development, and extent of the fractures, as well as the fracture mechanism itself. The microseismic data would provide an important measure of how thermal-induced strains are accommodated discretely in the salt body and how they lead to major structural events. A passive seismic monitoring system will provide insight into the presence and source of brittle phenomena.

Geophysical techniques are expected to be developed, demonstrated, and potentially deployed to monitor salt drift properties important to the test. A period of time is needed 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 established techniques, but some may not be appropriate for this salt testing program due to such issues as minimum spatial resolution, accommodating the viscoplastic nature of salt, the corrosive hot saline environment, 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, demonstration and debugging will be done in smaller-scale tests will be used to develop advancements that address the resolution and sensitivity issues.

8.3 Hydrologic Measurements

Hydrologic measurements of liquid and vapor phase water will be a key component in determining the water movement expected during the demonstration test. These will be challenging measurements that most past thermal tests in salt did not prioritize during the initial design of the test programs. There are several candidate techniques that may be employed, but each will require adequate upfront preparatory time, including laboratory work to demonstrate and refine the techniques. Moisture measurements will be prevalent throughout the test, concentrating on measurements in the salt backfill and in the intact salt near the heaters. Otto and Miller (2013) provide a review of many instrumentation techniques used by themselves and others to measure saturation, humidity, matric potential, and more. Hansen et al. (2015) also review options for hydrologic measurement.

- Time Domain Reflectometers – Time domain reflectometer (TDR) probes can be inserted or buried in crushed salt or intact salt. The TDR is a wave guide extension on the end of the coaxial cable. Reflections of the applied signal along the waveguide will occur where there are impedance changes. The impedance value is related to the geometrical configuration of the TDR (size and spacing of rods) and also is inversely related to the dielectric constant of the surrounding material. A change in volumetric water content of the medium surrounding the TDR causes a change in the dielectric constant. This is seen as a change in probe impedance which affects the shape of the reflection. The shape of the reflection contains the information used to determine the water content and bulk electrical conductivity of the medium.

Because the signal also depends on salinity, it is unknown whether TDRs will work effectively in salt. As salinity levels increase, the signal reflection from the ends of the rods in the TDR probe is lost because of conduction of the signal through the saline medium between the rods. There have been attempts to solve this problem by coating the probe rods. However, coating the rods introduces some other problems (change in calibration, loss of sensitivity, wear of the coating affecting results, etc.). More investigation on this would be necessary before committing to this instrument for use in a large-scale thermal field tests.

- Heat Dissipation Probes – A heat dissipation probe (HDP), or water matric potential sensor, consists of a heating element and thermocouple placed in epoxy in a hypodermic needle, which is encased in a porous ceramic matrix. To calculate soil water matrix potential, a current is applied to the heating element, and the thermocouple measures the temperature rise. The magnitude of the temperature rise varies according to the amount of water in the porous ceramic matrix, which changes as the surrounding salt wets and dries. These sensors are small and could be buried directly in the salt backfill or emplaced in small boreholes in intact salt.

- Electrical Resistivity Tomography – Electrical Resistivity Tomography (ERT) has been demonstrated to be an effective method to infer various hydraulic properties including water content and hydraulic conductivity from electrical measurements typically made by installing a number of electrodes along parallel paths. An electric current is induced into the test bed through two electrodes, and voltage is monitored through two adjacent electrodes. The process is repeated until current has been applied to all pairs of adjacent electrodes. The data from the electrodes is then processed to image the resistivity distribution. Based on the calibration curves (determined in the laboratory) of electrical resistivity as a function of water saturation, the correlation of water saturation level to electrical resistivity has about 1 percent precision in saturation levels below 40 percent. ERT has been successfully used to monitor brine injection in the DRZ at Asse, Germany (Jockwer and Wieczore, 2008).

- Acoustic transducers may be used to track sound speed which relates to associated physical changes (e.g. dry-out) during testing. Transducers can either be common PZT disks or quartz or LiNiO3 depending on application and susceptibility of withstanding long term salt/brine exposure. Transducers may be used singly or in arrays (e.g., tomography). Standard amplifiers and signal generation equipment will be used for transmitting and receiving acoustic signals in the salt (Uchino, 2000).

- Active Neutron Probe – These instruments consist of a neutron source, generally a small isotopic source, and several neutron detectors spaced at various distances from the source. Usually there are both thermal and epithermal detectors. The active neutron probe measures the attenuation of the neutron flux as a function of the distance from the neutron source. The attenuation of the neutron flux is primarily a measure of hydrogen density, which is then used to infer the water concentration or formation porosity in a saturated formation. Access to the formation of interest is by means of a cased borehole. This technique is well documented in soils and other media but will need to be tested and calibrated in the lab prior to use in the salt backfill and the surrounding salt mass to ensure the technique can accurately measure such low moisture contents.

- Ground Penetrating Radar (GPR) – This technology may provide high-resolution subsurface images to answer water-related questions. GPR is based on the transmission and reception of VHF-UHF (30–3000 MHz) electromagnetic waves into the subsurface, whose propagation is determined by the electromagnetic properties of the medium and their spatial distribution. As the dielectric permittivity of water overwhelms the permittivity the solid or air phase, the presence of water in the soil principally governs GPR wave propagation. Therefore, GPR-derived dielectric permittivity is usually used as surrogate measure for water content. Access to the formation of interest is by means of a cross borehole configuration. Saline fluids are very conductive and may pose challenges to GPR signal propagation and data interpretation. This will need to be investigated further before use in large-scale tests.

- Gas Sampling Ports – Gas sampling is commonly used to obtain real-time samples in test beds using pre-emplaced tubing which could be installed directly in the salt backfill. Considerations for the design include: 1) sampling rate: The faster the sampling, the larger the pressure differential, 2) induced vacuum: dependent on variables such as moisture content as well as length and internal diameter of sampling line, 3) system volume/length of tubing: System should be relatively small to minimize the volume of dead space that must be purged, 4) effect of connections and fittings: minimize connections and fittings so that there are no leaks, and 5) effect of porosity: leakage along the tubing and induced fractures can impart high permeability to materials that would

- Brine Sampling Ports – Using techniques similar to that described above for gas sampling, tubing could be emplaced directly in salt backfill or in fractures to enable sampling of brine during the test. Alternatively, drilled holes in the test bed or in fractures could be used to measure the brine that collects.

- Neutron probes – Neutron probes have recently been successfully used for moisture measurements in salt samples (Unpublished DOE-EM work). This method requires calibration and radiological controls.

If sufficient liquid is present at the heater surface, minimal sampling to determine brine composition and pH will be performed to assess whether, at the temperature regimes measured, there is formation of corrosive acid brine. This information would verify laboratory testing to determine heated brine acid formation.

8.4 Miscellaneous Measurements

There will be measurements to monitor heat transfer properties, the characteristics of air, and properties associated with the performance of the heating system. Measurements may also include diagnostics associated with the data collection system and other instrumentation systems and real-time video observation of the test drifts and test area.

- Thermal Flux Meters – Thermal flux meters are used to measure heat transfer and may be used to monitor heat flow from the heaters into the rock mass or the salt backfill.

- Power Meters – Power meters will be used to measure the electric power consumed by the heaters.

- Air Velocity Gages – Environmental and ventilation gages will be installed in the test to evaluate thermal losses from the heated drifts to the underground ventilation system. The environmental gages will likely consist of thermocouples emplaced inside the heated test drifts to measure the temperature of the air within the rooms. The ventilation gages will likely include thermocouples and air velocity sensors installed in access drifts in the vicinity of the heated test drifts. The ventilation thermocouples will measure air temperatures upstream and downstream from the heated test drifts, while the air velocity sensors will measure the velocity of the air moving through the access drifts by the mine ventilation system.

- Gas/Air Pressure Transducers – Gas and air pressure can be measured both from within the test drifts and in boreholes drilled near the test drifts or tubing installed in the crushed salt using pressure transducers and pressure lines.

- Air Humidity Sensors/Chilled Mirror Hygrometers – Whereas air humidity sensors (i.e., capacitive thin-film polymer sensors) are reliable, stable, accurate in most applications and commercially available, past experience using them in salt has resulted in early failures of the instrument and erroneous readings resulting from salt dust (sodium chloride) buildup on the sensor (e.g., a constant reading of ~75% RH).

