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Field-scale Thermal Testing in a Generic Salt Disposal Environment Underground Research Laboratory (URL): Delineation of Principal Purpose, Objectives, and Hypotheses

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General URL Purpose and Import to a Generic Investigation Program within the Used Fuel Disposition Campaign

Consistent with the generic disposal strategy being implemented by DOE Nuclear Energy (DOE-NE) Used Fuel Disposition (UFD) Campaign, the purposes of doing field testing in a generic salt Underground Research Laboratory (URL) are to:

1. Support/confirm the bases of a safety case for a generic (non-site specific) geologic repository in salt host rock; to facilitate resolution of identified uncertainties/issues;
2. Enhance the technical bases (increase confidence) for safe disposal of high-heat generating waste in a generic salt repository (the ultimate long-term goal);
3. Develop science and engineering tools and capabilities that will facilitate future site-specific work.

Note that the UFD Campaign focus is on generic disposal of used (or spent) nuclear fuel (generally at the high end of heat generating waste forms), but extends to disposal considerations for high-level waste (HLW) also.

This report outlines a phased approach to thermal field testing that will allow flexibility to adjust plans as UFD Campaign resources evolve. This phased approach involves phasing both the scale and level of configuration complexity of the field tests and starts with an idealized, smaller-scale borehole test to constrain specific field properties and processes, and then progresses incrementally to larger in-drift configurations that represent more realistic emplacement schemes all the way up to full-scale demonstration testing. Proposed strawman tests for each of these scales are described in the next section. The detailed background information and rationale for the proposed approach and objectives for field testing within the UFD Campaign are presented in an attachment below the strawman tests descriptions.

A. Strawman for Borehole Field Thermal Test

Background

The amount of brine present in domal salt formation is far less than in bedded salts (e.g., 0.01 to 0.1% compared with 1 to 3%). In salt domes, shear deformation associated with diapirism has caused existing brine to coalesce, leading to flow and expulsion. Brine migration behavior was investigated in bedded salt at WIPP (Nowak and McTigue 1987, SAND87-0880), and in domal salt at Asse (Coyle et al. 1987, BMI/ONWI-624). Test methods were not standardized, and the tests involved large diameter boreholes (17 to 36 in. diameter) and large apparatus. The tested intervals were proximal to mined openings (within approximately 1 diameter) where in situ stresses are redistributed due to excavation. The tests showed that (1) brine inflow rates can range over at least 2 orders of magnitude for domal vs. bedded salt, (2) that brine inflow is strongly associated with clay and interbedded permeable layers in bedded salt, and (3) that measurement systems can readily collect very small quantities of moisture over time frames of 2 years or longer. Brine inflow rates declined slightly with time in both test series, but neither series approached a state of apparent depletion. This range of flow magnitude could be significant to repository design and performance assessment, especially if inflow rates can be predicted using stratigraphic and geomechanical inputs, and can be shown to approach zero in a predictable manner.

Test Concept

A small, standardized heater test fielded in vertical and horizontal boreholes (both in the DRZ and away from the mechanical influence of mined openings—e.g., three diameters), would address generic open issues from these previous tests, provide fundamental data for the local salt system of interest, and would be low cost and efficient to deploy as a standard modular test. The test would be designed with long-lived components and simple instrumentation so that it 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 that tests would be readily repeatable with different thermal and mechanical loading conditions, and in different salt formations. This standardized test design could be implemented in salt formations with low and high water content, possibly with international collaboration.

The test will consist of an electrically heated, instrumented probe with a packer/plug system to isolate the test interval (Figure 1). Depending on local lithology, the test may be implemented in either a vertical or horizontal configuration. The basic probe configuration will include heaters, temperature sensors, dry-gas moisture collection, borehole closure measurements, 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 for heated and unheated conditions to compare HM with THM responses. Because of the flexibility of this test configuration, it could be used to evaluate the range of possible thermal loads, as well as effects of varying heating and cooling rates.

One variant of the test could have an over-core slot drilled around the test borehole, prior to drilling the test borehole. The over-cored slot would be filled immediately with impermeable, bonding material that forms a zero-migration boundary. This variant 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 and bulk deformation of the salt.

