Department of Energy
Carlsbad Field Office
P. O. Box 3090
Carlsbad, New Mexico 88221
April 30, 2019

Ms. Lee Ann B. Veal, Director
Radiation Protection Division
Center for Federal Regulation
Environmental Protection Agency
1200 Pennsylvania Ave. N. W.
Washington DC 20460

Subject: Response to the EPA Letter dated March 26, 2019 and Status on the Salt Disposal Investigation and Salt Defense Disposal Investigation at the Waste Isolation Pilot Plant

References:
1) SDI Heater Testing Long-Term Thermal Effects Calculation, May 27, 2011, AP-156 Revision 0, ERMS-555622, Sandia National Laboratories (SNL 2011)

2) DOE Letter CBFO:OESH:RLP:ANC:11-1312:UFC 5486.00 from Edward Ziemianski, Interim Manager, to Jonathan Edwards, Director, dated August 11, 2011, Subject: Notification of Intent to Begin the Salt Disposal Investigations (U.S. DOE 2011)

3) DOE Letter CBFO:OESH:GTB:ANC:12-0743:UFC 5486.00 from Jose Franco, CBFO Manager, to Jonathan Edwards, Director, dated June 20, 2012, Subject: Notification of Revisions to the Salt Disposal Investigations Testing Concepts (U.S. DOE 2012)

4) DOE Letter CBFO:OESH:RLP:HL:13-0800:UFC 5400.00 from Jose Franco, CBFO Manager, to Jonathan Edwards, Director, dated December 12, 2013, Subject: Notification of Intent to Begin the Salt Defense Disposal Investigation (U.S. DOE 2013)

5) DOE Letter CBFO:OEP:GTB:AC:17-1085:UFC 5486.00 from Todd Shrader, CBFO Manager, to Lee Ann B. Veal, Director, dated November 16, 2017; Subject: Waste Isolation Pilot Plant 2016/2017 Annual Change Report (U.S. DOE 2017)

6) DOE Letter CBFO:OEP:MRB:AC:18-0366:UFC 5486.00 from Todd Shrader, CBFO Manager, to Lee Ann B. Veal, Director, dated November 14, 2018: Subject: Waste Isolation Pilot Plant 2017/2018 Annual Change Report (U.S. DOE 2018)

Dear Ms. Veal:

The purpose of this correspondence is to provide a response to the Environmental Protection Agency (EPA) letter dated March 26, 2019. The above references provide additional background related to the non-Waste Isolation Pilot Plant (WIPP) underground thermal experiments, Salt Disposal Investigation (SDI) and Salt Defense Disposal Investigation (SDDI). The Department of Energy/Carlsbad Field Office (DOE/CBFO) understands the EPA expectations related to the EPA review of non-WIPP underground experiments and DOE/CBFO continues to plan to provide EPA final drift-scale heater test design(s) for review.

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Currently, small-scale prototype thermal tests are being conducted primarily for the purpose of refining items such as, but not limited to, equipment, sensors, methodologies, and systems for the final designs for future drift-scale thermal tests. The prototype tests do not represent the final drift-scale SDI/SDDI designs.

There are three prototype tests currently being conducted at WIPP: (1) small-scale prototype canister (singular) heating test; (2) small-diameter borehole testing in an existing borehole; and (3) small-diameter (about 5 inches in diameter) borehole thermal tests. These prototype tests are lower in thermal heat load, smaller in scale, and shorter in duration than drift-scale tests. The results for these prototyping tests will provide input for refinements in types of equipment, sealing techniques between heater apparatus and the borehole and salt material, and the use of various geophysical sensors to observe the response of the salt to heat. The results of these prototype tests will also be used to collect data on a small-scale related to the thermal response of salt to heat (e.g., brine liberation and chemistry) and to refine optimal equipment and system configurations for the more elaborate drift-scale final design.

Several documents have been provided to EPA that describe the status and the progression of intermediate small-scale prototype tests to the larger drift-scale tests. In a December 12, 2013 letter from Franco to Edwards (U.S. DOE 2013), the DOE provided the EPA with a notice of intent to begin the drift-scale SDDI part of the investigation and provided the EPA with an analysis titled, "WIPP Performance Impacts Associated with SDDI" in addition to the test specifications for the SDDI thermal test in WIPP. This document supported the original 2011 analysis that demonstrated the SDI testing plan has negligible impact to the WIPP facility disposal operations. The three prototyping tests discussed above are much smaller in scale, shorter in time duration, and lower in thermal heat load than the drift-scale SDI or SDDI thermal tests and, therefore, the potential impact of the small-scale prototype tests are bounded by the existing impact analysis and have negligible impact on the WIPP facility disposal operations and long-term repository performance.

Enclosed is the April 30, 2015, "Test Proposal Document for Phased Field Thermal Testing in Salt" (Enclosure 1) developed by Los Alamos National, Sandia, and Lawrence Berkeley National laboratories. This research is part of the generic research being performed by the DOE Office of Nuclear Energy (DOE-NE) Used Fuel Disposition campaign to explore geologic disposal in salt, granite, clay/shale, and deep boreholes. Heater canister prototype testing (#1 described above) has been ongoing at the WIPP in the underground drift location of West-620 and North-150 since September of 2017 and is summarized in Table 1 in the 2016 and 2017 Annual Change Report (reference 5). The small diameter borehole prototype testing in existing boreholes (#2 described above) has been ongoing at the WIPP in drift location of East-140 and North-1100 since June 2018 and is summarized in Table 1 of the 2017 and 2018 Annual Change Report (reference 6). These prototype heater tests are smaller in scale, shorter in duration, and lower in thermal heat load than the drift-scale tests planned for SDI/SDDI and primarily are for the purpose of helping the scientists understand and develop the optimal equipment, sensors, processes and system configurations for a future drift-scale test. Sandia National Laboratories (SNL) made a presentation on Borehole Heater Tests at WIPP on Coupled Processes at the September 2018 US/German Workshop in Hannover, Germany. The 2018 SNL presentation at the US/German Workshop summarized the tentative plans for the prototype small-diameter borehole testing. The purpose of the small-scale prototype tests are to test viability of equipment (e.g., packers, thermocouples, flowmeters, gas analyzers, data acquisition) on a small-scale to help the scientist refine the equipment and systems that will be incorporated into final design(s) for a drift-scale test.

Additionally, data will be collected from these prototype tests to improve the scientists understanding of brine availability and brine composition on a small-scale in bedded salt that will help inform the design of the more complex drift-scale tests in the future. Two documents are enclosed that provide supplemental background information on the prototype tests; April 30, 2018, "Project Plan: Salt in Situ Heater Test" (Enclosure 2) and the March 28, 2017, "Consensus on Intermediate Scale Salt Field Test Design" (Enclosure 3).

If you have any questions, please contact Mike Brown at (575) 234-7476, or George Basabilvazo at (575) 234-7488.

Sincerely,

Todd Shrader, Manager
Carlsbad Field Office

Enclosures (3)

cc: w/enclosures

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Dear Ms. Veal:

The purpose of this correspondence is to provide a response to the Environmental Protection Agency (EPA) letter dated March 26, 2019 to clarify an apparent misunderstanding. Several letters and enclosures (see reference list above) from 2011 through 2018 have formally been provided to EPA regarding status and intentions directly related to the non-Waste Isolation Pilot Plant (WIPP) underground thermal experiments, Salt Disposal Investigation (SDI) and Salt Defense Disposal Investigation (SDDI).

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CORSPDNCE/UFC # 19-0016 /UFC:5486.00
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The Department of Energy/Carlsbad Field Office (DOE/CBFO) understands the EPA expectations related to the EPA review of non-WIPP underground experiments and DOE/CBFO continues to plan to provide EPA final drift scale heater test design(s) for review. However, the tests (some form of "heater tests") that your staff indicated they informally heard about are in fact small scale prototype thermal tests being conducted primarily for the purpose of refining items such as, but not limited to, equipment, sensors, methodologies, and systems for the final designs for future drift-scale thermal tests. Therefore, the prototype tests do not represent the final drift scale SDI/SDDI designs.

The salt scientists often use the terminology heater tests in a generic manner to describe even slightly elevated temperature prototype thermal tests but the prototype thermal tests are not the same as the higher heat load experiments discussed in the SDI and SDDI drift scale plan. Generically using "heater tests" or "thermal tests" is common in the scientific community and at technical presentations and the colleagues in the scientific community understand the nature of the prototype testing of equipment, local salt rock material properties and processes, and systems versus the future SDI/SDDI final drift scale design high thermal load heat tests that will be larger in scale, higher in thermal heat load, and longer in duration than any prototype tests at WIPP.

There are three prototype tests currently being conducted at WIPP, (1) small-scale prototype canister (singular) heating test, (2) small-diameter borehole testing in an existing borehole, and (3) small-diameter (about 5 inches in diameter) borehole thermal tests. These prototype tests are lower in thermal heat load, smaller in scale, and shorter in duration than drift-scale tests. The results for these prototyping tests will provide input for refinements in types of equipment, sealing techniques between heater apparatus and borehole and salt material, and the use of various geophysical sensors to observe the response of the salt to heat. The results of these prototype tests will also be used to collect data on a small scale related to the thermal response of salt to heat (e.g., brine liberation and chemistry) and to refine optimal equipment and system configurations for the more elaborate drift-scale final design.

Several documents have been provided to EPA that describe the status and the progression of intermediate small-scale prototype tests to the larger drift-scale tests. In a December 12, 2013 letter from Franco to Edwards (U.S. DOE 2013), the DOE provided the EPA with a notice of intent to begin the drift-scale SDDI part of the investigation and provided the EPA with an analysis titled, "WIPP Performance Impacts Associated with SDDI" in addition to the test specifications for the SDDI thermal test in WIPP. This document supported the original 2011 analysis that demonstrated the SDI testing plan has negligible impact to the WIPP facility disposal operations. The three prototyping tests discussed above are much smaller in scale, shorter in time duration, and lower in thermal heat load than the drift-scale SDI or SDDI thermal tests and, therefore, the potential impact of the small-scale prototype tests are bounded by the existing impact analysis to have negligible impact on the WIPP facility disposal operations and long-term repository performance.

Enclosed is the April 30, 2015, "Test Proposal Document for Phased Field Thermal Testing in Salt" (Enclosure 1) developed by Los Alamos National, Sandia, and Lawrence Berkeley National laboratories. This research is part of the generic research being performed by the DOE Office of Nuclear Energy (DOE-NE) Used Fuel Disposition campaign to explore geologic disposal in salt, granite, clay/shale, and deep boreholes. Heater canister prototype testing (#1 described above) has been ongoing at the WIPP in the underground drift location of West-620 and North-150 since September of 2017.

The small diameter borehole prototype testing in existing boreholes (#2 described above) has been ongoing at the WIPP in drift location of East-140 and North-1100 since June 2018 and is summarized in Table 1 of the 2017 and 2018 Annual Change Reports (reference 5 and 6). These prototype heater tests are smaller in scale, shorter in duration, and lower in thermal heat load than the drift-scale tests planned for SDI/SDDI and primarily are for the purpose of helping the scientists understand and develop the optimal equipment, sensors, processes and system configurations for a future drift-scale test. Sandia National Laboratories (SNL) made a presentation on Borehole Heater Tests at WIPP on Coupled Processes at the September 2018 US/German Workshop in Hannover, Germany attended by the EPA. The 2018 SNL presentation at the US/German Workshop summarized the tentative plans for the prototype small-diameter borehole testing. The purpose of the small-scale prototype tests are to test viability of equipment (e.g., packers, thermocouples, flowmeters, gas analyzers, data acquisition) on a small scale to help the scientist refine the equipment and systems that will be incorporated into final design(s) for a drift-scale test. Additionally, data will be collected from these prototype tests to improve the scientists understanding of brine availability and brine composition on a small scale in bedded salt that will help inform the design of the more complex drift-scale tests in the future. Two documents are enclosed to provide supplemental background information on the prototype tests; April 30, 2018, "Project Plan: Salt in Situ Heater Test" (Enclosure 2) and the March 28, 2017, "Consensus on Intermediate Scale Salt Field Test Design" (Enclosure 3).

In summary, three small scale prototype thermal tests are being conducted at WIPP. Two small scale prototype tests (a canister test and a single borehole test in existing boreholes) have been summarized and provided to EPA in the 2017 and 2018 Annual Change Reports of nonsignificant changes. Another small scale prototype borehole test is planned to be conducted to help scientists understand and develop optimal equipment, and system configuration to be able to complete a final design for a drift-scale tests of SDI/SDDI, as well as collect data related to the understanding of brine availability and brine composition on a small scale in bedded salt. This prototype test will be included in a future Annual Change Report to EPA. These prototype tests are smaller in scale, shorter in time duration, and lower thermal heat load than the drift scale SDI and SDDI conceptual plans. The SNL Impact Analysis of the SDI demonstrated that the higher thermal loading, larger scale, and longer time durations has negligible impact to WIPP facility disposal operations and long-term repository performance. Therefore, the small scale prototypes tests are bounded by the SNL Impact Analysis. DOE/CBFO will provide final design(s) of the drift-scale test to EPA for review as agreed to in 2011.

If you have any questions, please contact Mr. Mike Brown at (575) 234-7476, or George Basabilvazo at (575) 234-7488.

Sincerely,

Todd Shrader, Manager
Carlsbad Field Office

Enclosures (3)

CBFO:OOM:GB:LM:19-0016:UFC 5486.00

cc: w/enclosures

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*ED denotes electronic distribution

Leslie McMinn (CONTR)

From: Myles Hall
Sent: Thursday, April 04, 2019 3:10 PM
To: Leslie McMinn (CONTR); Todd Shrader; Kirk Lachman
Subject: RE: REQUEST FOR EXPEDITED ELECTRONIC REVIEW/CONCURRENCE: Letter 19-0016
Attachments: 19-0016 Ltr (MH rev).doc

No legal objection – minor suggested revisions in the attached.