  Chilled mirror hygrometers (CMHs) will likely be a more robust and accurate measurement in these underground conditions for measuring the humidity of the drift air and the ventilated air entering and leaving the bulkheads. The CMH makes a direct measurement of the dew point temperature of a gas by allowing a sample of gas of unknown water vapor content to condense on an inert, chilled, mirror-polished metal surface. Thermoelectric modules are typically used to chill the surface. A beam of light, usually from a light-emitting diode (LED), is reflected from the surface into a photo-detector. There are a variety of other types of condensate detecting schemes, but light reflection from a mirrored surface is the classic method.

  A typical CMH, in contrast to many other humidity sensors, can be made very inert, rendering it virtually indestructible and minimizing the need for recalibration. Drift air can be brought to the detector using sampling and pressure tubes run to various points of interest within the test bed. However, salt dust deposition on polished surfaces can lead to erroneous CMH measurements.

- Real-Time Remote Video – Visual observation inside a borehole or test drift can be made through windows that will be installed in each bulkhead. In addition, medium to high-temperature video cameras will be mounted within the test drift and surrounding areas to provide real-time and remote observations of tests. Depending on the test temperatures, cameras with a variety of features can be installed including pan, tilt, zoom, and thermal imaging features.

8.5 Discussion

Gage selection and shakedown in smaller-scale tests will be a critical component of a successful test program given the harsh conditions expected during testing. The selection process will be initiated by reviewing commercially available instrumentation in an effort to minimize design and field trials, and reviewing instrumentation previously used (and lessons learned) at WIPP (Munson et al., 1997b) and the salt thermal testing conducted in Germany (Droste, 2003). Some applications will likely require instruments to be designed or built, including geophysical techniques, because suitable instrumentation from commercial sources may not be available. Gages will be sought that can operate in the hot saline underground test environment where brine and heat can be detrimental to instrument performance. In addition, it will be required that the instruments be durable enough to provide data for the duration of the tests (up to several years). Prior to purchase, candidate instruments will be evaluated on the ability to meet anticipated operating conditions. Gage components that are determined to be susceptible to failure may be modified to minimize environmental degradation, and modifications will be passed on to the manufacturers through detailed specifications in purchase orders. Additional modifications to enhance gage operation may be made at the URL testing site by the test team personnel before gage installation. All instrumentation providing qualified data will be calibrated under the requirements of the quality assurance program prior to installation and post-test calibrated, as feasible.

As past thermal testing in salt has shown, the presence of brine can hinder the performance of the instrumentation systems and can also result in the degradation of equipment and instrumentation components. Field experience from previous WIPP and Asse studies quickly demonstrated that in the presence of brine and elevated temperatures, materials like stainless steel, aluminum, mild steel, Delrin plastic, etc., can corrode, resulting in the need to replace or reconfigure the equipment and instrumentation (Munson et al., 1997; Droste, 2003).

Certain fixes, such as anodizing an aluminum surface, can help prolong the materials. Additionally items under tension can experience stress corrosion cracking leading to component failure, and the combination of dissimilar metals can create galvanic reactions that can accentuate that process. As was learned in past WIPP thermal tests, because brine was present in quantities greater than expected and its deleterious effects proved to be very aggressive, active maintenance was essential and continuous throughout an experiment. Without active maintenance, instrumentation would have failed in periods as short as weeks. Gage maintenance will be an essential component of these tests.

The gages must be capable of measuring the full range of the predicted test drift response, or be adjustable as needed to allow measurements to continue over the full duration of the test. During the detailed test planning phase, calculations will be performed to provide estimates of test drift response for each of the tests. This modeling, together with the experience and technical judgment of the test designers, will enable the development of initial predictions of test room deformation, hydrologic responses, and temperature. Preliminary specifications for gage will therefore be based on the pretest response estimates for the test drifts (Munson et al., 1997a).

9. Appendix E : Associated Laboratory and In-Situ Investigations

Short, small-scale laboratory tests can be quickly designed and run to provide support by isolating individual processes to parameterize constitutive models for appropriate conditions in salt, and wherever it becomes apparent that uncertainties in these processes have a strong impact on final results. Laboratory tests can control for temperature, moisture, and air flow in ways that the in-situ tests cannot; existing lab space, equipment, and personnel are already available to support the needs of the in-situ testing team; and focusing on fewer processes allows for better delineation and understanding of fundamental relationships. For these reasons, laboratory investigations can greatly enhance the results of in-situ experimental efforts for less additional cost than field tests. They may also be used to collect data for parameterization and validation of numerical models at various spatial scales that will be used to analyze the field tests.

Laboratory investigations may be grouped into the following categories, each of which addresses data gaps or conceptual uncertainties for the expected conditions to be experienced in a thermal field test:

- *Thermal/mechanical laboratory studies on intact salt.* The fundamentals of high-temperature, intact salt response must be studied through unconfined and confined deformation experiments at temperatures up to 300^{o} C, to extend the range of temperatures to values expected under the highest possible heat loads in a salt repository. This temperature is likely to be at or above the currently accepted design limit (200^{o} C) for the geologic medium in a salt repository.

- *Thermal/mechanical laboratory studies on crushed RoM salt.* Consolidation of crushed salt is being studied under uniaxial and triaxial compression at temperatures up to 300^{o}C; the thermal conductivity of compacted crushed salt can also be measured as a function of porosity to enable appropriate values of thermal properties to be used in coupled models of near-field thermal behavior in the crushed salt and waste form.

- *Brine migration in intact salt.* Further development of the conceptual model for brine migration and liberation in intact salt will be achieved by: 1) studying the phenomenology of fluid inclusion migration and transport of intergranular brine at relevant temperatures and applied stresses, and 2) measuring the liberation of water using weight loss and fluid capture techniques.

- *Brine and vapor migration in RoM salt.* Bench-scale experiments to isolate hydrological processes and parameters in RoM salt backfill will provide key model validation and enhance the safety case for waste emplacement designs that include RoM backfill.

- *Chemical/mineralogical studies of constituents of bedded salt formations.* To account for the dehydration of clays and hydrous minerals over the relevant temperature and partial water pressure range, laboratory studies are are being conducted to analyze and characterize phases produced upon heating to temperatures up to 300^{o}C, and to assess the potential impact on the water source term and physical properties of the transformed minerals. The production of acidic vapors is being better constrained to support the pre-closure safety case.

- *Equipment and instrumentation tests.* Studies of interactions of fluids with typical engineered materials at repository temperatures, waste package materials, and new sensors/instrumentation will provide valuable lessons learned for the field tests and repository operations.

- *Chemical/hydrological studies of radionuclides.* Solubility, speciation, and redox state experiments of key radionuclides in high-ionic-strength solutions at elevated temperatures are relevant to the long-term safety case.

Generic categories of bench-scale investigations related to the field tests, and their link to the safety case, are presented in Table 11.

Table 11. Safety Case Issues Addressed by Laboratory Investigations.

Associated bench-scale investigations:	**Elements addressed**	**Safety case issues addressed by test (see** Table 5**)**
Thermal/mechanical studies on intact salt	Post-closure, Confidence-building	6, 16, 32, 33, 34, 37, 39, 43, 47
Thermal/mechanical studies on RoM salt	Pre-closure, Post-closure, Confidence-building, RDO	5, 6, 32, 33, 34, 37, 39, 43, 47
Brine migration in intact salt	Post-closure, Confidence-building	15, 18, 31, 32, 33, 34, 37, 39, 43, 47
Brine & vapor migration in RoM salt	Pre-closure, Post-closure, Confidence-building, RDO	2, 3, 7, 15, 25, 31, 32, 33, 34, 37, 39, 43, 47
Chemical/mineralogical studies of constituents in bedded salt formations	Pre-closure, Post-closure, Confidence-building, RDO	2, 3, 15, 25, 27, 32, 37, 39, 43, 47
Chemical/hydrological studies of radionuclides	Post-closure, Confidence-building, RDO	12, 27, 43, 47
Waste package materials and instrumentation tests	Pre-closure, Post-closure, Confidence-building, RDO	9, 11, 28, 39, 47

Understanding the mobilization of native brine is beneficial to establishing the evolution of the underground setting. 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 the laboratory in order to assess such parameters as the brine quantity and mobility and its ability to influence processes. In addition, as the potential carrier of radionuclides, the brine origin and transport processes represent essential components of the repository source term for scenarios in which brine-waste interactions are evaluated. Laboratory experimental efforts will also directly relate to this in-situ test by helping to fill data gaps and parameterize/validate the models used to design, instrument, and understand the drift-scale tests.