In a previous workshop (Sevougian et al. 2013, see Table 7-2) this test was found to have first-order influence on mechanical and hydrologic research questions, and THM coupling (Issues 15, 16 and 17). It was also considered to have high relevance to Issues 39 and 40, concerning instrumentation development and methods for in situ testing and characterization. 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.

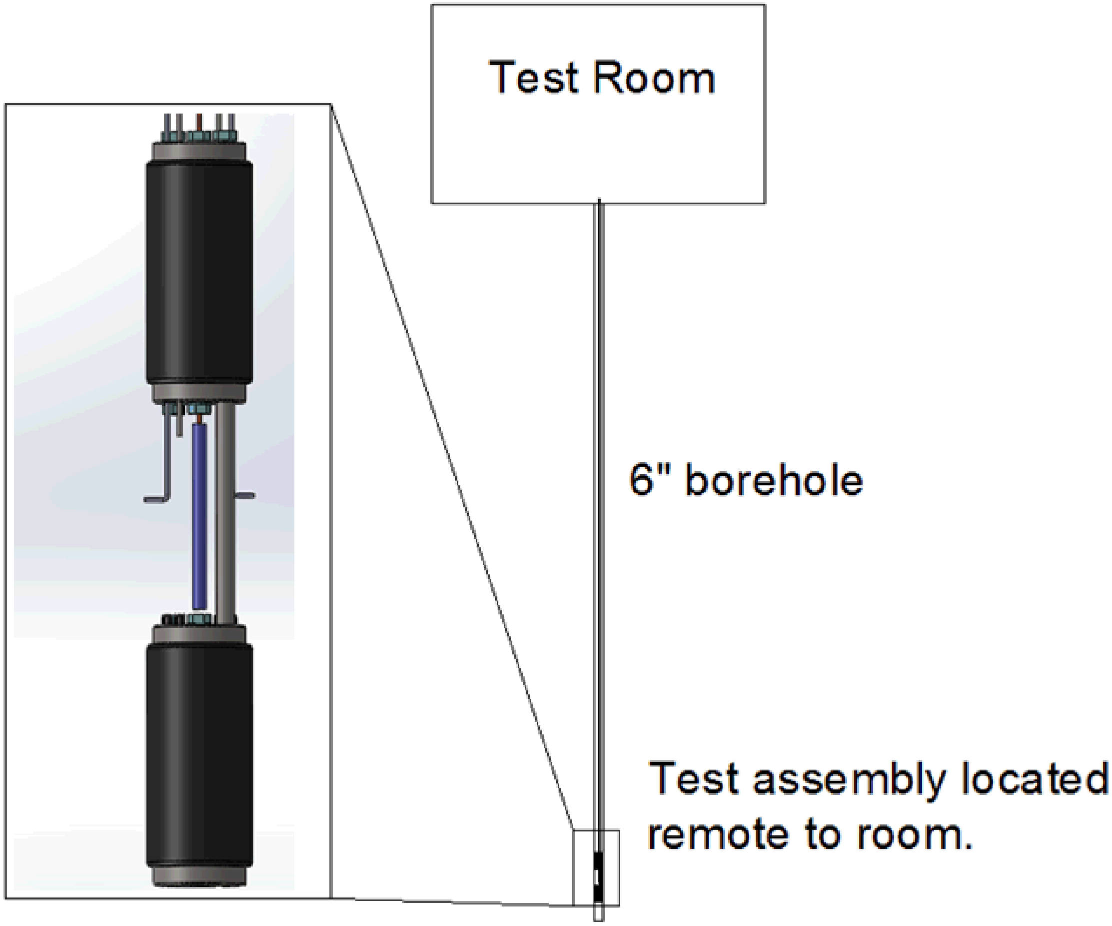


Figure 1. Simple schematic of standardized borehole heater test in salt, shown with borehole in vertical orientation.