Thank you.

V/r,

Myles Hall
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Sent: Thursday, April 04, 2019 2:05 PM
To: Todd Shrader <Todd.Shrader@cbfo.doe.gov>; Myles Hall <Myles.Hall@cbfo.doe.gov>; Kirk Lachman <Kirk.Lachman@cbfo.doe.gov>
Subject: REQUEST FOR EXPEDITED ELECTRONIC REVIEW/CONCURRENCE: Letter 19-0016

Letter 19-0016 is attached for your **expedited** review/comment and electronic concurrence. Provide your comments and concurrence back to myself via email at your earliest convenience.

19-0016 – Response to the EPA Letter dated March 26, 2019 and Status on the Salt Disposal Investigation and Salt Defense Disposal Investigation at the Waste Isolation Pilot Plant

Thank you,

MAIL ROOM COPY

Leslie McMinn

Administrative Team Lead
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Leslie McMinn (CONTR)

From: Kirk Lachman
Sent: Thursday, April 04, 2019 3:03 PM
To: Leslie McMinn (CONTR); Todd Shrader; Myles Hall
Subject: RE: REQUEST FOR EXPEDITED ELECTRONIC REVIEW/CONCURRENCE: Letter 19-0016

I have no comments.

From: Leslie McMinn (CONTR)
Sent: Thursday, April 04, 2019 2:05 PM
To: Todd Shrader <Todd.Shrader@cbfo.doe.gov>; Myles Hall <Myles.Hall@cbfo.doe.gov>; Kirk Lachman <Kirk.Lachman@cbfo.doe.gov>
Subject: REQUEST FOR EXPEDITED ELECTRONIC REVIEW/CONCURRENCE: Letter 19-0016

Letter 19-0016 is attached for your **expedited** review/comment and electronic concurrence. Provide your comments and concurrence back to myself via email at your earliest convenience.

19-0016 – Response to the EPA Letter dated March 26, 2019 and Status on the Salt Disposal Investigation and Salt Defense Disposal Investigation at the Waste Isolation Pilot Plant

Thank you,

Leslie McMinn

Administrative Team Lead
Carlsbad Technical Assistance Contractor (North Wind – Portage)
Contractor to the Department of Energy
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Carlsbad, NM 88220
(575) 234-7176

NORTHWIND PORTAGE, INC.

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Enclosure 1

Test Proposal Document for Phased Field Thermal Testing in Salt

Fuel Cycle Research &
Development

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Test Proposal Document for Phased Field Thermal Testing in Salt

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
Milestone M2FT-15LA08119016

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April 30, 2015

FCRD-UFD- 2015-000077
Los Alamos National Laboratory LA-UR-15-23154

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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 (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)
Review Documentation Provided
☐ Signed TR Report or,
☐ Signed TR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below

Name and Signature of Reviewers
Hari Viswanathan

Peer Review (PR)
Review Documentation Provided
☐ Signed PR Report or,
☐ Signed PR Concurrence Sheet or,
☐ Signature of PR Reviewer(s) below

*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.

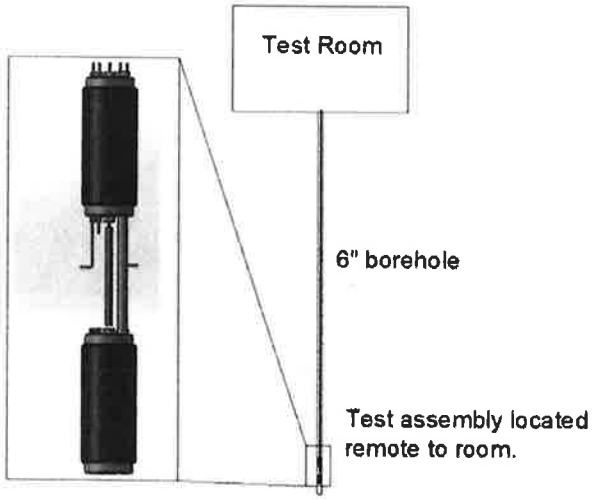


Figure ES-1. Schematic of a Standardized Vertical Borehole Heater Test in Salt.

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.

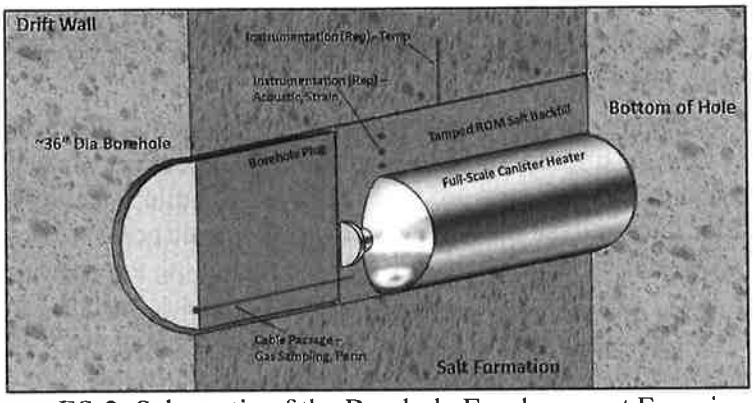


Figure ES-2. Schematic of the Borehole Emplacement Experiment.

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.

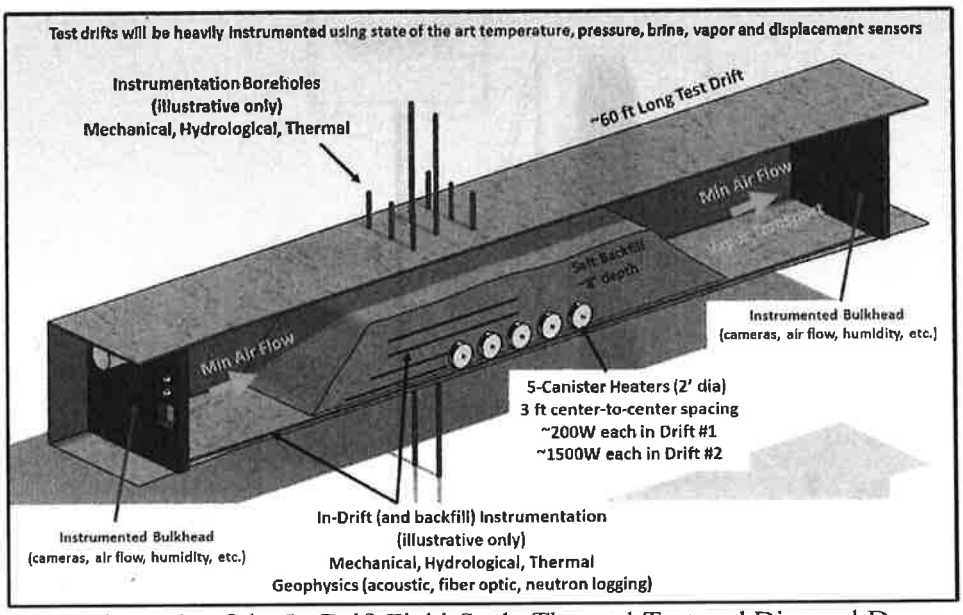


Figure ES-3. Schematic of the In-Drift Field-Scale Thermal Test and Disposal Demonstration.

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.

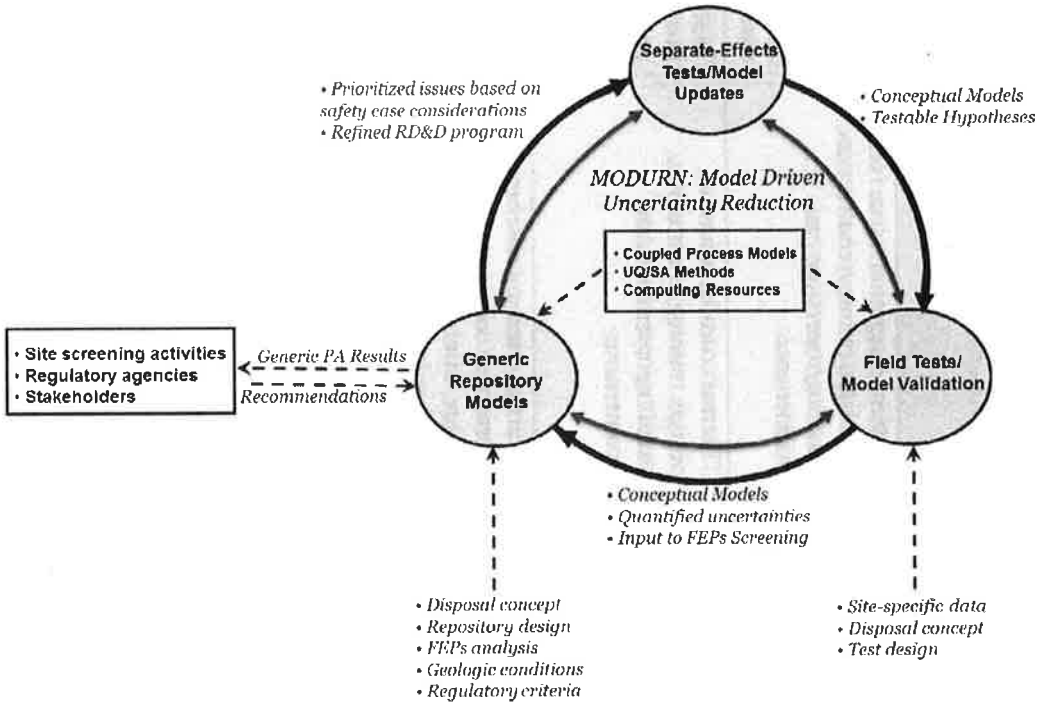


Figure 1. Conceptual Schematic of Iterative, Adaptive, Model-Driven Process for Repository Investigations (after Figure 2, Robinson et al., 2012).

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, 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" (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).

Error! Reference source not found. 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 **Error! Reference source not found.**, 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).

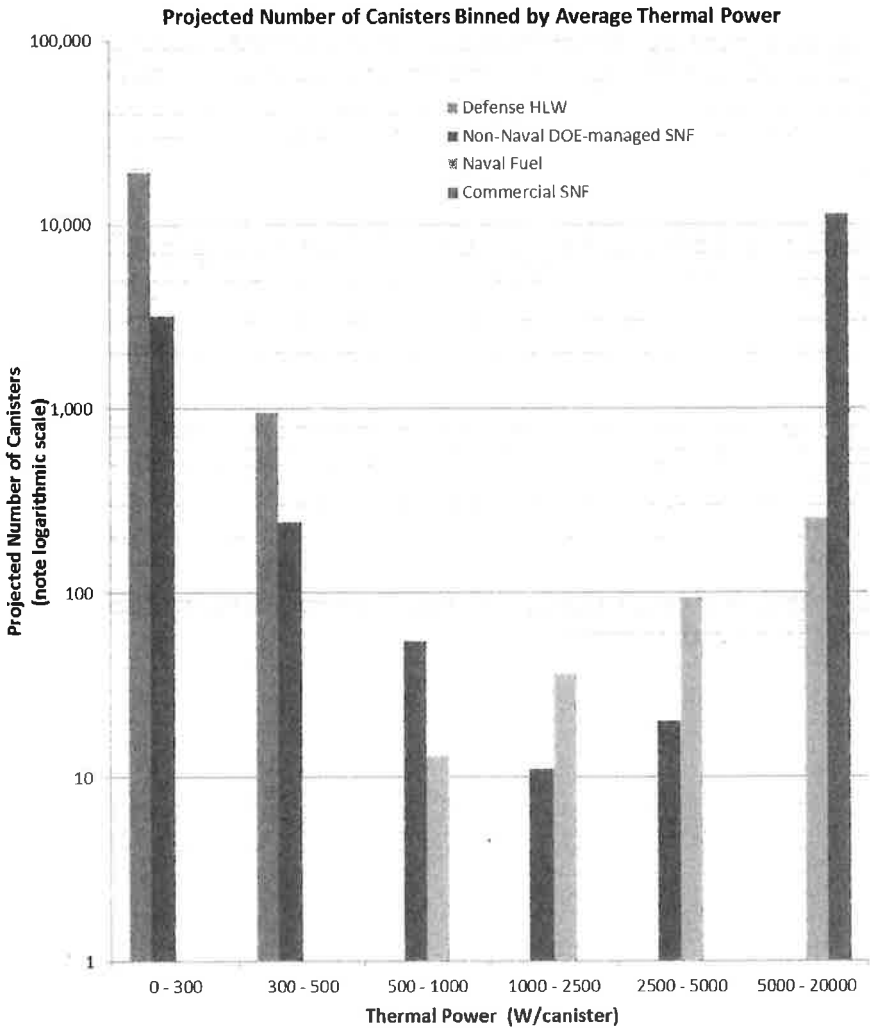
2.3 Proposed Field Thermal Testing Approach

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 $\geq$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°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).

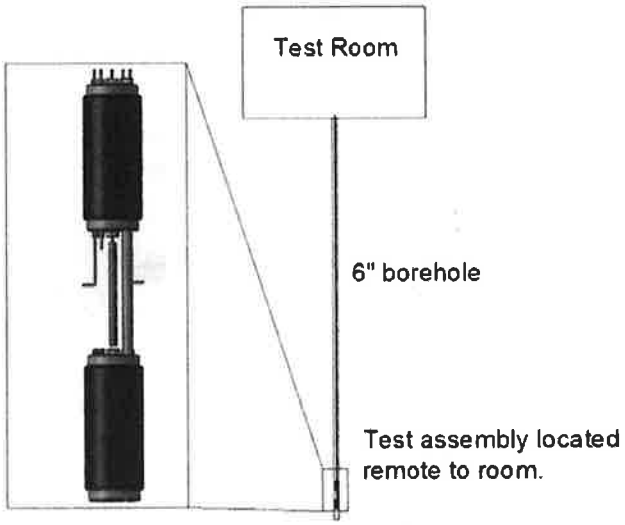


Figure 3. Schematic of a Standardized Vertical Borehole Heater Test in Salt.