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 for a generic salt repository will build upon the scientific basis developed for Asse, Salt Vault, Avery Island, and 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 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.

Experiments to evaluate consolidation of hot, dry RoM salt will evaluate their stress-temperature-porosity behavior that will be used to model elements of the large-scale field tests. In addition, an assessment of thermal conductivity as a function of porosity will properly account for the transient evolution of the disposal area: as the RoM salt consolidates and porosity decreases, thermal conductivity increases. Therefore, the thermomechanical laboratory tests on granular salt produce information that is directly applicable to disposal in salt. Basic characterization methods are also being conducted at LANL to identify the spatial distribution of hydrous minerals within the region affected by the thermal pulse, as well as in the RoM salt, and to evaluate the geochemical conditions (aqueous chemistry and mineralogy). The following sections present recent DOE-NE and DOE-EM funded laboratory and in-situ experiments that could be expanded to support of the proposed field testing.

9.1 Brine Migration Experimental Studies in RoM Salt (LANL)

Laboratory experiments are currently taking place at LANL under the scope of the Draft Test Plan for Brine Migration Experimental Studies in RoM Salt Backfill (Jordan et al., 2014) to better understand RoM salt. This set of experiments addresses the safety case issues shown in Table 11 under the category “Brine and Vapor Migration in RoM salt.” A 2 ft by 2 ft tank will be filled with (a) pure granular salt and (b) RoM salt and used in heated and unheated studies (Figure 22). These laboratory investigations support in-situ field tests by producing key data on granular and RoM salt validate and parameterize the model (specifically, diffusivity of water vapor in RoM salt, evaporation from the porous crushed salt surface) as well as identifying other potential processes to be constrained in the field tests (e.g., hygroscopic behavior of granular salt and its effects on water vapor transport.

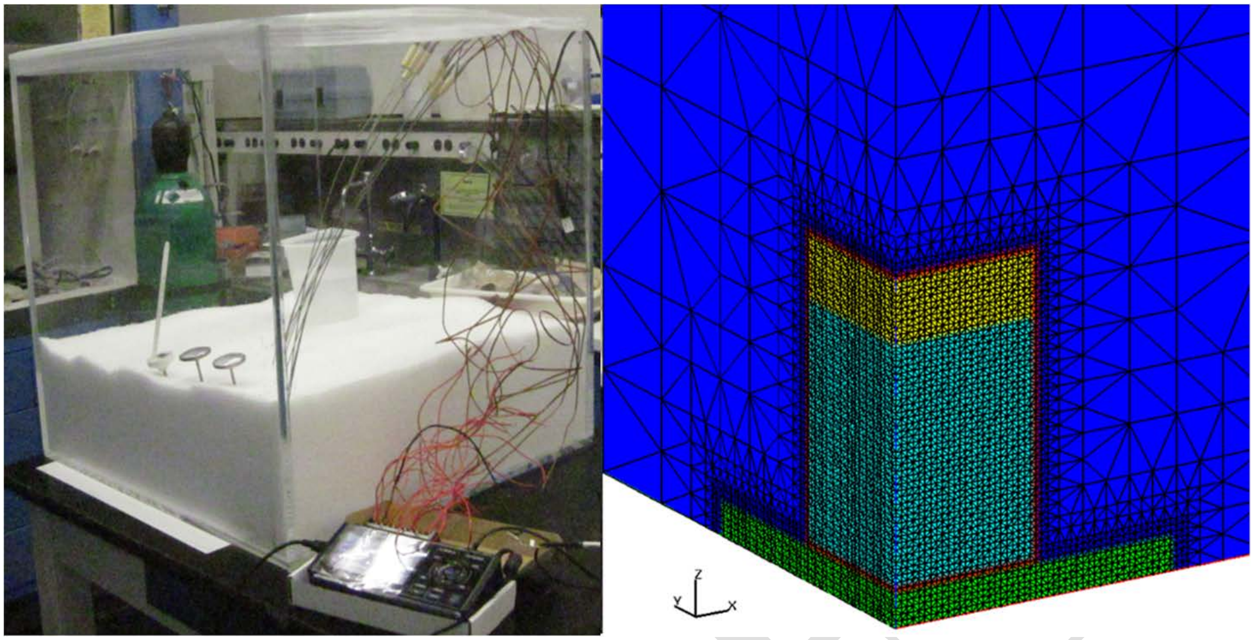

Figure 22. a) LANL equipment for laboratory investigations of granular salt under ambient and heated conditions. (b) Computational mesh for coupled THC simulations of these experiments.

9.2 Pressure Vessel Experiments (LANL)

A preliminary experiment was planned at LANL to simulate in-situ conditions of RoM salt and to simulate conditions during and after viscoplastic compaction begins to occur. This set of experiments addresses the safety case issues shown in Table 11 under the category “Thermal/mechanical studies on RoM salt.” The experimental pressure vessel (Figure 23) is designed for up to 10000 psi of confining pressure (currently up to 6000 psi) at elevated temperatures up to 300 C with multiple feedthroughs to monitor conditions within the salt pack, e.g., to listen for acoustic emissions from salt under difference T and P conditions. Experiments on glass bead packs to test the equipment have been completed. The apparatus is currently operational and pressure and temperature testing on run of mine salt on a laboratory scale can easily be done as needed for modeling support. The experiment also allows simulating the effects of confining pressure and temperature on the salt itself at a fast time scale with the potential to introduce brine and flow in a controlled fashion as well. It could also be possible to test the aging and robustness of small sensors in RoM salt at elevated pressures and temperatures.

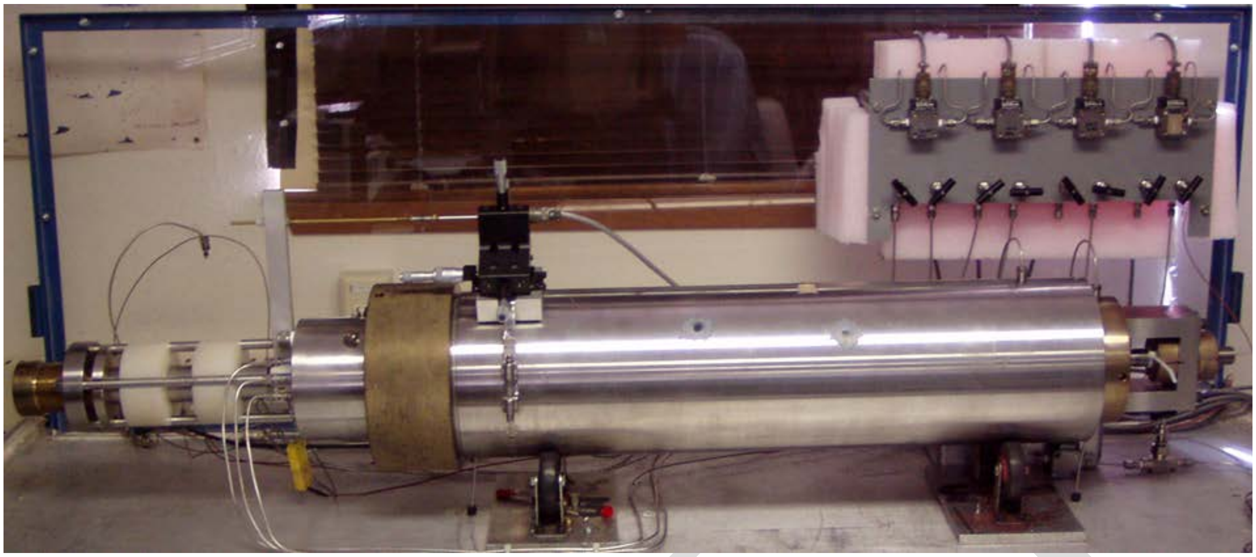

Figure 23. High Pressure and Temperature Vessel at LANL.

9.3 In-situ Small-Scale Evaporation Experiments

A passive evaporation test was performed underground at WIPP, with evaporation of brine from a beaker over time measured by weight change, along with local temperature, relative humidity, wind speed, and barometric pressure (Figure 24). This set of experiments addresses the safety case issues shown in Table 11 under the category "Brine and Vapor Migration in RoM salt." A control beaker of distilled water was also measured. Results showed that that a layer of salt built up on the brine beaker, which then began to show hygroscopic behavior and gained water from the air, even at relative humidity of around 25-30% (Otto, unpublished data, 2013-2014). In January 2014, the experiment was reconfigured with three high resolution scales to monitor two pans and a bucket of RoM salt in addition to the brine beaker. These measurements give an approximate rate of evaporation of WIPP brine from the RoM salt in the underground under specific ventilation characteristics. The experiments were terminated after the February 2014 WIPP shutdown.