B. Strawman for Intermediate Drift Test (truncated drift and 1 or 2 heaters)

Background

A modular standard borehole test (see above) provides an efficient and relatively low cost field test that can be implemented with various thermal loads to evaluate primarily thermal and hydrological processes driven by the thermal-mechanical perturbation of the intact salt host rock. This type of a modular test does not allow extraction of data on fundamental processes related to the major elements of a disposal concept (e.g., placement of waste containers on the floor, crushed salt backfill covering canisters, and ventilation effects from access drifts). A thermal test within a truncated (i.e., dead-end) drift can include effects from elements of a disposal concept to allow extraction of data on fundamental processes, evaluation of multiple thermal loads and physical scales, and evaluation of test controls (sealing of drift), test instrumentation layout and effectiveness of methodologies. Such intermediate scale testing provides a bridge to larger-scale testing (e.g., 1/2- to full-scale – see strawman below) that captures specifics of potential repository design/configuration as closely as possible, but which is more complex in nature, has a duration of up to a decade, and is more costly to implement.

For example, it was found in a full-scale thermal test with longitudinally emplaced canister heaters covered with crushed salt backfill in domal salt at Asse, Germany, that 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 thermal drift allowed ready dilution with gas from the access drift. Estimates of water remaining (from humidity measures) 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 much fundamental data and constraints on processes were gained 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. In addition to fundamental data on behavior of potential configurations, intermediate-scale idealized thermal tests in truncated drifts would allow development of methodology to constrain quantitatively such thermal hydrologic processes.

Test Concept

The intermediate test concept is a single truncated drift with a canister heater (or two) placed on the floor, backfilled with crushed salt, and sealed using a number of bulkheads for isolation from ventilation. This drift would be about 30 m deep with the canister(s) in the last 10 (to 15) m of the drift and a series of bulkheads (3 or 4 to provide 2 or 3 air gaps) placed in the outer 20 (15) m to isolate/quantify ventilation effects from the test. Bulkheads in the test should serve to isolate the drift at least to the extent of the primary gas transfer being only through the DRZ. The test could be implemented in multiple variations to evaluate scaling effects directly, or to evaluate effects at various thermal loads, as discussed below.

Isolation of the test from ventilation effects does not mean complete sealing the test drift; rather the bulkheads would be designed so that flow is limited to that through the DRZ around the excavation with intermediate air spaces between the bulkheads. Pressure and humidity sensors within boreholes in the DRZ would be useful for monitoring/measuring parametric changes due to flow therein. Using a number of bulkheads provides air gaps for more stable thermal isolation of the test drift from external ambient conditions. The bulkheads would also include monitored “valves” to allow for increasing the flow through them beyond the baseline amount flowing through the DRZ. This would allow for quantification of various ventilation scenarios on the test itself. Making flow measurements across a range of air-flow conditions would allow extrapolation to a no-flow condition and provide an method to quantify the flow through the DRZ. If a fully sealed test would be desirable, the bulkhead(s) would need to penetrate the DRZ and seal that zone to the permeability level of the intact host rock. This decision would be made within the context of an operating field thermal testing program.

The excavation of the drift can be full scale in terms of its diameter/cross-sectional dimensions, but could also be constructed and implemented at 1/2-scale or 1/4 –scale in a relatively straightforward manner. Consideration of specific excavation methods that would facilitate sealing/isolating the drift would also prove useful. Implementing such a test across these various large-scales would allow direct evaluation of scale effects for assessment/validation of scaling relations used for test design of a large-scale configuration test such as described in the next section. Observations at these various scales provide data to test models of the coupled processes and evaluate different model behavior predicted at these various scales. Additionally this testing would provide a clear indication of whether or not a large-scale configuration test that was smaller than full-scale would be expected to have major scale artifacts or not.

Lastly, these tests could be implemented for a range of thermal loading and evaluate effects of various cooling rates on the drift configuration as well as the host rock at scales that would be directly relevant to emplacement drifts. Comparison of two same-scale truncated drifts with thermal loads representing high-level waste (~500 W) and representing spent nuclear fuel (~5 kW) would be facilitated by the idealized configuration of the test layout. Beyond the flexibility and efficiency of fielding such intermediate-scale tests, such testing would also provide valuable *in-situ* experience for designing and implementing a large-scale field test that would capture more of the specific layout elements of a potential repository configuration as discussed in the next section.