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, **Error! Reference source not found.**. 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.

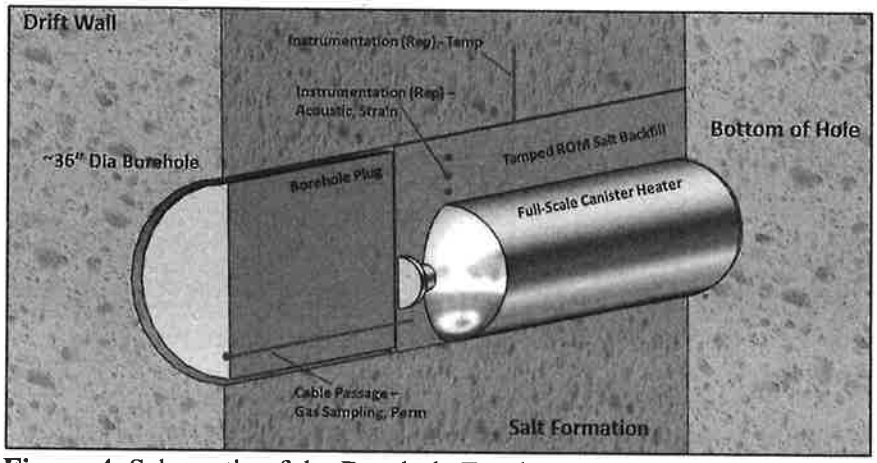


Figure 4. Schematic of the Borehole Emplacement Concept for this Test, including Representative Suggestions for Instrumentation.

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).

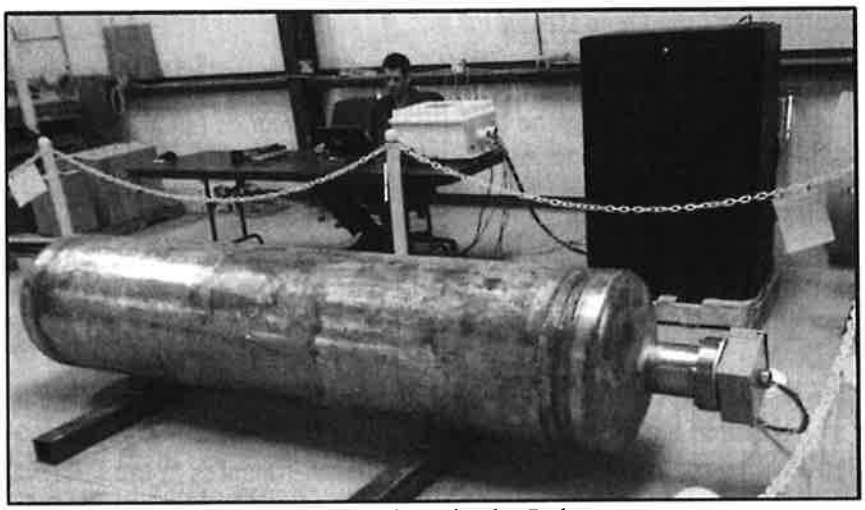


Figure 5. Prototype Heater Canister in the Laboratory.

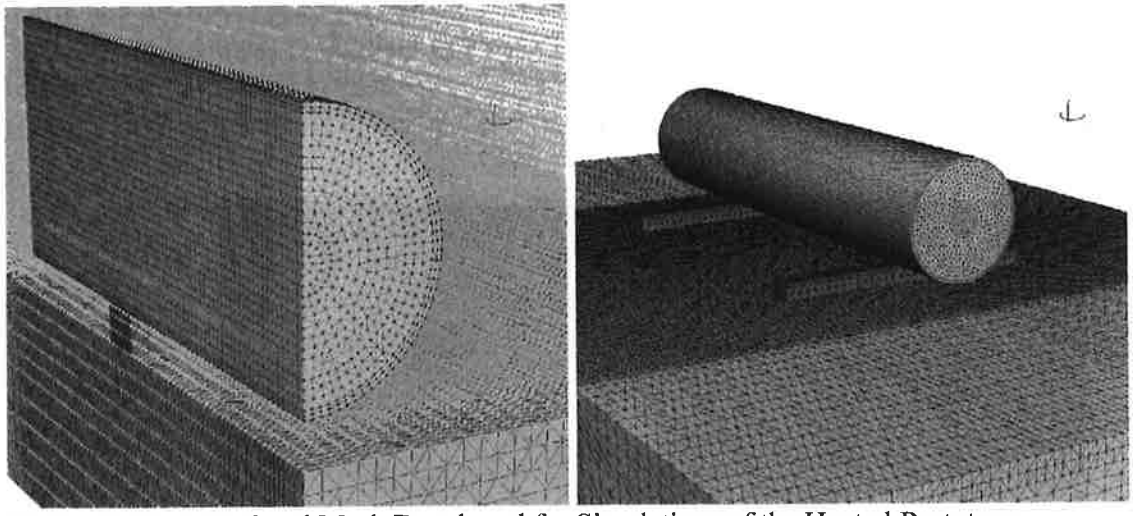


Figure 6. Computational Mesh Developed for Simulations of the Heated Prototype Canisters in the Laboratory.

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, **Error! Reference source not found.**. 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, **Error! Reference source not found.**. 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).

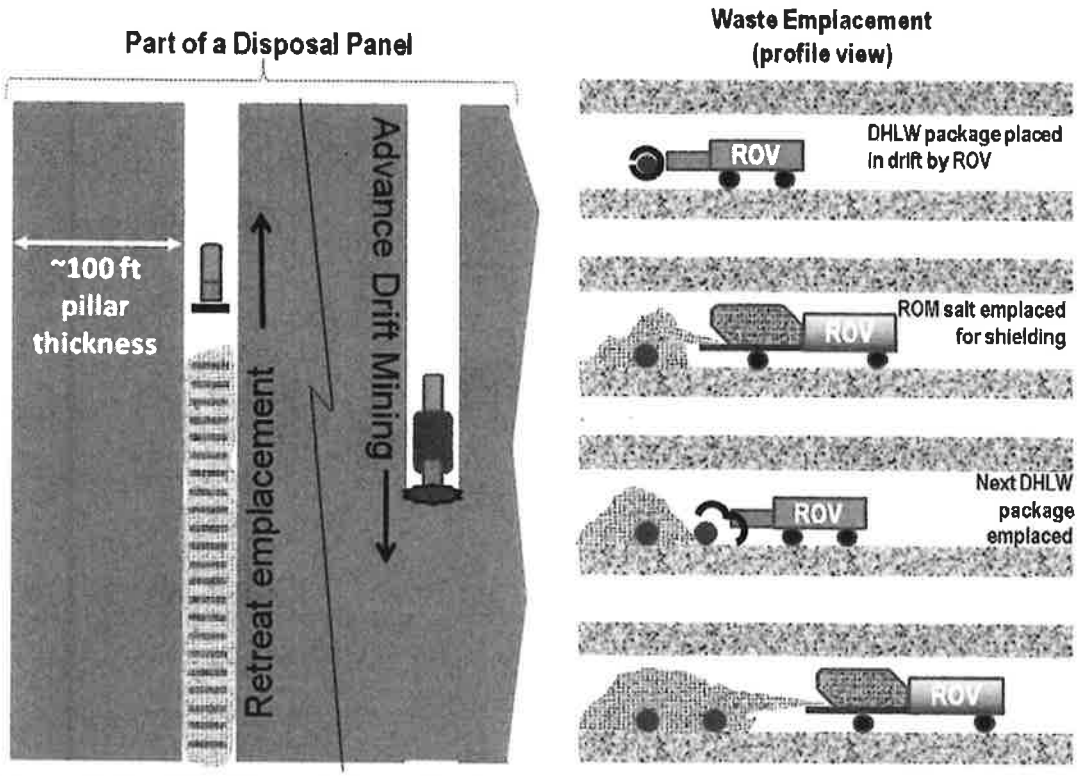


Figure 7. In-Drift Disposal Waste Emplacement Strategy. From Carter et al., 2012.

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.

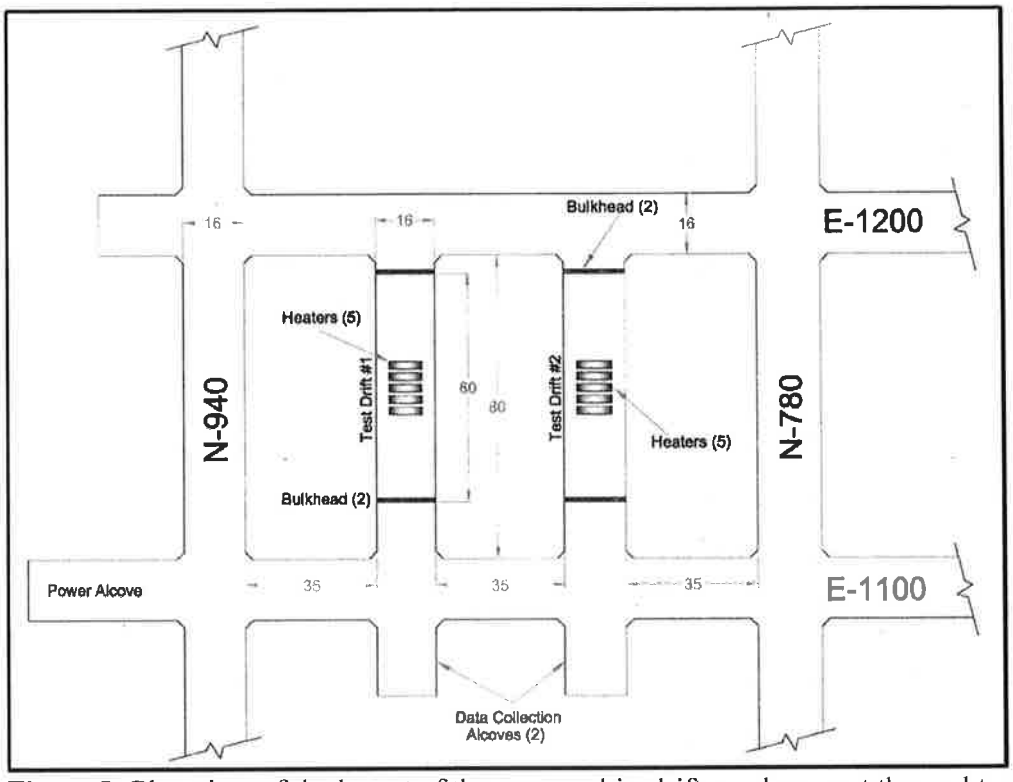


Figure 8: Plan view of the layout of the proposed in-drift emplacement thermal test and disposal demonstration.

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.

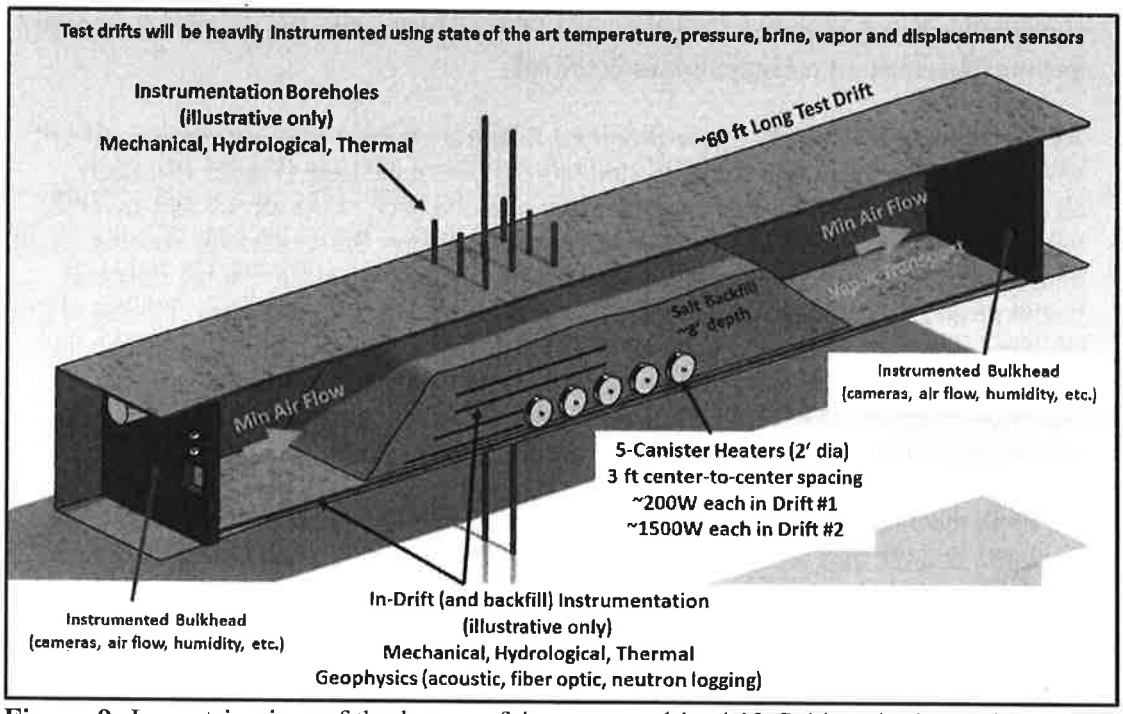


Figure 9: Isometric view of the layout of the proposed in-drift field-scale thermal test and disposal demonstration.