Figure 24. Brine and RoM Evaporation Experiments in WIPP.

9.4 Mineralogical and Chemical Considerations (LANL)

Investigations of clay and hydrous mineral constituents in bedded salt formations will continue to improve our understanding of the chemistry of impure salt and the potential for acid production. This set of experiments addresses the safety case issues shown in Table 11 under the category “Chemical/mineralogical studies of constituents in bedded salt formations.”

The results from the FY14 examination of water content in run of mine salt and brine migration in intact multi-crystalline salt show moisture content in salt is strongly correlated to the clay content. The data also show that moisture release from salt is directly related to clay dehydration behavior. Brine is also present in salt crystals as fluid inclusions that migrate towards the heat source. Brine migration crosses grain boundaries unhindered. However, the presence of clay impurities in salt seems to stop the migration of brine. The implications of moisture accumulation in clay and its potential effects on salt properties are not known.

Clay dehydration experiments from Caporuscio et al. (2013) indicate corrensite (a “clay” mineral common in bedded salts) releases 5 to 13 wt. % interlayer water between 65-75 ^{o}C and is then stable in dehydrated form to at least 300 ^{o}C. This reaction is also fully reversible when temperature is below 65 ^{o}C and water is available for rehydration. High temperature (300 ^{o}C, 160 bar) experiments conducted in 2014 determined corrensite and gypsum stability in the presence of WIPP brine that provide the following results. Corrensite is stable at the repository conditions over a range from 0 wt. % to 49 wt. % WIPP brine. At these same high P, T conditions gypsum changes to anhydrite, a new anhydrous mineral phase.

Caporuscio et al. (2013) concluded that over that same temperature range (65-75 ^{o}C) the gypsum to bassanite phase dehydration transformation releases 15 wt. % water. Time-dependent experiments in 2014 also provide data for a sulfate only system, where gamma anhydrite forms concurrently with bassanite at early times (17 hours). By 80 hours, gamma anhydrite becomes the dominant sulfate phase. In the sulfate –salt dehydration experiment, the bassanite transformation occurs early on. Gamma anhydrite does not crystallize until approximately 80 hours, and metastable bassanite still occurs (Caporuscio et al., 2014). Determining the metastable bassanite stability field at various RH conditions would be critical to understanding the water release timing and amounts in a high-temperature repository setting.

Accessory minerals present in salt can be partially dehydrated by heating. Most of the minerals undergo reversible hydration/dehydration processes based on temperature and relative humidity. However, some mineral phases such as magnesium chloride undergo hydrolytic decomposition. For most mineral phases these processes will result in phase change, volume change, and a release of decomposition products. For most mineral phases this is not a problem. However, this process causes many problems when it involves the phase transformations of magnesium chloride. The dehydration of magnesium chloride goes through several stages at different temperatures releasing different amounts of water (Figure 25). In addition to water, it releases HCl gas, which is corrosive in nature.

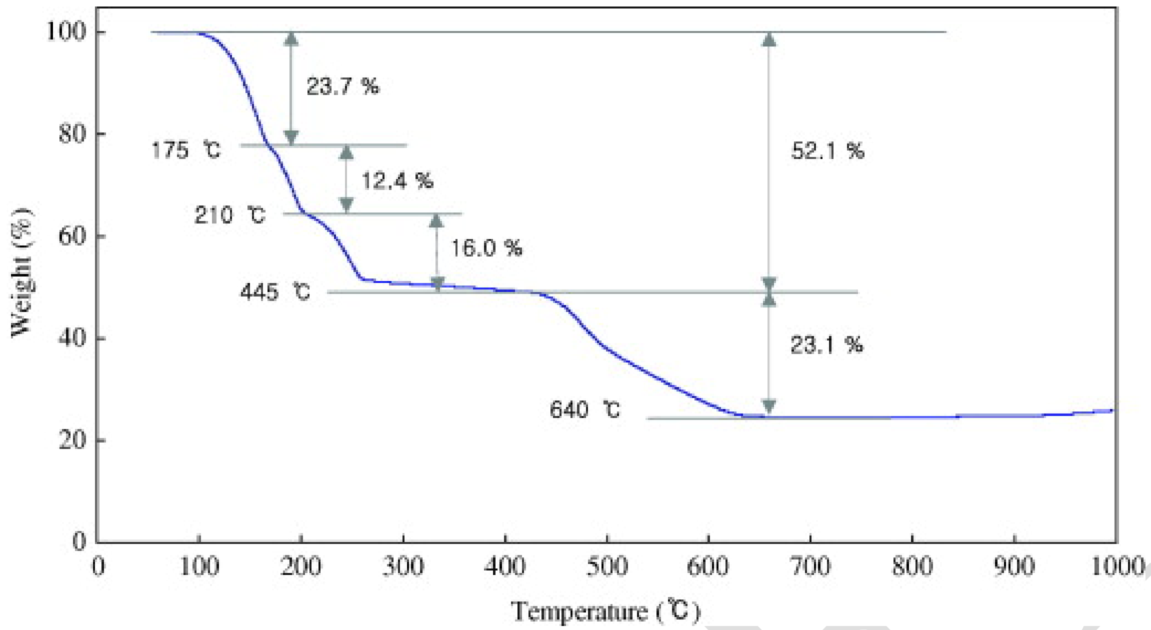

Figure 25. Thermogravimetric (TGA) Curve Showing the Dehydration of Magnesium Chloride in Air (Hyoung-Choon, 2010).

The dehydration and phase transformation of magnesium chloride is described by the following set of reactions:

$$MgCl_2.4H_2O \longrightarrow MgCl_2.2H_2O + 2H_2O \quad 1$$

$$MgCl_2.2H_2O \longrightarrow MgCl_2.H_2O + H_2O \quad 2$$

$$MgCl_2.H_2O \longrightarrow MgOHCl + HCl \quad 3$$

$$MgOHCl \longrightarrow MgO + HCl \quad 4$$

Figure 25 shows HCl generation is expected from $MgCl_2$ $4H_2O$ in the temperature range 210–445 ^oC and then from 450–650 ^oC. The data in Figure 25 were obtained under ambient pressure and water vapor conditions in an open cylindrical oven and reflect the temperature regime under which these processes could be relevant under ambient pressure conditions in the life cycle of a salt repository and could have significant implications for choice of the backfill

material (e.g. NaCl instead of run of mine salt), ventilation, and workers safety. However, if the system is confined and pressure increases, these transformations are expected to occur at wider range of temperatures depending on pressure. High-pressure conditions are likely to be relevant for the post-closure environment where pressures are expected to increase.

Contrary to the above data, during heating experiments on WIPP salt samples, we found some fractions of the condensed water collected during the heating were very acidic. Some of the acidic water measured approximately 5 M HCl. Our initial characterizations determined that acid evolution from salt was mostly HCl. In SNL-conducted heater experiments in Rooms A1 and B at WIPP in the 1980s (Nowak and McTigue, 1987; Matalucci, 1987; Tyler et al., 1988, Krumhansl et al., 1991), the generation of a pH 0.93 brine condensate in Room B (1500 W heaters with wall temperatures of ~180 ^oC) and a condensate with a “slightly less acidic” pH in

Room A1 (470 W heaters with wall temperatures of ~70 ^oC) (Molecke, 1986; Tyler et al., 1988) were reported. Some of the monitoring equipment in Room B failed due to massive corrosion (Tyler et al., 1988). Krumhansl et al. (1991) attributed the acidity of the condensate to HCl released from the thermal decomposition and hydrolysis of hydrated magnesium chloride. This report also acknowledges the potential evolution of sulfuric acid from the decomposition of hydrated sulfate minerals, but it states that no traces of sulfuric acid were detected.

We performed an initial examination of the dehydration of the clay minerals associated with the WIPP salt using thermogravimetric analysis between 25 and 350 ^oC (Figure 26). In this figure, the m/e = 18 trace (blue curve) distinguishes three major dehydration events at ~ 50, 100, and 150 ^oC. The pink curve is the temperature derivative of the brown curve (heat flow, W/g) and helps show where water is being driven off of the mineral phases.