C. Strawman for Large-Scale (1/4-, 1/2- or full-scale) Thermal Test

Background

The high thermal conductivity of intact geologic salt is one of the reasons for pursuing a salt repository for heat-generating waste. Emplacement of waste into boreholes would maximize the conduction of heat from waste canisters to the intact salt. In-drift disposal has been proposed as an alternative to borehole emplacement, as it avoids complications associated with drilling large-diameter boreholes or placing heavy waste canisters into boreholes. 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).

For borehole emplacement in bedded salt, Project Salt Vault in the 1960s (Bradshaw and McClain, 1971), the Waste Isolation Pilot Plant 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 of vertical boreholes in the floor, 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.

Compared to borehole heater tests in salt, there have been fewer in-drift heater tests in salt. At WIPP (bedded salt), TRU 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). 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).

These latter tests indicate that full-scale *in situ* experiments elucidate the important physical processes concerning emplacement of heat-generating waste in salt repositories using the in-drift disposal approach. For generic bedded salt repository R&D investigations, half-scale (or even quarter-scale) test designs would address many of the same issues, as well as offer a cost efficient approach to the upper end of a staged program of field testing. Fielding of a full-scale field test would be possible, but may be most appropriate for implementation within a site specific program.

Test Concepts

One primary difference between bedded and domal salt is brine content (both in the intact and run-of-mine salt), with domal salt containing about one tenth the brine of bedded salt (presence of interbeds of dissimilar mineralogy is another difference). Single-heater borehole heater tests (see above) would provide information on the brine content and release mechanisms from the intact salt, but will not generally include the effects of the mined waste emplacement drift. Intermediate-scale tests (single heater in smaller drifts—see above) would address some of the configuration aspects of placing a canister(s) within drifts backfilled with crushed salt, but are not designed to evaluate all processes specific to a particular emplacement concept. Larger scale, layout specific tests provide a 3-dimensional test configuration that facilitates gathering data for model benchmarking and improving understanding in of the following concepts: (1) the quantity and nature of inflow of brine into the emplacement drifts and the associated DRZ, (2) the effects of mine ventilation on the emplacement drift, and 3) the behavior of the run-of-mine salt emplaced on waste in the drift.

Brine inflow into both mined and bored drifts under isothermal conditions has been monitored in the WIPP BSEP (Deal et al., 1995) and Room Q (Jensen et al., 1993) experiments. Additional investigation of brine inflow via the DRZ and brine inflow into heated drifts in a large-scale (1/2- or ¼- scale) test for a generic repository configuration would elucidate the contribution and fate of brine related to the heated excavation (which is expected to be different than simply a scaled-up borehole, due to geometry, in-drift configuration, and mining damage effects). From previous testing, open issues remain because even though brine inflow to heated rooms was observed in heater tests at WIPP, it was not quantified or controlled. Evaluation of brine inflow into a large-scale test with a potential disposal drift configuration would entail specific design aspects such as heater canisters placed (a) directly on the floor, (b) into grooves or troughs cut into the floor, or (c) upon a bed of crushed salt on top of the drift floor. In each of these possible placements, the canisters would be covered with crushed salt. A large scale disposal configuration thermal test using any (or all) of these options 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.

The 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). 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 heater tests to determine if those fractures represent significant sources and/or reservoirs for brine around the excavation.

Isolating an excavated drift from active mine ventilation remains a challenge (Jensen et al., 1993), due to significant gas flow through the DRZ. The effect ventilation has on the heated emplacement drift during repository operations (and during a thermal test) may be significant. The challenge of quantifying such effect during a thermal test would 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 bulkheads penetrate the DRZ and cut off connected DRZ pathways to the external drifts. As discussed above, bulkhead design would be evaluated within more idealized controlled drifts (e.g., dead-end drifts with controlled levels of mine ventilation) that would be used to observe the dry-out or accumulation of brine in the DRZ.