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.

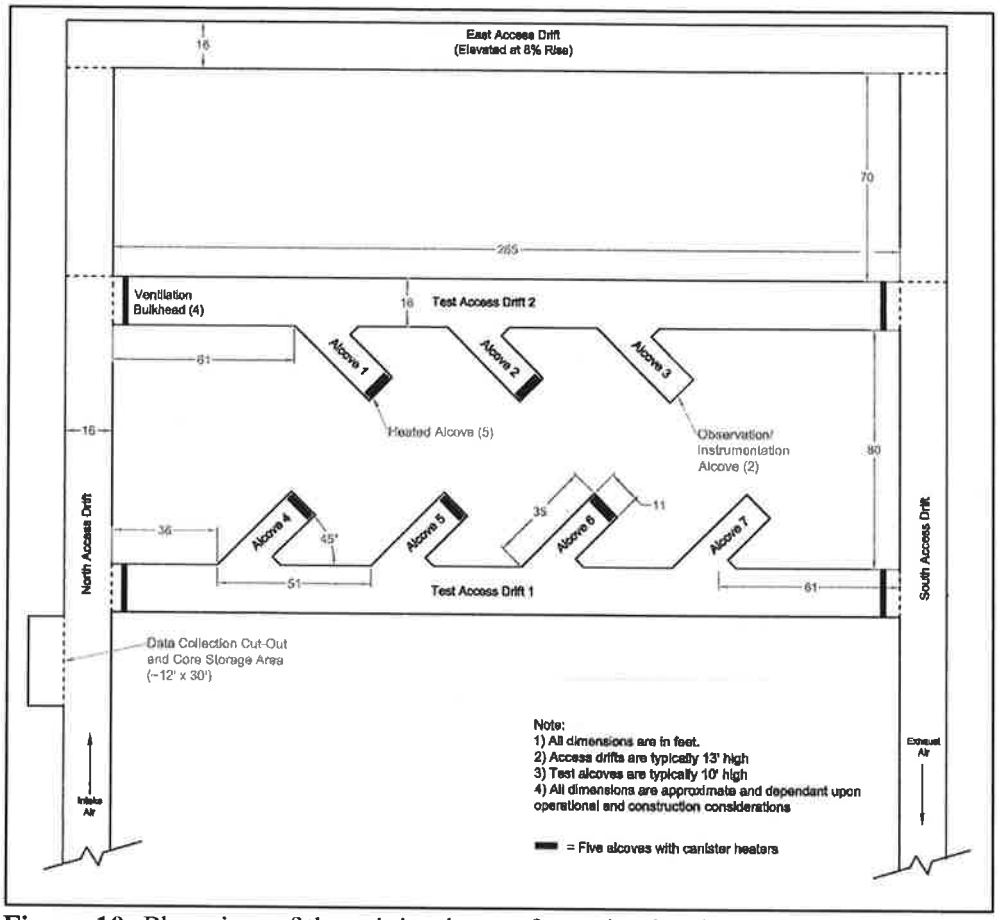


Figure 10: Plan view of the mining layout for an in-situ thermal test of the alcove disposal concept.

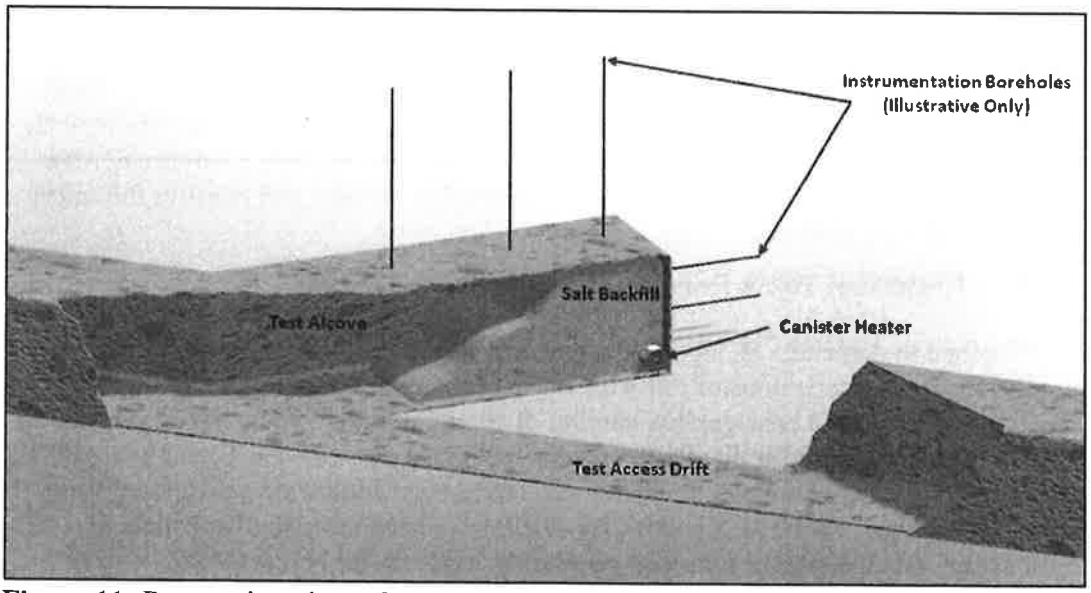


Figure 11: Perspective view of a test alcove, with a canister heater buried in crushed salt.

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.

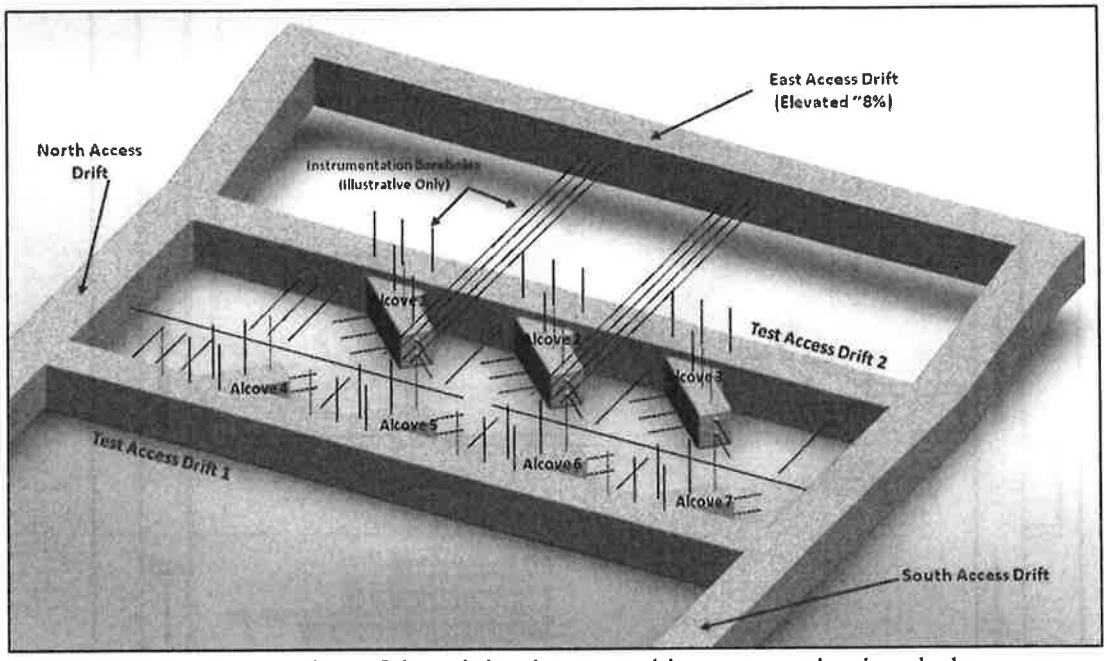


Figure 12: Perspective view of the mining layout and instrumentation borehole configuration for an in situ thermal test of the alcove disposal concept.

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).

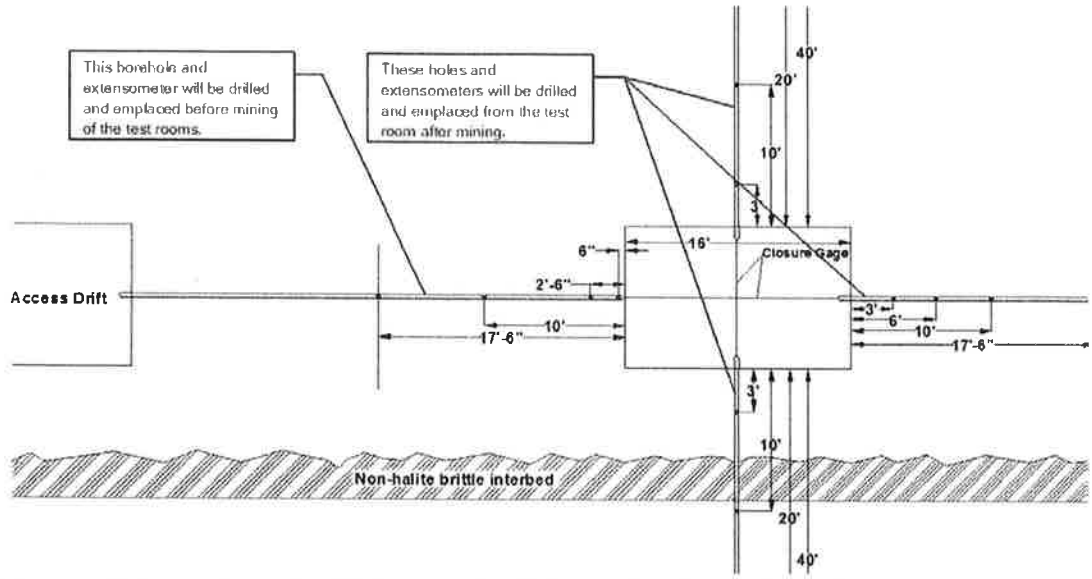


Figure 13: General Layout Suggested for Deformation Borehole and Gauges for Mechanical Characterization Boreholes. From Howard (2014).

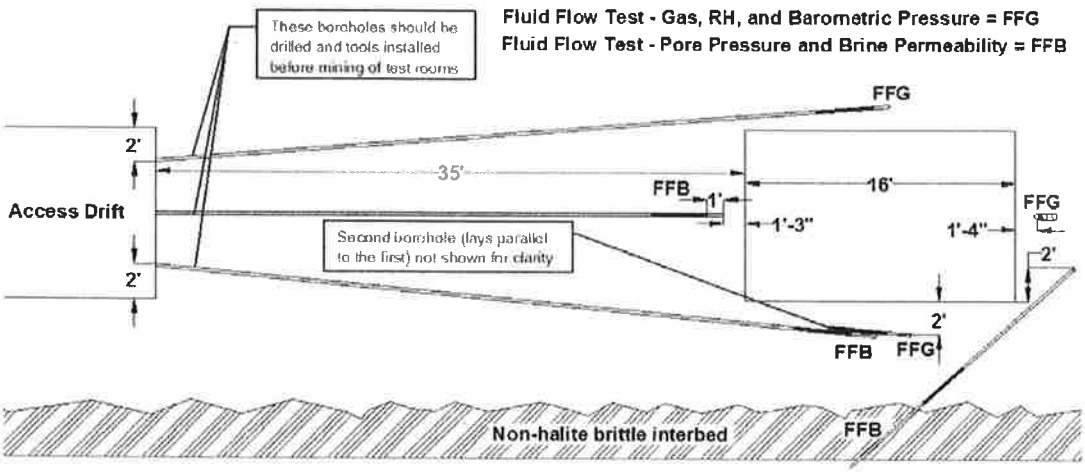


Figure 14: General layout of brine and gas testing borehole relative to the thermal test drifts. From Howard (2014).

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

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[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.

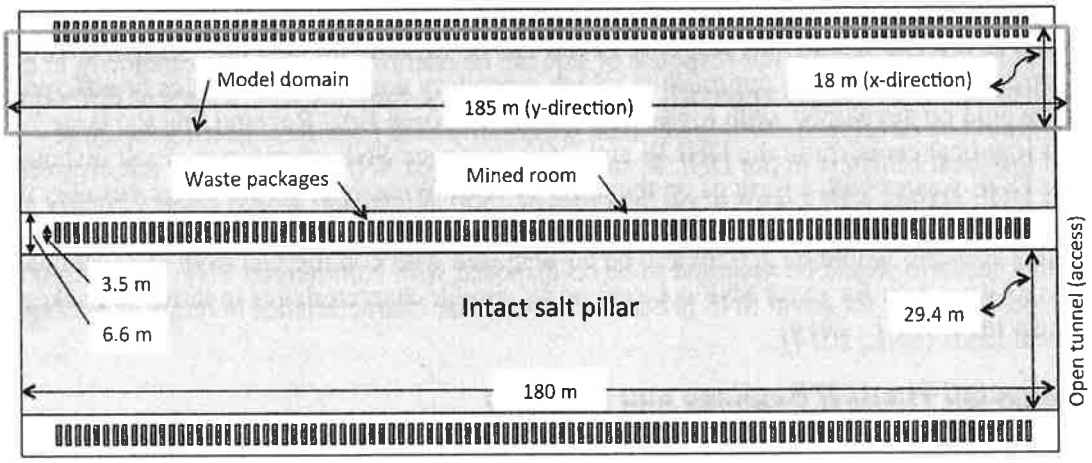


Figure 15. Plan view of repository heat transfer model for low-heat defense waste (from Harp et al., 2014).

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°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].