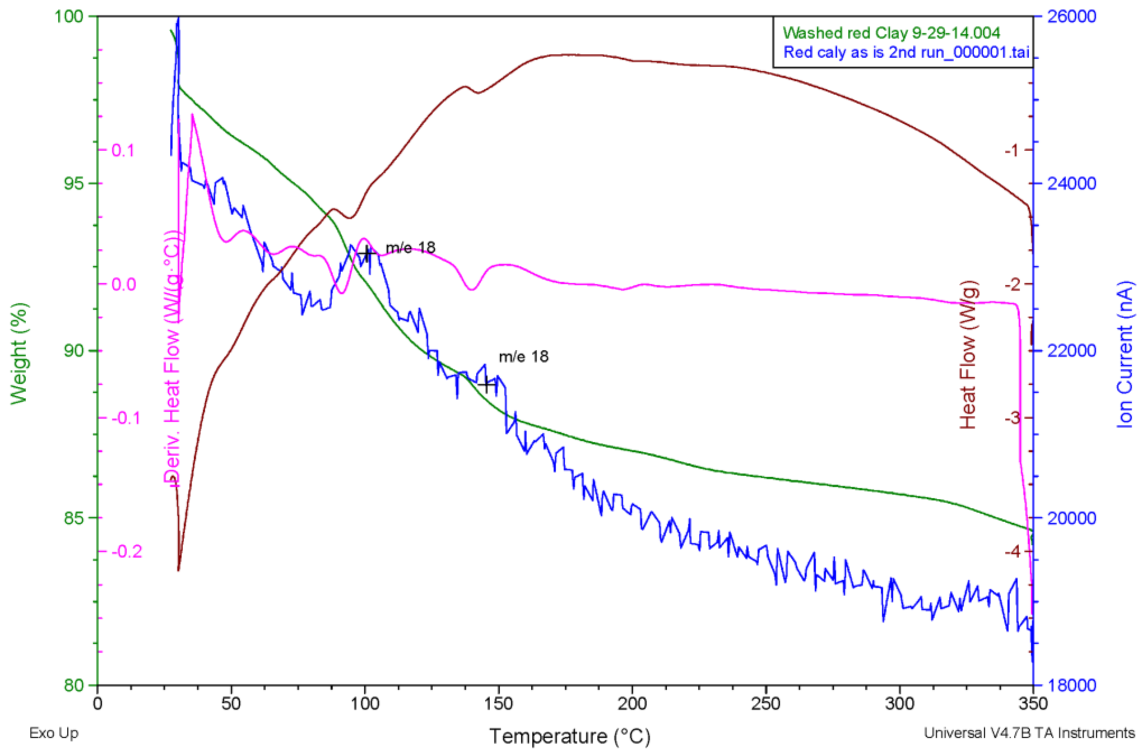

Figure 26. Preliminary Data Showing the Dehydration of Clay Separated from Clay Seam F at WIPP.

Initial data show that the dehydration of the clay fraction associated with WIPP salt is more complex than the dehydration of pure clay and suggest that the process involves multiple dehydration stages, which include the dehydration of all the other mineral impurities associated with salt. No HCl evolution was detected from the sample analyzed during this specific run. This indicates that the HCl evolution is dependent on the samples $MgCl_2nH_2O$ content.

In addition, our initial data and literature findings suggest HCl gas evolution from heated salt could be significant and could interfere with examination of the salt medium under heating conditions and ultimately for the disposal of thermal waste in salt.

Figure 27 shows the potential corrosive effects of acid generation from heated salt. This image shows an oven following a salt heating experiment involving ~1.5 kg of salt heated to 350 ^{o}C overnight. The brown/orange stain around the lower oven opening resulted from degradation of the oven seal. The oven glass was also etched and discolored by the acid vapor. We propose to more closely examine the issue of acid generation in heated salt. The experiments proposed will utilize state-of-the-art X-ray characterization techniques and micro-calorimetric examination to identify the mineral transformations and temperatures that control the processes responsible for the evolution of acid vapors from impure salt and develop a predictive capability for how much acid can be produced during salt heating experiments.

Figure 27. Oven Corrosion after Heating WIPP salt from Clay Seam F to 360 ^{0}C.

The characterization of different type of waters in salt (e.g., water in the forms of fluid inclusions, surface water present as grain-boundary fluids, and water bound within secondary minerals, like clay or gypsum), and their mobility and evolution as function of temperature are pertinent factors for salt repositories. Our preliminary data on the potential use of low-field NMR for the characterization of moisture content in salt is very promising (Caporuscio et al., 2014). We were able to determine the water content of an intact salt core, and more importantly we were able to determine the relaxation time of the water present in salt and determine if it is free or bound water. This is a very promising technique that could allow rapid and accurate determination of water content in salt and it distribution among the different water categories (intra-crystalline water, hydration water, etc.).

Proof-of-principle measurements were conducted to evaluate the use of stable isotopes to trace water movement in heated bedded salt repositories. An experimental system was developed for testing deuterium spiked water as seen in Figure 28. We then calculated elevations of δD and δ^{18}O (δD/δ^{18}O) resulting from different combinations of *net* evaporation rates of 99%-enriched D_2O or $H_2{}^{18}O$ and turnover times of air in a WIPP test drift (Table 12). Calculations assume a salt pile height of 8 feet (3500 ft^3 pile of 35% porosity).

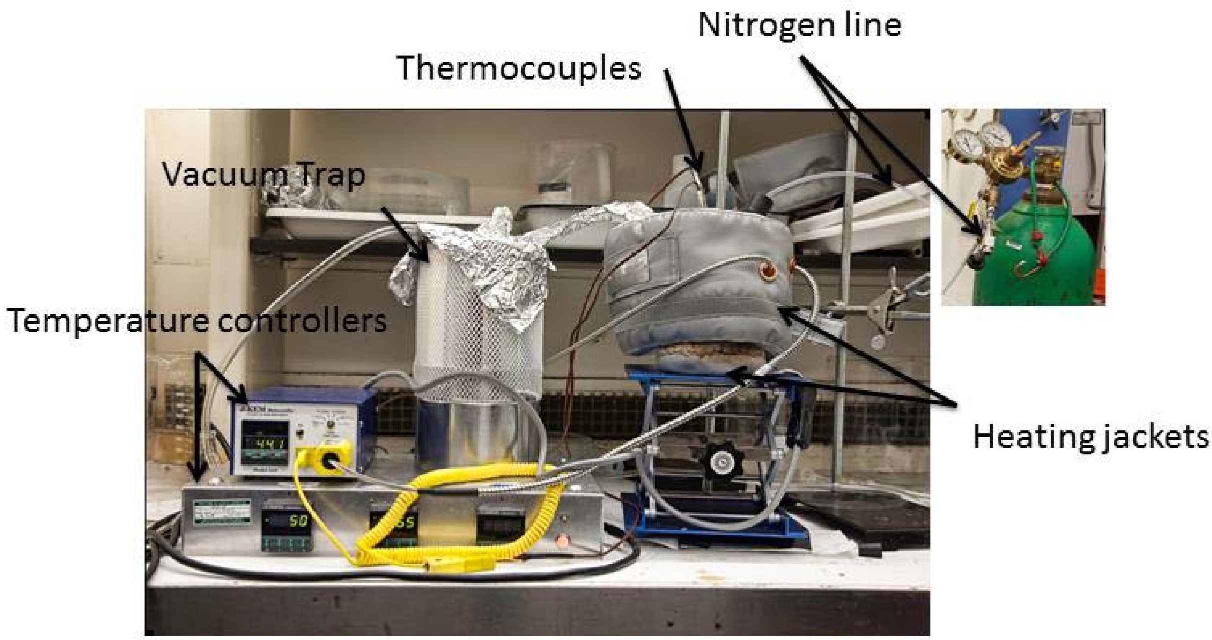

Figure 28. **Testing Deuterium Spiked Water Fractionation in Salt**.

Table 12. Calculated δ D and δ ^{18}O resulting from different combinations of net evaporation rates of 99%-enriched D_2O or $H_2{}^{18}O$ and turnover times of air in a WIPP test drift.