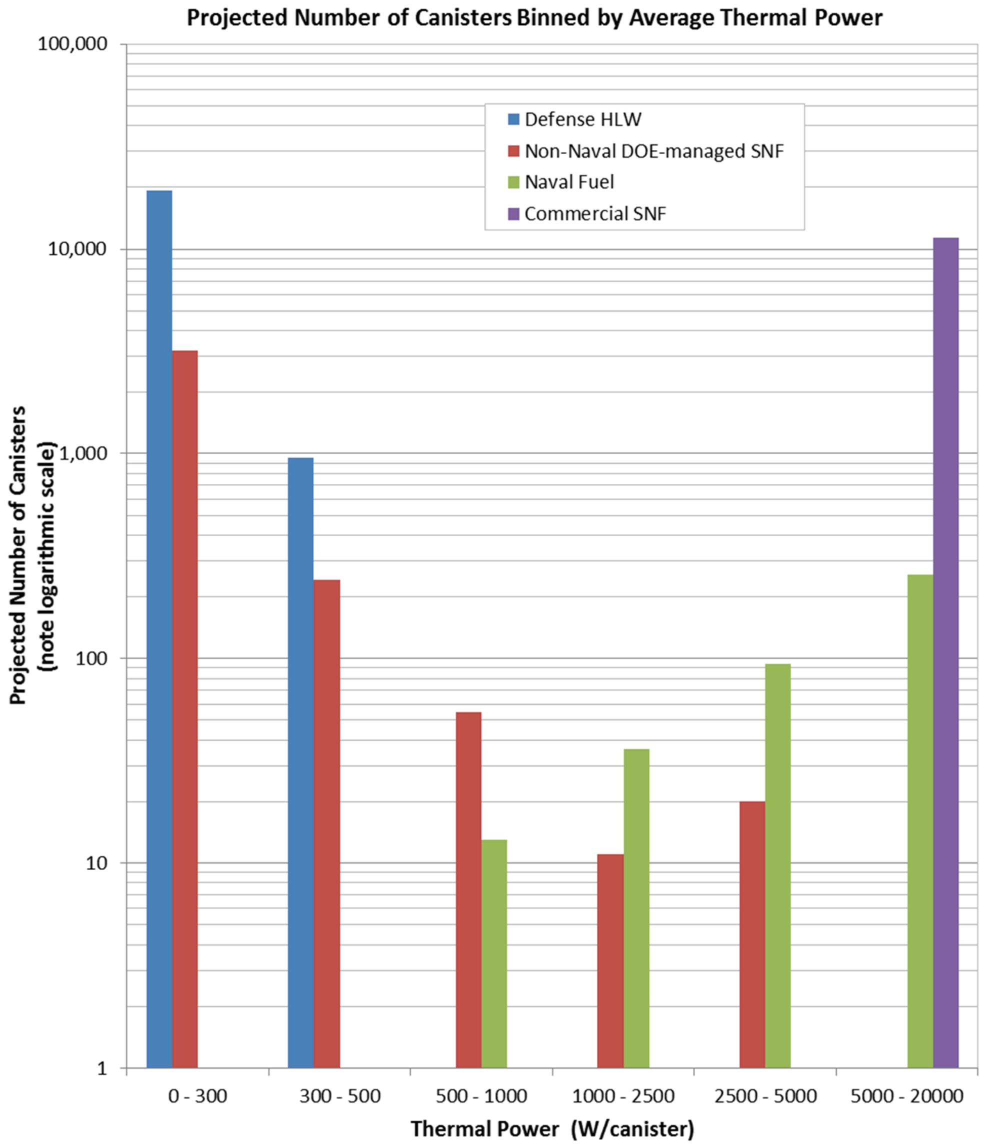
Run-of-mine salt has distinctly different mechanical, thermal, and hydrologic behavior from intact salt. These large-scale tests (and the idealized drift tests discussed above) would be conducted to evaluate the evolution of run-of-mine salt properties under repository-relevant stress and temperature conditions, potentially both for pre-closure ventilation conditions and “sealed” ventilation conditions that may be more relevant to post-closure behavior. For example, monitoring the evolution of the run-of-mine salt porosity and permeability resulting from both thermal 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.

Attachment: Detailed Background and Rationale for Approach and Objectives to Field Testing within the UFD Campaign

Carefully considered science and engineering field studies have the potential to reinforce the current strong technical basis for geologic disposal 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 R&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.