[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.*

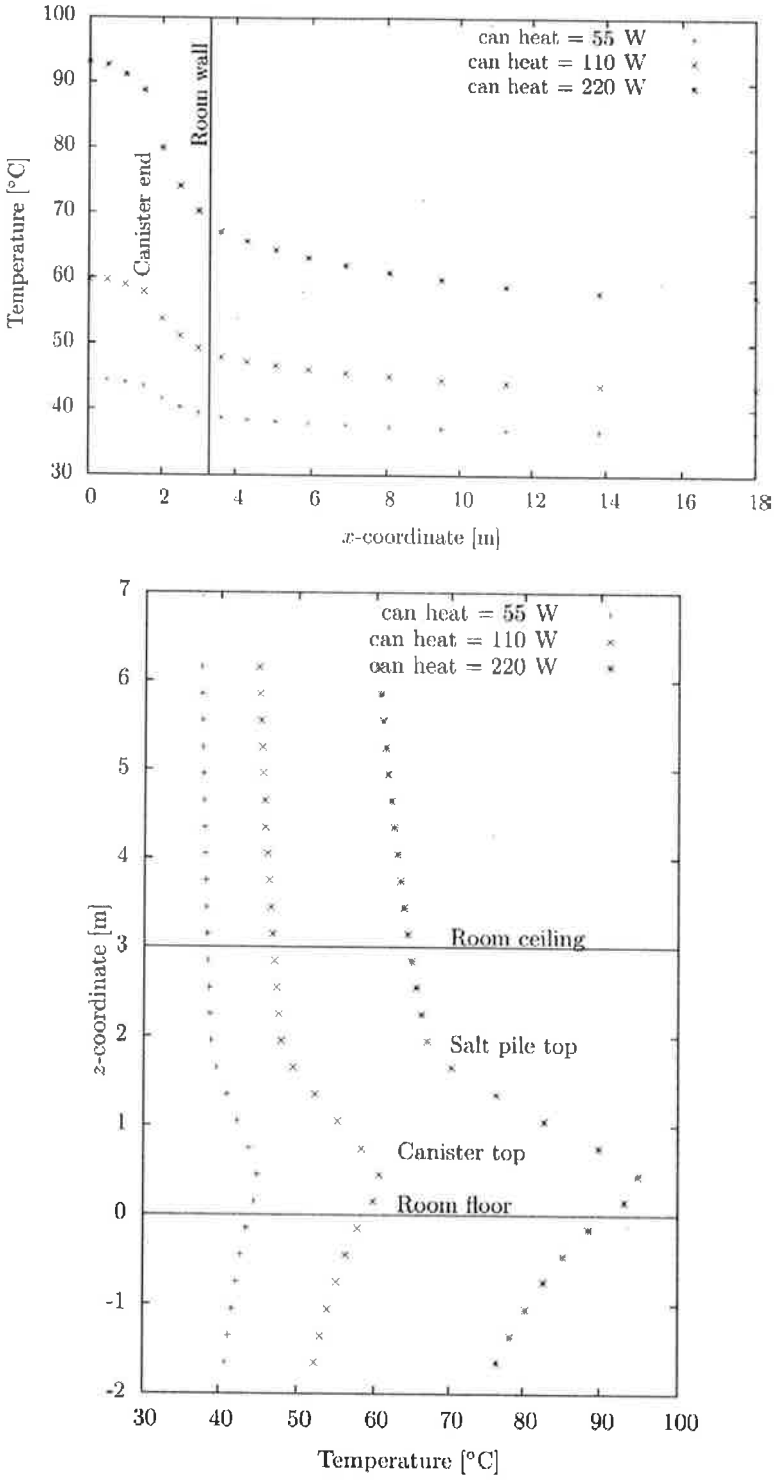


Figure 16. Steady-state horizontal (top) and vertical (bottom) temperature profiles for closely spaced canisters (0.9 m or 3 ft center-to-center spacing) in the defense waste repository model (from Harp et al., 2014)

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 °C are expected. Thus, drift closure rates are expected to be somewhat enhanced by the increased temperatures, but the effects should be relatively modest.

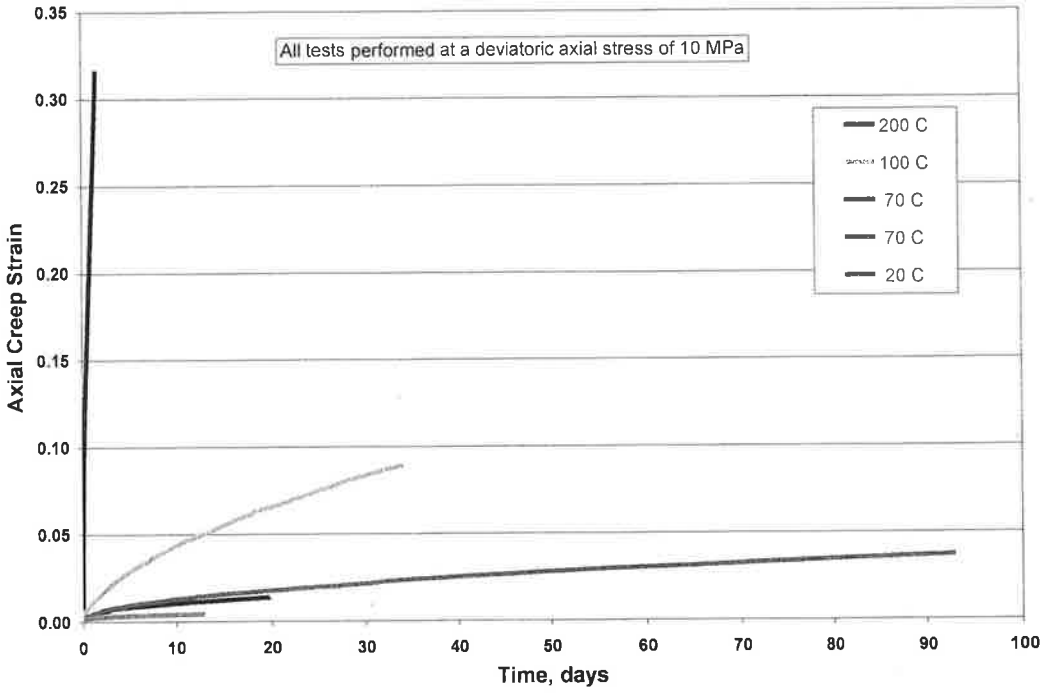


Figure 17. Impact of temperature on creep of salt (from DOE, 2011).

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

[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°C.

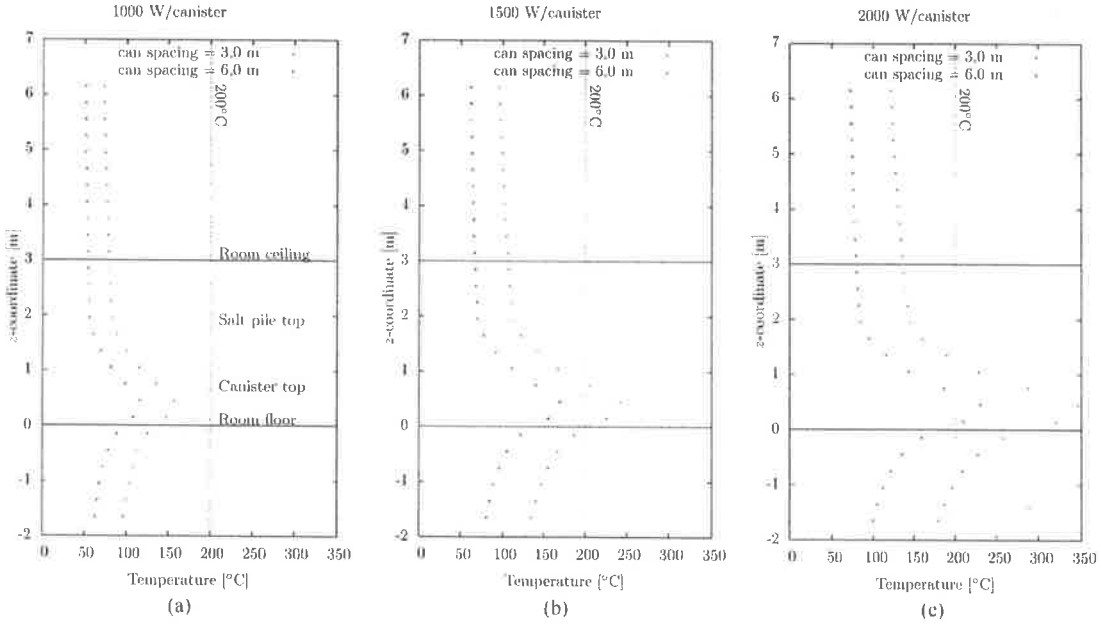


Figure 18. Steady state vertical temperature profiles for 1000W, 1500W, and 2000W canisters at 3 m and 6 m spacings (from Harp et al., 2014). Note: Temperatures far in excess of 200°C would probably not be considered in an actual design but are included here to illustrate the sensitivity of maximum temperature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

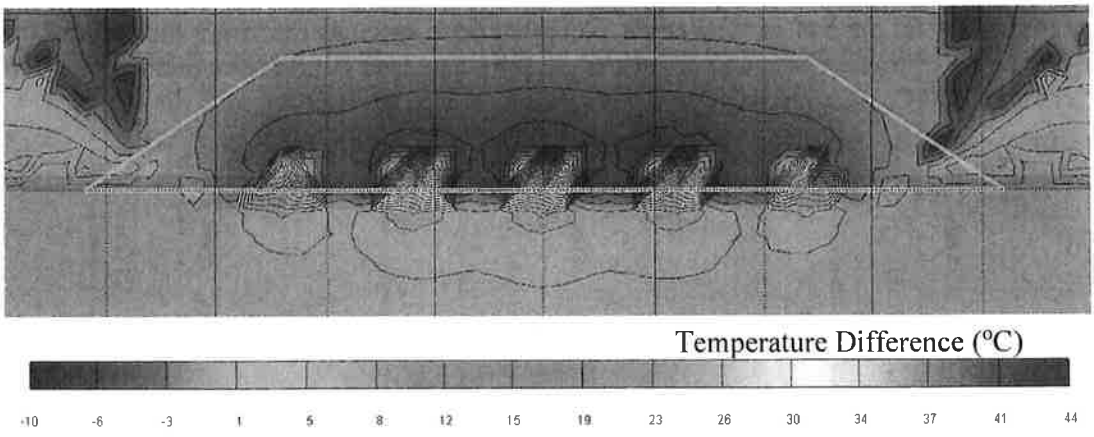


Figure 19. Temperature difference between a conduction-only and coupled TH simulation after 2 years (from Stauffer et al., 2012). This plot records the difference between the conduction-only temperature and the coupled TH temperature at each location. Red colors represent a higher (by as much as 44°C)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

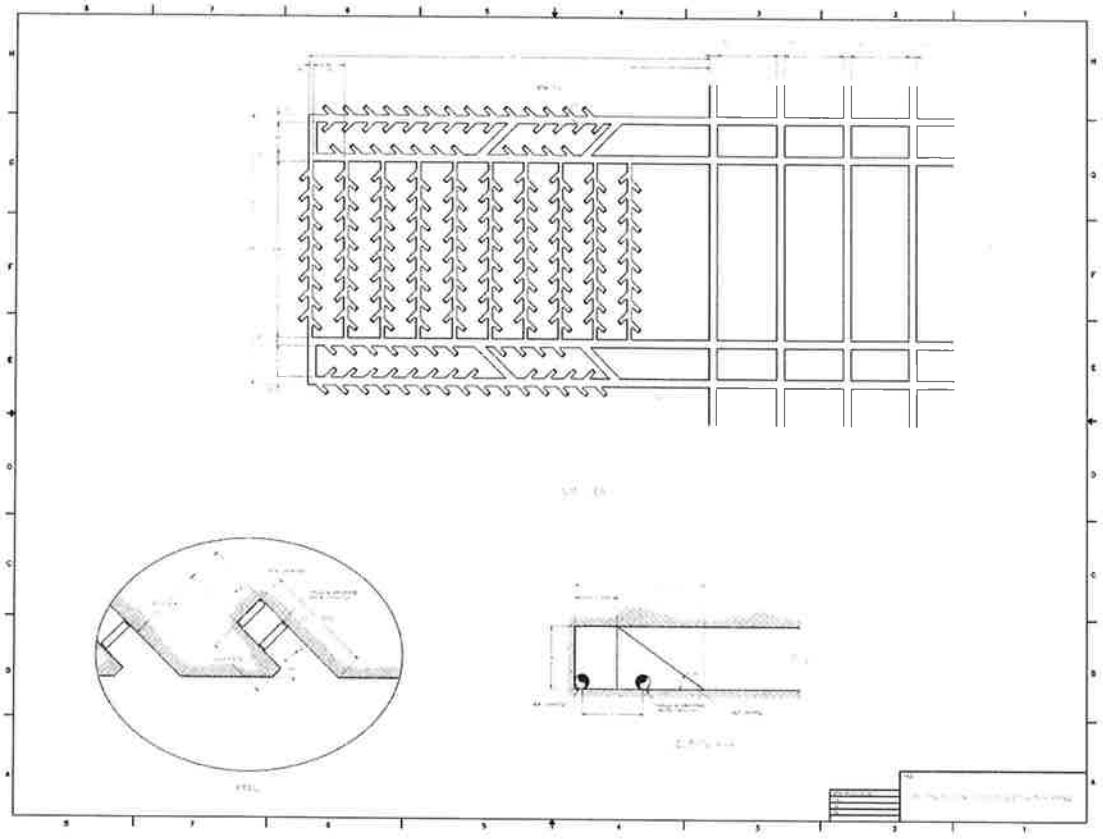


Figure 20. Layout for a portion of the repository for the high-heat disposal case (from Carter et al., 2011).