D_2O or $H_2{}^{18}O$ Evaporation Rate, g/day	**5 day turnover (δD / δ^{18}O)**	**50 day turnover (δD / d^{18}O)**	**500 day turnover (δD / δ^{18}O)**
0.001	7.7 / 0.59	77 / 5.9	770 / 59
0.01	77 / 5.9	770 / 59	7700 / 590
0.1	770 / 59	7700 / 590	76000 / 5900
1	7700 / 590	76000 / 5900	680000 / 53000

Because water in hydrous mineral phases dominates the overall water content in salt, the following experiments would be informative and beneficial to the technical basis for disposal of heat-generating waste in salt:

Clay/sulfate layers in intact salt. Investigate the release of water from clay/sulfate layers at appropriate temperatures. Initial experiments indicate water will begin releasing from clay at 75 ^{o}C (Jordan et al., 2015). The sulfate system gypsum-bassanite-anhydrite also begins dehydration at the same temperature, but with a time lag due to kinetic effects. Special attention will be devoted to the mineral layer interfaces (i.e., clay-salt, sulfate-salt) where water evolution may create dissolution pathways in the salt. If true, such dissolution channels may create fast brine pathways.

Further investigation of the sulfate system dehydration P, T trajectories. Initial experimental dehydration results show a span of temperatures involved, along with multiple influencing factors factors (e.g., time, relative humidity).Since the sulfate minerals will not rehydrate, the dehydration is a one-way path, the kinetics of the reactions involved and the "onset" temperatures of dehydration will be constrained. A more precise determination of the amount of water released will be captured.

Acid generation from heating of salt beds. This phenomenon was first described for bedded salt by Krumhansl (1991). The proposed tasks are: A) Identify mineral transformations that are responsible for acid vapor evolution though controlled laboratory experiments at temperatures between 65 and 170 ^{o}C using WIPP materials of variable composition from the proposed drift horizon, including RoM composites, B) Quantify amounts, acidity and composition of solutions evolved during heating experiments of the materials described above, C) Characterize the kinetic properties of the chemical transformations involved in acid generation, and D) Use in-situ X-ray-diffraction heating stage, hydrothermal apparatus, and micro-calorimetry to document mineral phases consumed and produced as a function of temperature for the materials described above. This work is being conducted for both worker health and safety issues, and the safety case.

Moisture characterization by low-field NMR. As shown by our preliminary investigation in FY 14, this technique holds great promise. To be able to provide quantitative results, the design will be refined for our applications and the calibrated to the salt bed minerals in question (halite, clays, sulfates). This instrument development should occur simultaneously with other characterization equipment.

Stable isotope methodology to trace water migration in bedded salts. This could support brine migration in salt by developing the following three items: A) Measure the temperature dependence of the fractionation of ^{2}H and ^{18}O between a saturated WIPP brine that is highly-enriched in D_2O and the vapor in equilibrium with it, B) establish the ability to measure a wide range of stable water isotope ratios in water vapor samples collected by cold trapping of water over a saturated brine, and C) Identify any issues associated with sample collection and sample analysis related to the harsh salt/brine environment so that these can be corrected prior to the field testing.

9.5 Monitoring Brine Migration in Salt with Electrical methods (LBNL)

Figure 29. ERT Test Core Extraction Images.

The presence and migration of brine is important to the security of salt nuclear waste repositories. Existing research has demonstrated the feasibility of using geoelectrical methods to map brine saturation and study brine migration in rock salt formations. We propose to use geoelectrical methods, specifically electrical resistance tomography (ERT), to monitor brine saturation and migration at the WIPP test site.

9.5.1 Summary of Experimental Data

Laboratory experiments were conducted at LBNL to study the electrical properties of WIPP rock salt. We evaluated the baseline electrical signals as well as responses to thermally induced moisture content changes. Core received from WIPP was sub-cored to acquire a clean, workable sample (~ 4' L x 2' ID) for the existing experimental laboratory setup (Figure 1). Electrical measurements were acquired using a data acquisition system based on National Instrument data acquisition platforms with a four electrode Wenner type configuration using Ag/AgCl electrodes. Spiral electrodes were used at the two faces of the core for current injection and miniature sintered electrodes were used for potential measurements on the core body (Figure 2). Baseline electrical measurements of the core revealed very similar responses to previously reported data for the Asse salt mine cores and has as high resistivity value of ~ 500K Ohm.m at low frequencies with a strong frequency dependent behavior at frequencies higher than ~ 100 Hz (Figure 3). Such high resistivity indicates that the core is very tight and dry, a characteristics typical to rock salt samples.

After our initial baseline measurements, the cores were subjected to oven drying and brine saturation to vary their moisture content and to establish petrophysical correlations between resistivity and moisture content. The saturating brine solution was made with RoM salt from WIPP (with presumably the same chemical makeup as in-situ brines), so that it does not selectively dissolve the minerals in the core. After being saturated in brine solutions for ~ 48 hours, the core was removed and paper towel dried to remove excessive water on the surface before starting baseline measurements. After baseline measurements at the highest moisture content were taken, the core was subjected to oven drying at 60˚C followed by higher temperature drying at 85 ˚C and 110 ˚C in later steps. Electrical measurements were conducted at each step and the weight of the core was carefully measured for calculation of moisture loss during each step. Figure 4 shows the petrophysical correlation between moisture content and electrical resistivity at 1 Hz (typical frequency used in the field). Figure 4 indicates an exponential correlation between moisture content and resistivity ($R^2 > 0.9$). A five order of magnitude increase of resistivity (from ~ 100 ohm.m to >10M ohm.m) was observed when the volumetric moisture content dropped from ~ 0.9% to 0.1%. Such a significant change in resistivity with a small variation of moisture content (within 1%), indicates great sensitivity of resistivity to moisture content in WIPP rock salt. Our laboratory data demonstrated the great sensitivity of resistivity to moisture content in the WIPP cores and indicated its potential for moisture saturation monitoring at field scales.