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 directly coupled to a specific bedded salt deposit. 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 defense high-level waste (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 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 waste form thermal output, and specific properties of 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 Defense HLW Canisters Binned by Average Thermal Power (From DOE 2014, Figure 3, with data sources: Carter and Leduc 2013; SNL 2014.)

In addition, 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 (minimums of hundreds/thousands of years for post-closure). Therefore, consideration of heating rates and cooling rates are also primary in order to assess what processes may be affected/generated by the rates themselves versus the absolute peak temperature. This may be particularly the case for the cooling rates as these will be very gradual in a post-closure salt repository due to the gradual decay of heat generating radionuclides and the large thermal mass that will be extant in the host rock. A fast cooling rate (i.e., shutting off the heat input) may induce mechanical stress of a very different nature than would be expected for long slow cooling. In addition, processes that occur slowly and that perhaps need long times (hundreds to thousands of years) to reach threshold changes are inherently somewhat inscrutable in such shorter term testing. Such considerations would be handled directly in both the pre-test planning/analyses and post-test analyses, but are central to delineating clear objectives for post-closure studies in a generic salt repository.

For investigating pre-closure aspects of the system, the operational functions should be considered to evaluate the duration of waste emplacement within drifts prior to backfilling and sealing those drifts. Processes occurring within this preclosure affect the initial conditions of the post-closure period. Representing post-closure evolution accurately is facilitated by a robust understanding of the effects of heating during pre-closure and starts with accurate initial post-closure conditions.

Approach to Delineate Objectives within a Risk-informed Safety Case (i.e., FEPs-based approach)

Evaluation of issues in generic salt disposal research within the context of the safety case was undertaken at a workshop using a methodology for rating importance of issues relative to their impact on postclosure safety, preclosure safety and design, or in demonstrating confidence in the performance of those safety/design aspects (used for models and testing data) (Sevougian et al., 2013, see Section 5 therein). At a high level the general objectives of field-scale testing within the context of a safety case include:

- Address features, events, and processes (FEPs): Confirm our understanding and ability to model features, events and processes that affect the performance of a deep geologic repository for heat generating radioactive waste in salt.
- Building confidence: Build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods.
- International collaboration: Enhance technical credibility through engagement of the international community
- Evaluating concepts: Evaluate designs and operational practices
- Validating models: Predict and confirm evolution of processes at large scales

Follow-on work (Sevougian and MacKinnon, 2014) from the 2013 workshop further delineated the context of how any study would support the Safety Case for a generic salt repository in Figure 3.

In many cases, the workshop investigations showed issues supported more than one of the above areas. For example, Table 5-4 (Sevougian et al., 2013) shows that the modeling issues support both post-closure safety and confidence building areas in conjunction with field testing. The analyses done in the workshop (Table 7-2; Sevougian et al., 2013) show some changes to priorities suggested by the breakout groups, but the modeling issues remained as rated prior to the workshop. This is one area that is a key objective of a field thermal test based on evaluation of the FEPs related to a generic salt repository. Not only would such a test serve to test our conceptual models of how heat-generating wastes may affect the mechanical, hydrological, and chemical behaviors in such a system, but it would also provide a fertile data set for testing the accuracy of our quantitative models. This is one specific key example of and objective defined within the safety case context. Additional key objectives are given below, followed by some of the specific questions a field thermal test would be used to address.

Support Safety Case

- **Support Repository Design, Construction, and Operations**
  - Support Underground Layout and Drift Design
  - Support Ventilation and Drainage Systems Design
  - Support Access Shafts/Drifts Design
  - Support Backfill Design
  - Support Seal System Design
  - Support Ground Support Design
  - Support Power Supply Design
  - Support Waste Canister Design
  - Support Operations
- **Support Repository System Technical Bases**
  - Support EBS Technical Basis
  - Support Geosphere Technical Basis (including Site Characterization)
  - Support Biosphere Technical Basis
- **Support Preclosure Safety Evaluation**
- **Support Postclosure 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

Figure 3. Safety case objectives hierarchy (from Figure 4, Sevougian MacKinnon, 2014).