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 $39 W/m^2$ (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.

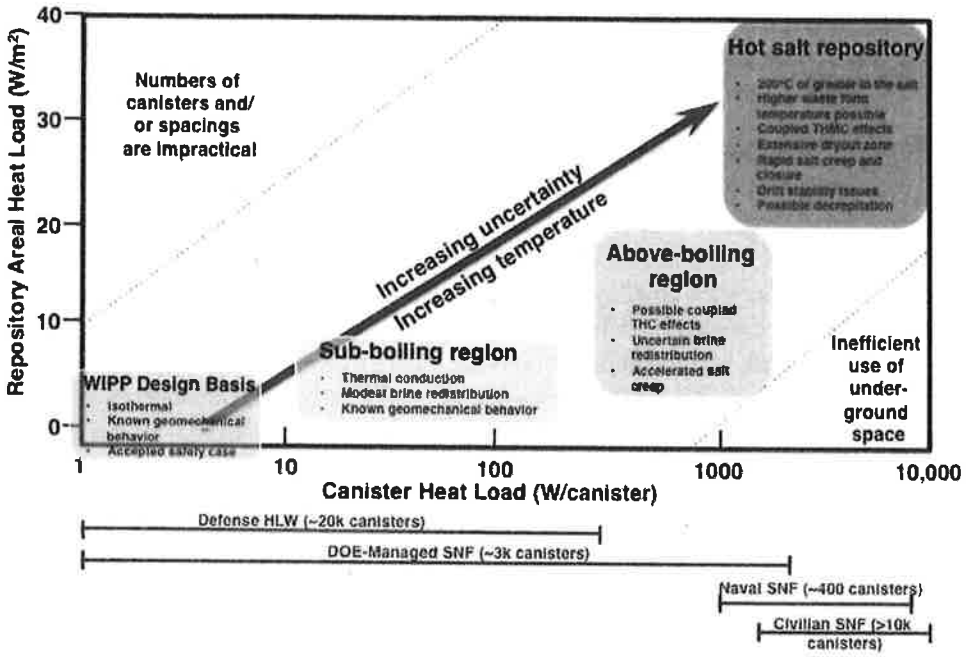


Figure 21. Schematic of Areal Heat Load versus Canister Heat Load

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°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°C near waste canisters, and temperatures would be between 150 and 200°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° 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° 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°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°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.

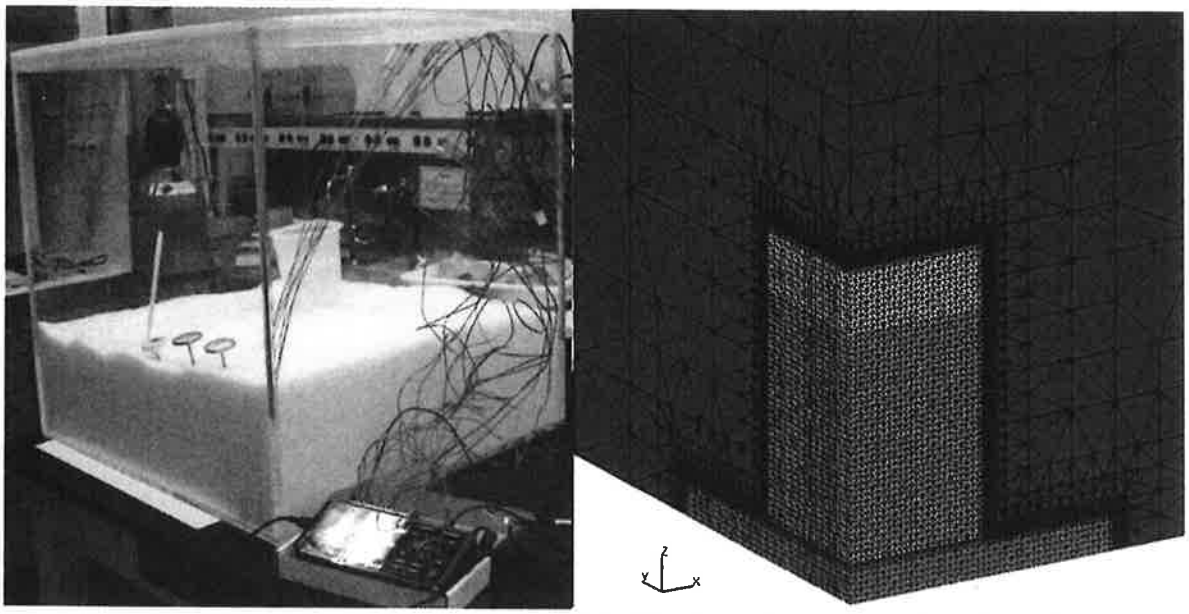


Figure 22. a) LANL equipment for laboratory investigations of granular salt under ambient and heated conditions. (b) Computational mesh for coupled THC simulations of these experiments.

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.

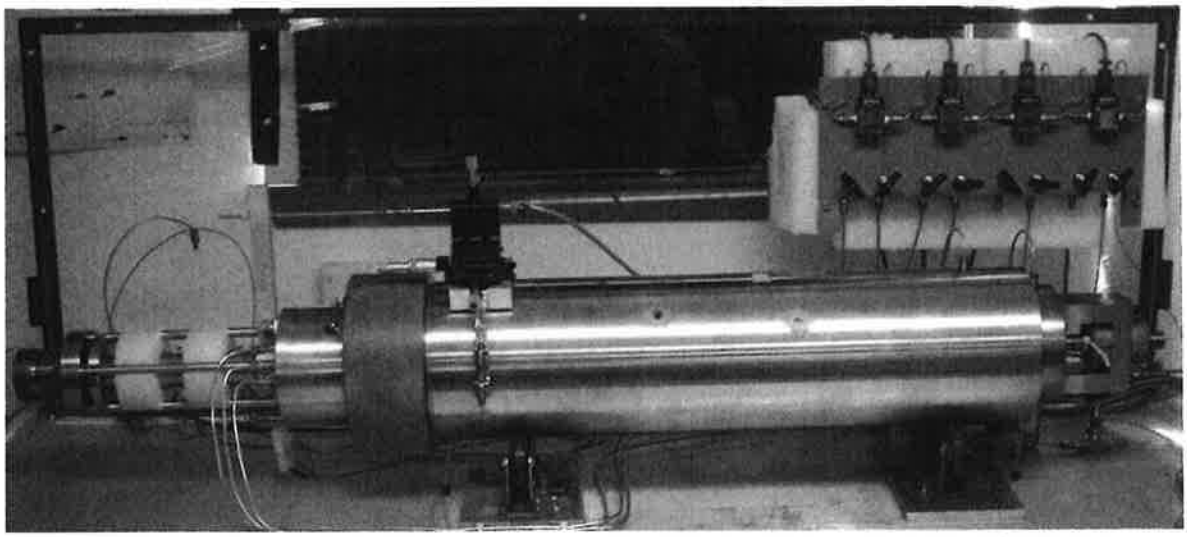


Figure 23. High Pressure and Temperature Vessel at LANL.

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.

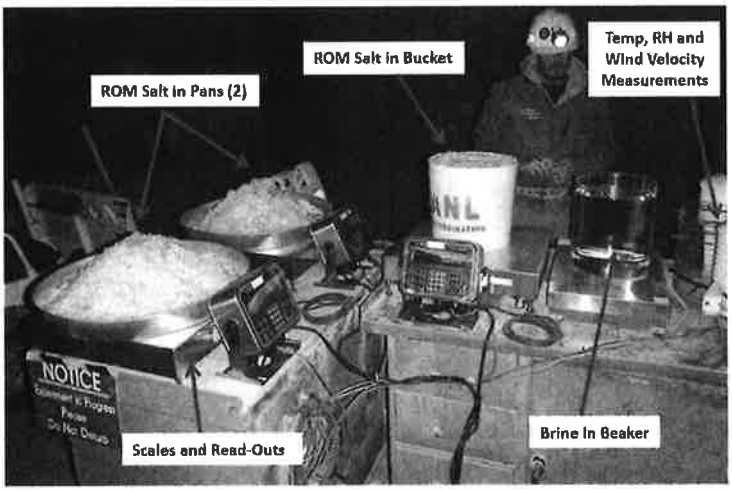


Figure 24. Brine and RoM Evaporation Experiments in WIPP.

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 °C and is then stable in dehydrated form to at least 300 °C. This reaction is also fully reversible when temperature is below 65 °C and water is available for rehydration. High temperature (300 °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 °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.

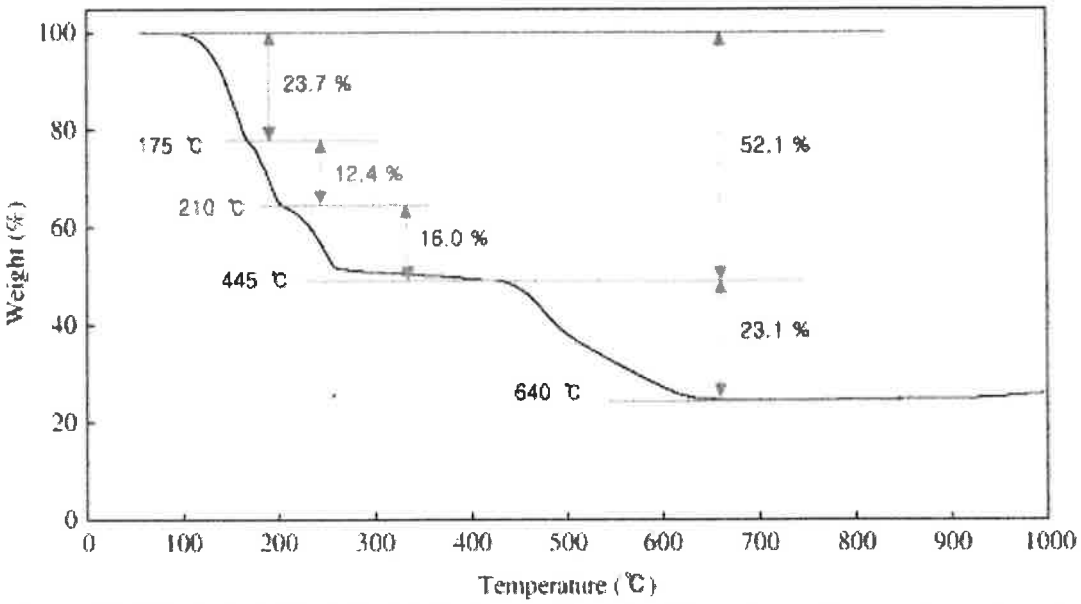


Figure 25. Thermogravimetric (TGA) Curve Showing the Dehydration of Magnesium Chloride in Air (Hyoung-Choon, 2010).

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 °C and then from 450–650 °C. 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 °C) and a condensate with a "slightly less acidic" pH in

Room A1 (470 W heaters with wall temperatures of ~70 °C) (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 °C (Figure 26). In this figure, the m/e = 18 trace (blue curve) distinguishes three major dehydration events at ~ 50, 100, and 150 °C. 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.