Figure 30. ERT Measurement Setup

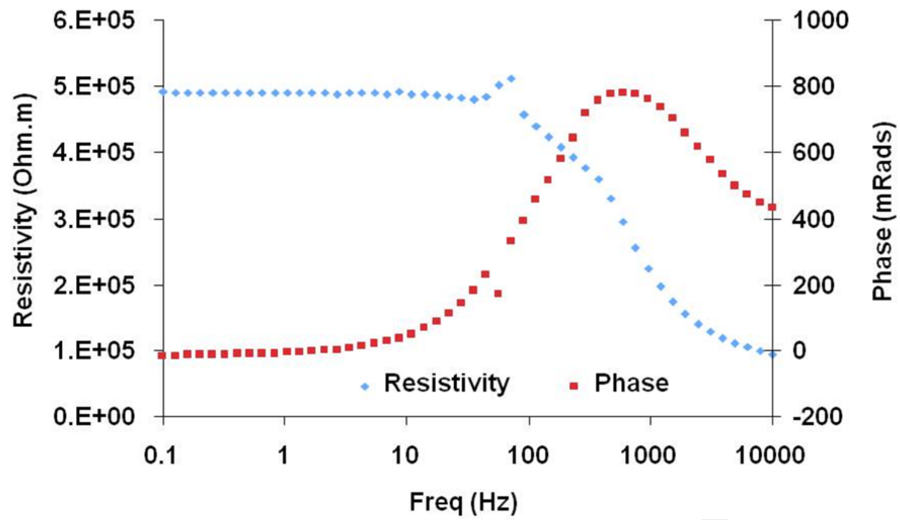

Figure 31. Baseline Electrical Signals

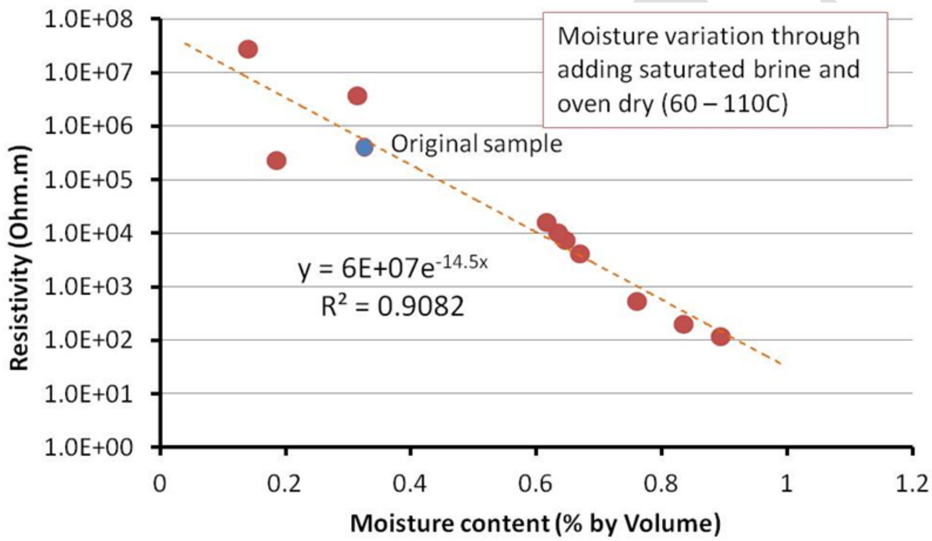

Figure 32. Correlation between Resistivity (1Hz) and Moisture Content

9.6 Distributed Fiber-Optics for Monitoring Subsurface Processes (LBNL)

9.6.1 Distributed Temperature Sensing

Distributed temperature sensing (DTS) is a fiber-optic technique dating back to the late 1980's. Initially developed at Southampton University and commercialized by York Systems. DTS is based upon changes in optical properties of commercial telecom fibers as a function of temperature, which can be detected by light from a laser pulse backscattered back to a detector at the start of fiber. The initial technology uses Raman scattering in a multimode fiber, which changes the wavelength and amplitude of Stoke's and Anti-stokes reflected light. Over the course of 25 years the accuracy and spatial resolution of Raman based instruments have continued to improve, while costs for the surface electronics have also declined. The temperature resolution is a function of integration time, with resolutions of 0.03 °C after measurement integration over 15 minutes commonly quoted among several different instrument manufacturers. Typically spatial resolution is 1 m, with Schlumberger's Sensa unit exhibiting 25 cm resolution and the Silixa Ultima (Silixa Ltd, Elstree, UK) having 12.5 cm resolution. DTS monitoring units have also been made to operate under low power (<40 W) and transmit data back to a central logging computer either through a radiolink or Ethernet connection.

For monitoring over large spatial extents the advantages of DTS over traditional discrete sensors is readily apparent. Where each discrete temperature sensor such as a thermistor or RTD requires between 2 to 4 insulated copper conductors to be connected to a data logger or multiplexor, a distributed fiber-optic cable contains a glass strand the size of a hair that can provide thousands of measurements. Limitations of the DTS arise from the difficulty in performing absolute calibrations on the systems response, which can vary is a function of laser diode performance within the DTS unit. In practice having zones of the fiber referenced at specific locations to known temperatures permits continuous calibration of the fiber-optic data and allows for accuracies of ±0.3 °C at thousands of locations. While high quality thermistors and RTDs can be calibrated to better than 0.01 °C, it rapidly becomes impossible to deploy discrete sensors at the same spatial density that can be done with optical fibers.

Raman based DTS operate using 50/125 micron multimode optical fibers. The most widely deployed form-factor for DTS fibers is within a gel-filled fiber-in-metal or polymer tube (FIMT). The FIMT can be further encased in a ¼" stainless jacket and then in some cases a polymer jacket is wrapped outside of the ¼" tube. The outer polymer provides additional crush resistance and protection from pinching when the cable is clamped to tubing strings and also can be used to insulate the cable to facilitate electrical measurements in the same area.

The optical fiber coatings dictate the working temperature of the fibers. For installations at temperatures below 85 °C standard acrylate coatings are appropriate. A higher temperature acrylate coating is available for use at temperatures up to 150 °C. At temperatures beyond 150 °C and below 300 °C a polyimide coating is appropriate. Temperatures above this point use metal coated fibers, which are both difficult to fabricate in the long-lengths needed for boreholes and even more difficult to splice under field conditions. A condition known as hydrogen darkening, where hydrogen diffuses into fibers and leads to a loss in optical transmission is common in higher temperature where hydrogen is present. Several cable construction techniques are used to counter the effects of hydrogen darkening. The gels selected to encapsulate the fibers can contain a hydrogen scavenging material. This is a property of Sepigel, one of the most commonly used gels in downhole FIMT construction. Carbon coating on cables below 200 °C are seen as beneficial, whereas at higher temperatures, the hydrogen diffuses quickly through the carbon coating.

An example of the use of fiber-optic data can be found in the characterization of borehole NC-EWDP-24PB as part of the DOE funded OSTI program (Freifeld et al, 2006). Figure 33 shows thermal traces taken from NC-EWDP-24PB under progressive additions of heat to the formation. The dark-blue line at the bottom is the baseline temperature profile. All other profiles were taken during heating; the first three profiles were taken at 15-minute intervals, the fourth profile taken 45 minutes later, and all subsequent profiles at one-hour intervals. What stands out most significantly are cooling trends indicative of high advective fluid flow in the subsurface. This data can be interpreted using a coupled conductive/convective transport model to estimate rates of fluid flow. This is just one example of the quantitative use of DTS data for investigating transport of fluids in the subsurface. Without the movement of fluids, heat-pulse thermal perturbations can be used to infer thermal conductivity, as was done in Freifeld et al. (2008), to estimate rock thermal properties in a mineral exploration boring in Canada.

9.6.2 Distributed Acoustic Sensing

Distributed acoustic sensing (DAS) uses continuous telecom fiber optic cable for measurement of ground motion. Discrete fiber optic sensors using a Bragg diffraction grating have been in RD&D and field testing for over 18 years with geophysical applications at least 15 years old (e.g. Bostick 2000). Weatherford has marketed an FBG (fiber Bragg grating) product called Clarion, however it has not gained significant market usage since its introduction. However developments in recent years have sought to remove the need for point sensors by using the fiber cable itself as a sensor (Mestayer et al, 2012a, 2012b, Miller et. al., 2012). Through Rayleigh scattering, light transmitted down the cable will continuously backscatter or 'echo' energy which can be sensed. Since light in an optical fiber travels at about 0.2 m/ns, a 10-nanosecond pulse of light occupies about 2 meters in the fiber as it propagates.

The potential of DAS is that each 10 nanoseconds of time in the optical echo-response can be associated with reflections coming from a 1-meter portion of the fiber (two-way time of 10 ns). By generating a repeated pulse every 100 μsec and continuously processing the returned optical signal, one can, in principle, interrogate each meter of up to 10 km fiber at a 10 kHz sample rate. Local changes in the optical backscatter due to changes in the environment of the fiber can thus become the basis for using the fiber as a continuous array of sensors with nearly continuous sampling in both space and time. Since the technology for deploying fiber optic cable in boreholes is well-developed for thermal sensing (distributed temperature sensing, or DTS), a DAS system has the potential of having thousands of sensors permanently deployed in the subsurface, at relatively low cost. Most DAS systems use single-mode fiber, as opposed to the multi-mode fiber typically used for DTS, but the type of fiber does not affect deployment, and multiple fibers are easily deployed in a single capillary tube. Some manufacturers are currently testing the use of multi-mode fiber for performing DAS testing.

For our proposed salt testing we considered the possibility that be collocating DAS fibers with DTS fibers it would be possible to measure increases in seismic velocity that would accompany compacting and fusing of the salt grains over time during heating. Given that the two fibers can be deployed together, the sensing infrastructure of combined DTS and DAS systems is no greater than adding an extra hair-sized fiber to a cable.

9.6.3 Fiber Optic Scoping Studies

As part of scoping studies at LBNL for use of distributed fiber-optics to monitor thermal processes in rock salt, a small heating experiment was set up inside a 25 gallon batch can. Co-located with a series of RTDs were numerous lengths of fiber-optic cable for performing DTS measurements as shown in Figure 34. A central vertical heater was used to apply uniform heating along the center vertical axis of the can. Figure 35 shows the experimental set –up with a close-up of the top showing the RTD wires and optical fibers penetrating into the salt. Figure 4 shows three layers of estimated temperatures using the fiber-optic data. Comparisons between the RTD and fiber-optic temperature data can be used to assess the limitations of the two methods.

A numerical model was set up using the TOUGH heat and mass transport code and used to model the thermal response observed during heating tests in the Batch Cans. Figure 36 shows an example of using data from two different radii to estimate the thermal conductivity. The variability in the estimates is attributable to the large variability in salt crystal size and heterogeneity in the packing.