Based on considerations outlined above, the key objectives for a field scale thermal test in salt (i.e., heating a volume of backfill salt and formation salt-both DRZ and intact host rock) include:

- 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
  - disturbed zone
  - backfill salt
- Explicit thermal-hydrologic-mechanical-chemical (THMC) model validation
- Develop technology and methodology needed for underground monitoring/measurement of THMC processes
- Demonstration of design and operations concept(s) for generic salt repositories including a range of heat-generating waste forms

- Build confidence for generic salt repository safety case
- Enhance communications with stakeholders
- International collaboration on R&D and operations

Examples of questions/theses to be addressed in a field-scale thermal test include:

1. Does decay heat substantially change rock characteristics and brine distribution/chemistry within intact host rock, disturbed rock zone (DRZ), and/or salt backfill in such a way that post-closure performance would be impacted?
2. 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?
3. 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?
4. 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?
5. 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?

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 number of considerations for test design would be incorporated into the test planning. A test would be designed to maximize the general applicability of data collected during testing using careful choice of test location and instruments 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 mechanical, hydrological, and chemical properties of salt are temperature-dependent. An isothermal test 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 relatively accurately represented, cooling rates are likely to be much faster than for any repository system that will cool over hundreds/thousands of years.

Mechanical, hydrological, chemical and thermal processes are quite coupled in salt with large overlap in the durations of major thermally-driven HMC variations. The duration of a test will be related to the objectives being addressed, specifically 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. As discussed above, 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 related to test duration would stem from clearly defined objectives for a test for a generic salt repository.

A program of field testing of thermally driven processes generally would consist of tests occurring over a range of spatial scales to address directly aspects of scaling of processes. Laboratory-scale tests are small scale and allow individual processes to be isolated and controlled more easily with generally lower cost—typically much less than field-scale tests. Laboratory testing for properties, parameters, and highly-controlled isolation of processes should be a continuous, integral part of planning a field-scale thermal test. Field-scale tests may elucidate processes that are tied to the scale of the native geology, or to the scale of the drift or DRZ.

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. This last scale of field test may be more appropriate to reserve until an actual site is selected for detailed analyses as a potential repository location. Fielding a half-scale (or possibly even a quarter-scale) test would satisfy virtually all of the same testing objectives, provide results that are likely more applicable generically, and be much less expensive.

For large-scale tests such as a ½-scale test, heat transfer and thermally-driven hydrologic and chemical processes (n.b., this refers to the conceptual aspects even though magnitudes of parametric variation may be slightly different) would be very close to those expected for a full-scale test, but care would be taken in the test design to implement the test to appropriately capture mechanical responses as close to those expected in a full-scale test as possible. Because of the coupled nature of the hydrology to the mechanical behavior, this is one area where parametric deviations would be expected from full-scale testing, but any conceptual deviations are expected to be negligible and would be evaluated with THMC models for test setup.

Numerical models facilitate evaluating scenarios and hypotheses, and demonstrate our understanding of the physical-chemical system. Development and application of THMC models to advance/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/cooling rates, boundary conditions, and coupled effects. These models would be developed and used in an iterative fashion with staged test design. Short, small-scale laboratory tests can be quickly designed and run to collect data for parameterization or validation of numerical models at various spatial scales.

To facilitate achieving the thermal test objectives and collect relevant data to answer test questions, field-testing principles and concepts will be considered including:

- questions to be answered by the test (i.e., hypotheses to be addressed)
- appropriate scale – spatial and temporal
- heater power (i.e., concept should be consistent with an overall acceptable and plausible repository layout and operation, including Waste package heat output; Waste package spacing; Ventilation heat removal and established thermal constraints on the near field host rock and engineered barriers)
    - rate
    - duration
    - rate of decrease to ambient
- types of observations/measurements to be made (what data do we need to collect to confirm or refute our initial hypotheses?)
- needed accuracy and precision for each measurement type (i.e., data quality objectives)
- test measurement requirements
    - initial and boundary conditions for thermal, hydrologic, mechanical, and chemical systems
    - density (spatial and temporal) of instrumentation/measurements

    - identification/evaluation/control of artifacts
        - e.g., isolation of test location from ventilation
- test physical controls and operation, including
    - engineered safety
    - operational protocols
    - personnel roles and responsibilities
    - data collection methodology
        - local vs remote
        - backup systems

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