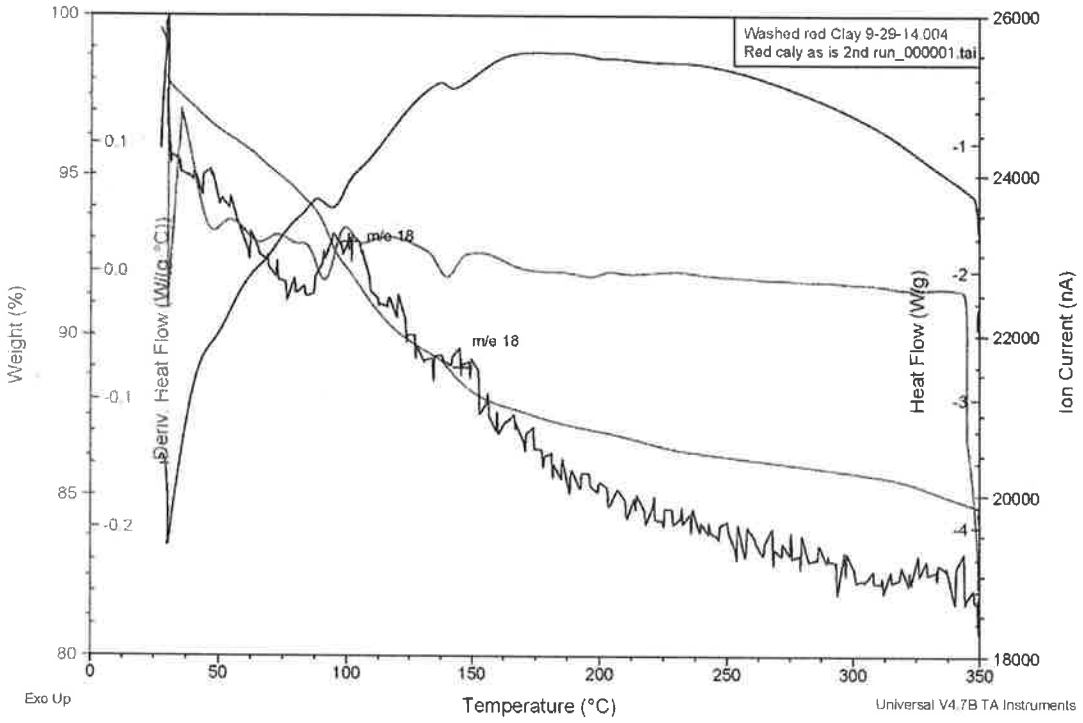
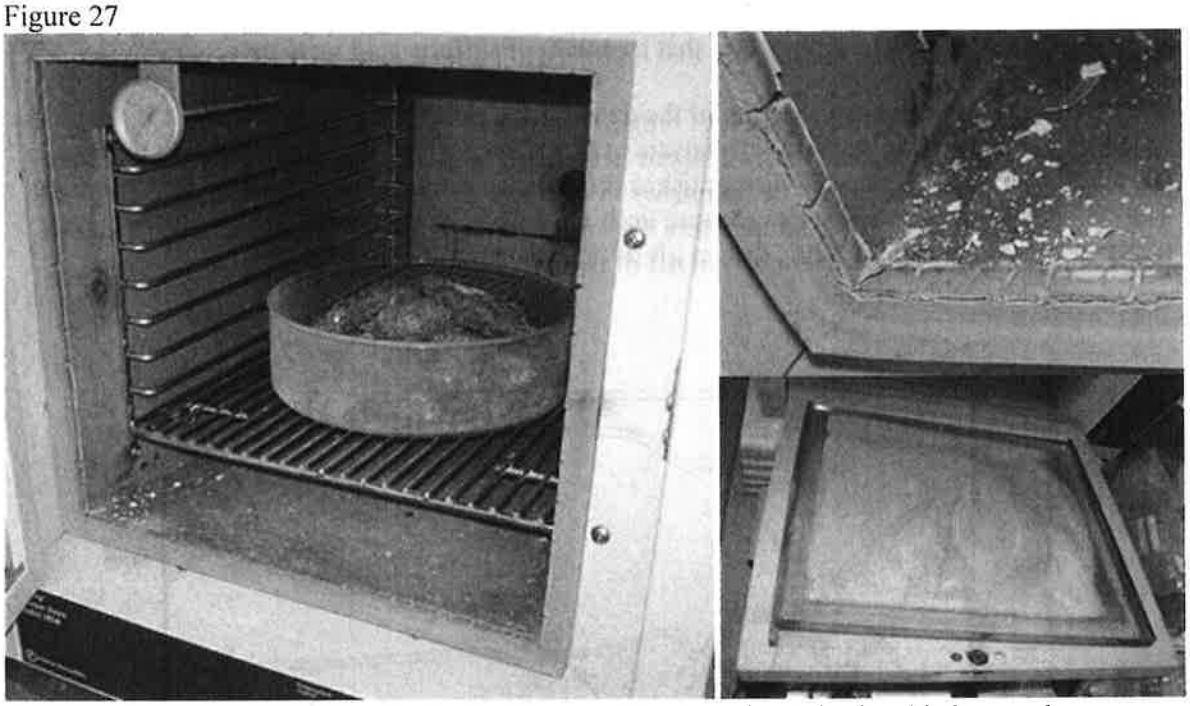


Figure 26. Preliminary Data Showing the Dehydration of Clay Separated from Clay Seam F at WIPP.

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 °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.

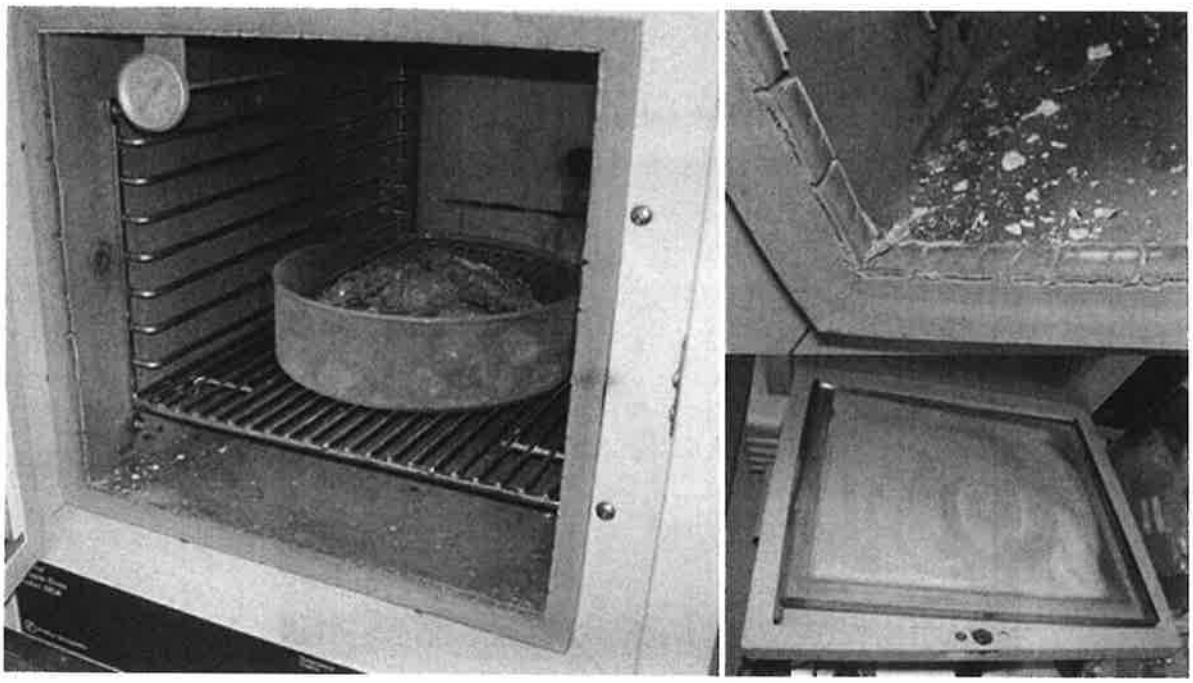


Figure 27. Oven Corrosion after Heating WIPP salt from Clay Seam F to 360 ^{0}C.

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 $\delta^{18}O$ ($\delta D/\delta^{18}O$) 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).

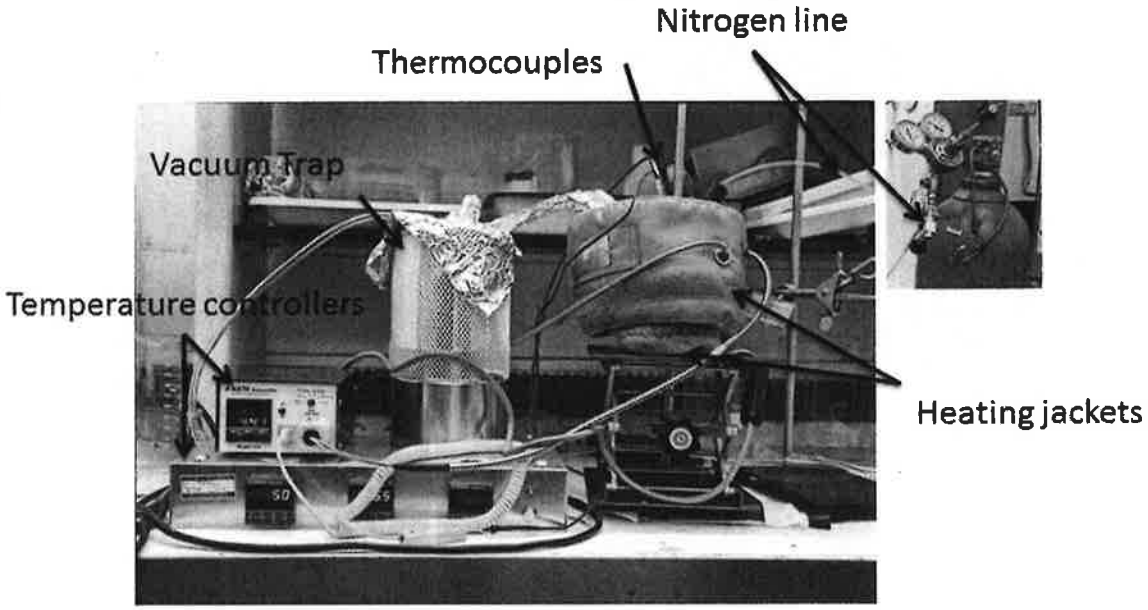


Figure 28. Testing Deuterium Spiked Water Fractionation in Salt.

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 / $\delta^{18}O$)**	**50 day turnover (δD / $d^{18}O$)**	**500 day turnover (δD / $\delta^{18}O$)**
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 °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 °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)

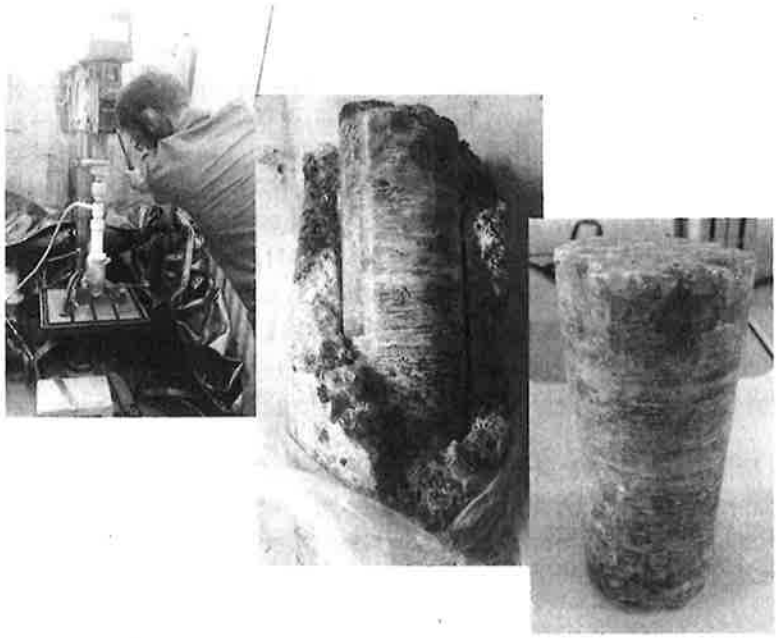


Figure 29. ERT Test Core Extraction Images.

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.

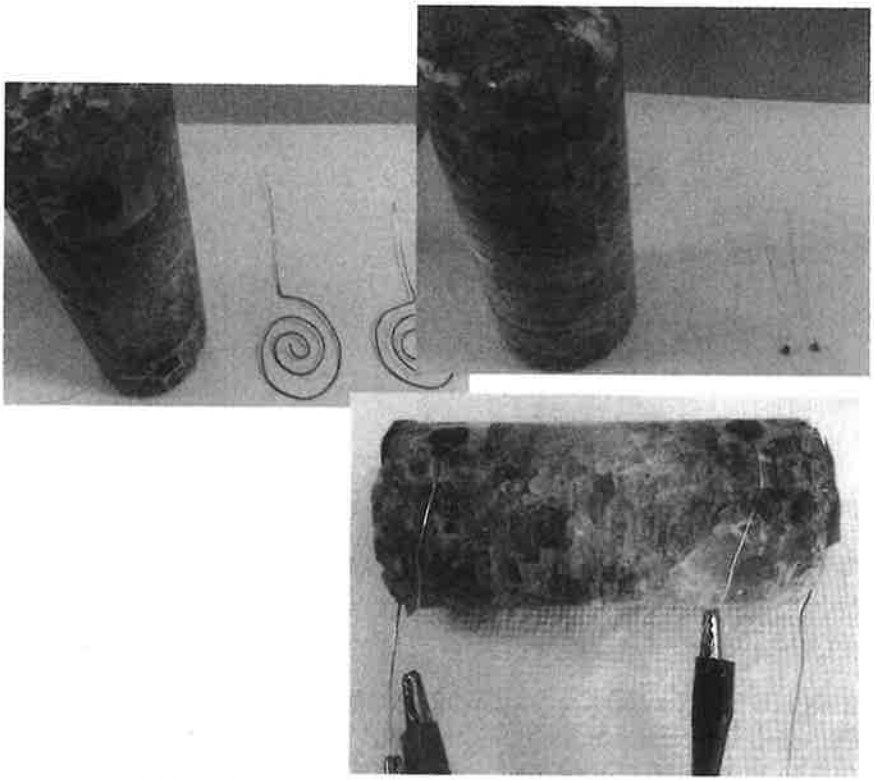


Figure 30. ERT Measurement Setup

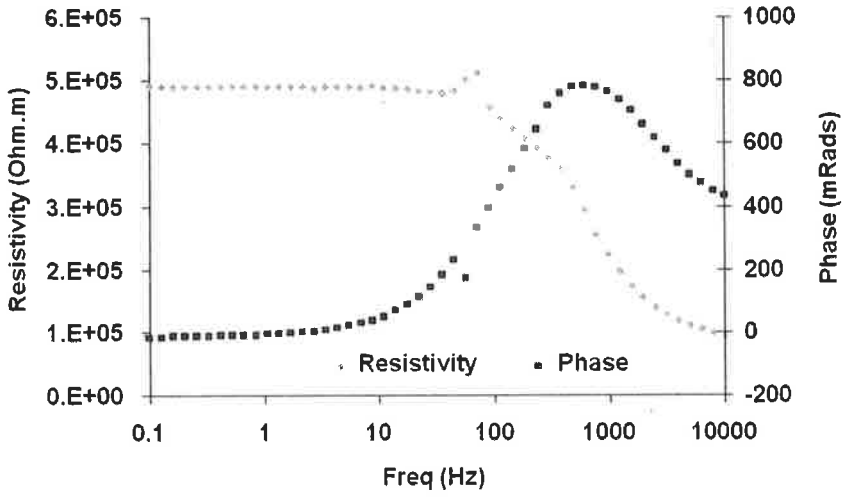


Figure 31. Baseline Electrical Signals

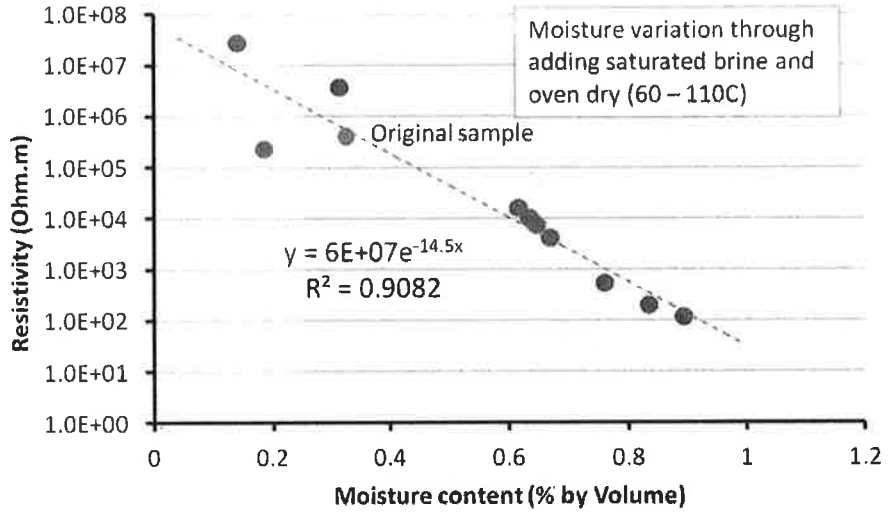


Figure 32. Correlation between Resistivity (1Hz) and Moisture Content

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.