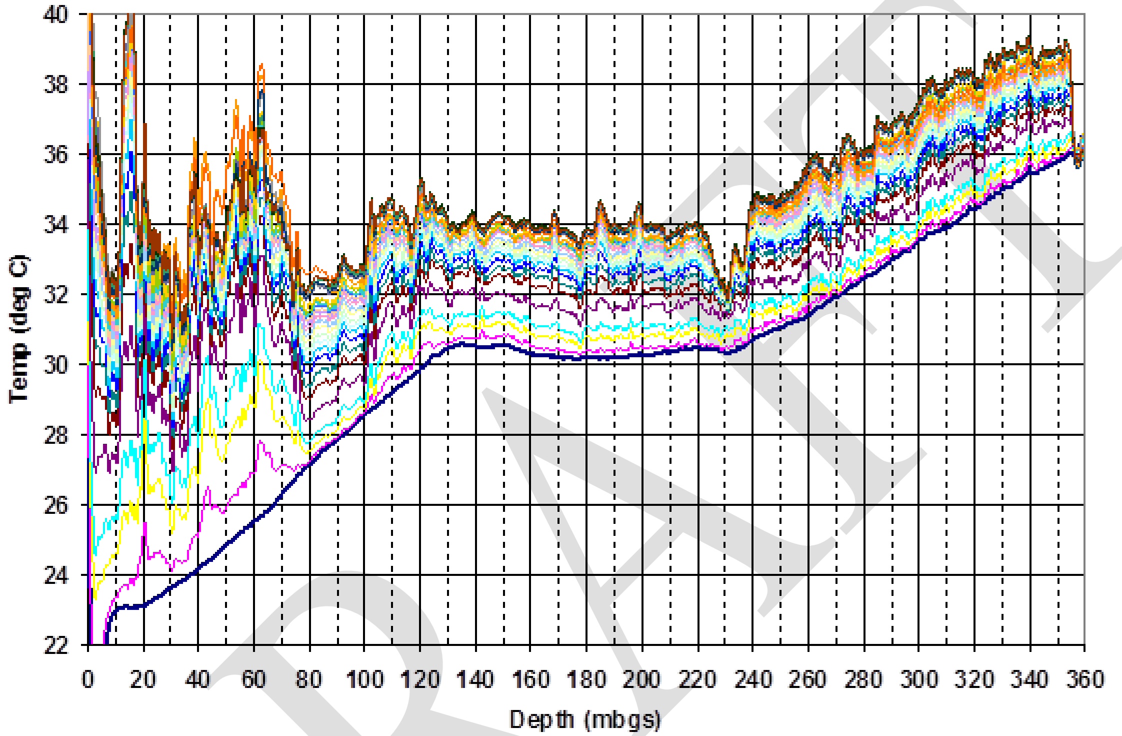

Figure 33. Thermal logs acquired during operation of the DTS in NC-EWDP-24PB.

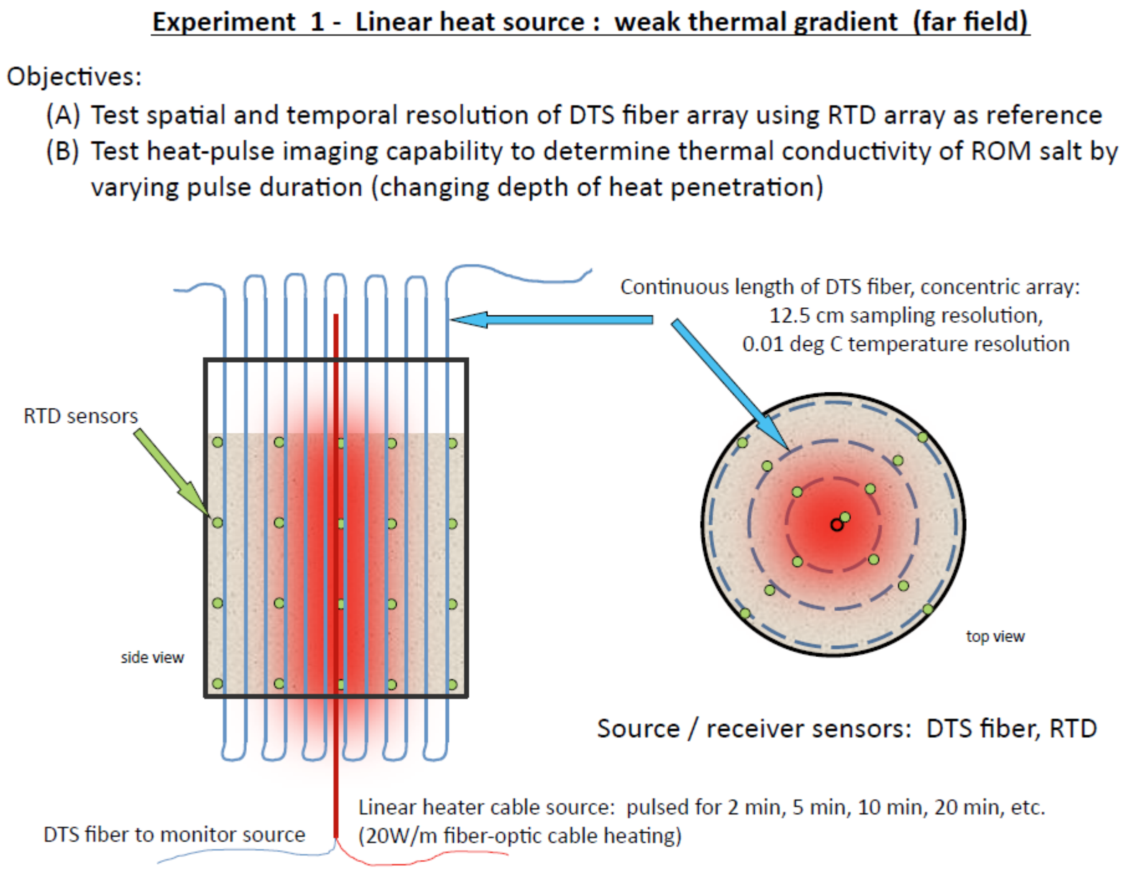

Figure 34. Schematic of the Batch Can Fiber-Optic Salt Test

Figure 35. Experimental set-up of the Fiber-Optic DTS Salt Heater Experiments.

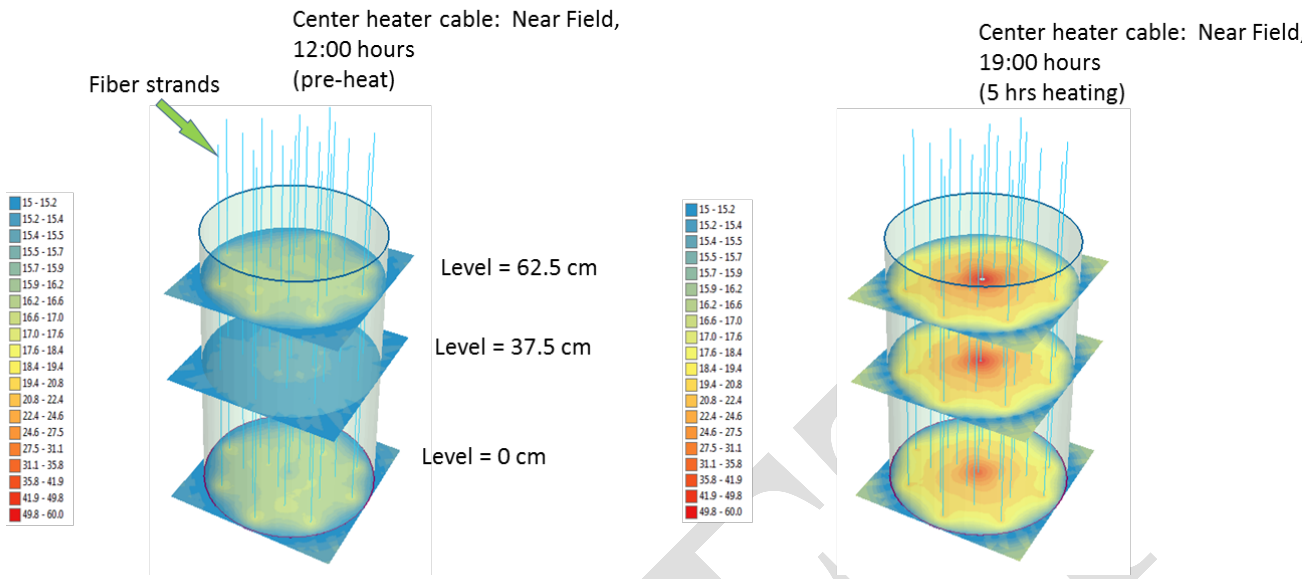

Figure 36. Data Acquired using the Fiber-Optic System prior to and after Heating for 5 hours.

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