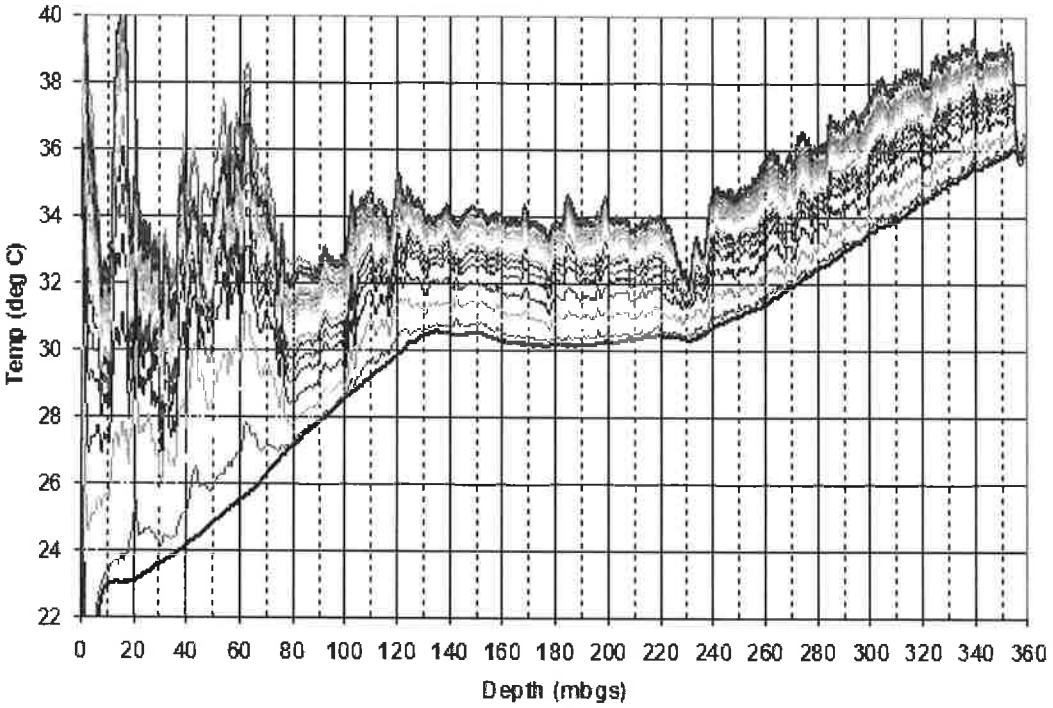


Figure 33. Thermal logs acquired during operation of the DTS in NC-EWDP-24PB.

Experiment 1 - Linear heat source : weak thermal gradient (far field)

Objectives:

(A) Test spatial and temporal resolution of DTS fiber array using RTD array as reference

(B) Test heat-pulse imaging capability to determine thermal conductivity of ROM salt by varying pulse duration (changing depth of heat penetration)

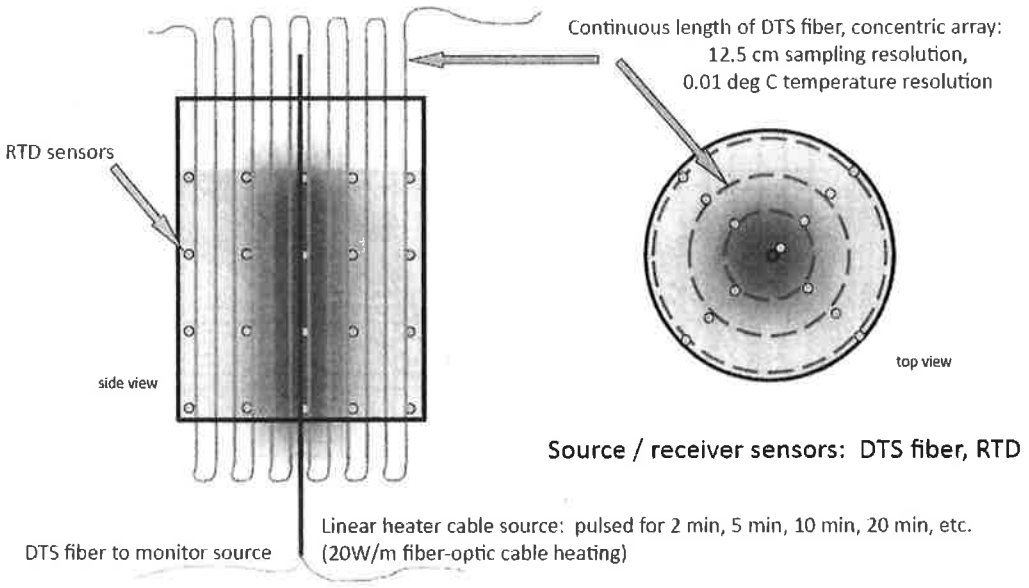


Figure 34. Schematic of the Batch Can Fiber-Optic Salt Test



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

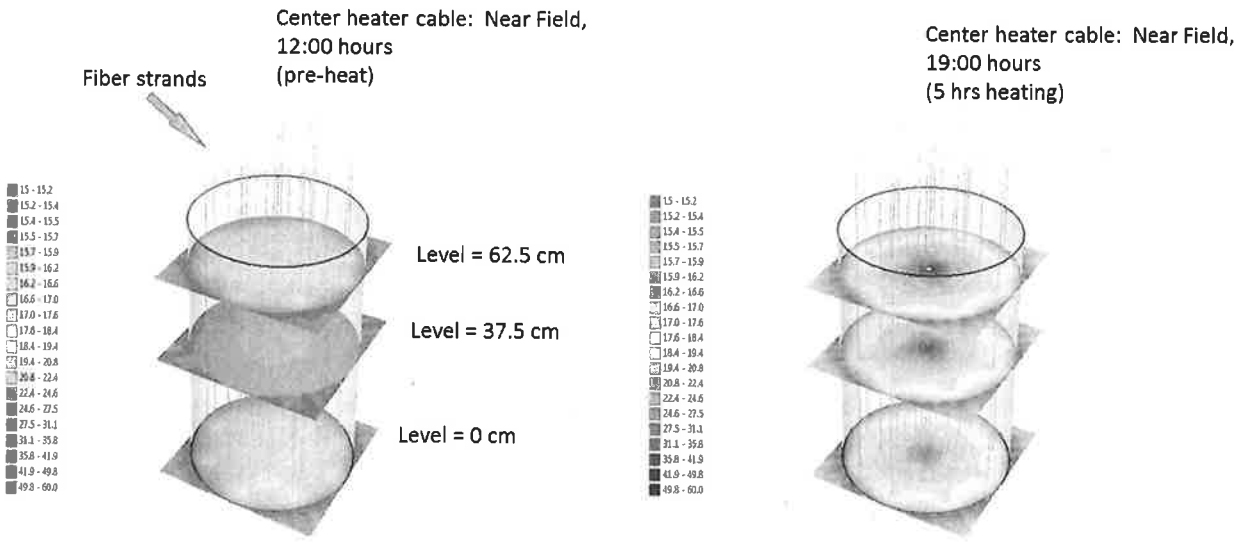


Figure 36. Data Acquired using the Fiber-Optic System prior to and after Heating for 5 hours.

10. References

Arguello, J. G. (2014). Potential use of geologic rock salt for fuel cycle sustainability – a computational modeling perspective. In 48th US Rock Mechanics / Geomechanics Symposium, number ARMA 14–7040.

Arguello, J. G. and Rath, J. S. (2013). SIERRA Mechanics for coupled multi-physics modeling of saltrepository behavior for NEAMS applications. In Mechanical Behavior of Salt VII, number SAND2011–6761C. MINES Paris Tech, Taylor & Francis, 2012.

Arguello, J. G. and Rath, J. S. Revisiting the 1980's WIPP Room D and B in-situ experiments: Performing thermo-mechanical simulations of rock salt using an stat-of-the-art code suite. In 47th US Rock Mechanics / Geomechanics Symposium, number ARMA 13–370.

Balay, S., Abhyankar, S., Adams, M. F., Brown, J., Brune, P., Buschelman, K., Eijkhout, V., Gropp, W. D., Kaushik, D., Knepley, M. G., McInnes, L. C., Rupp, K., Smith, B. F., and Zhang, H. (2014). PETSc users manual. ANL-95/11 - Revision 3.5, Argonne National Laboratory, http://www.mcs.anl.gov/petsc.

Beauheim, R. L., and Roberts, R. M. (2002). "Hydrology and hydraulic properties of a bedded evaporite formation," *J. Hydrol.*, 259, 66-88.

Bechthold W., Smailos E., Heusermann S., Bollingerfehr W., Sabet B.B., Rothfuchs T., Kamlot P., Grupa J., Olivella S., and Hansen F.D. (2004). Backfilling and sealing of underground repositories for radioactive waste in salt (Bambus II project). Final Report for European Atomic Energy Community EUR 20621, Office for Official Publications of the European Communities, Luxembourg. ISBN 92-894-7767-9.

Bechthold, W., T. Rothfuchs, A. Poley, M. Ghoreychi, S. Heusermann, A. Gens, and S. Olivella, (1999). *Backfilling and Sealing of Underground Respositories for Radioactive Waste in Salt (BAMBUS Project)*, EUR 19124 EN, Belgium: European Commission.

Blankenship, D.A. and Stickney, R.G. (1983). *Nitrogen Gas Permeability Tests at Avery Island.* ONWI-190(3), Columbus, OH: Office of Nuclear Waste Isolation.

Blanco Martín, L., Wolters, R., Rutqvist, J., Lux, K. H., & Birkholzer, J. T. (2015). Comparison of two simulators to investigate thermal–hydraulic–mechanical processes related to nuclear waste isolation in saliferous formations. *Computers and Geotechnics*, *66*, 219-229.

Bostick, F. X. (2000). Field Experimental Results of Three-Component Fiber-Optic Seismic Sensors, SEG Expanded Abstract.

Bradshaw, R.L. and W.C. McClain (1971). *Project Salt Vault: A demonstration of the disposal of high activity solidified wastes in underground salt mines*. ORNL-4555, Oak Ridge National Laboratory.

Callahan, G.D., Guerin, D.C., Levitt, D.G., Newell, D.L., Robinson, B.A., and Van Sambeek, L.L. (2012). *Salt Repository Synthesis Data of Non-Delaware Basin and International Programs for the Storage/Disposal of Nuclear Waste*. FCRD-UFD-2012–000312, U.S. DOE, Used Fuel Disposition Campaign.

Callahan, G. D. (1999) Crushed salt constitutive model. SAND98–2680, Sandia National Laboratories, Albuquerque, NM.

Caporuscio, F. A., H. Boukhalfa, M. C. Cheshire, A. B. Jordan, and M. Ding (2013). Brine Migration Experimental Studies for Salt Repositories, FCRD Used Fuel Disposition Campaign Milestone FCRD-UFD-2013-000204, September 25, 2013.

Caporuscio, F. A.; Boukhalfa, H.; Cheshire, M. C.; Ding, M. (2014) *Brine migration experimental studies for salt repositories*, Los Alamos National Laboratory Report LA-UR-14-26603: http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-14-26603.

Carter, J.T., F.D. Hansen, R. Kehrman, and T.A. Hayes (2011). *A Generic Salt Repository for Disposal of Waste from a Spent Nuclear Fuel Recycle Facility*. Savannah River National Laboratory Report SRNL-RP-2011-00149.

Carter, J.T., Rodwell, P.O., Robinson, B.A., and B. Kehrman (2012). Defense Waste Salt Repository Study. Prepared for U.S. Department of Energy Used Fuel Disposition, FCRD-UFD-2012-000113.

Carter, J., and Leduc, D. (2013). *Nuclear Fuels Storage and Transportation Planning Project Inventory Basis*. FCRD-NFST-2013-000263, Rev 0. Washington, DC: U.S. Department of Energy.

Carter, J. T., and D. J. McCabe, (2014). *ADDENDUM TO: Costing Study for a Generic Salt Repository: Systems Engineering and Analysis in Support of a Policy Review of Comingling Decision and Related System Design Considerations – Updated*, Savannah River National Laboratory Report SRNL-RP-2014-00192, Rev. 0 ADDENDUM, July 1, 2014 (Official Use Only).

Castagna, S., Olivella, S., Lloret, A., and Alonso, E. E. (2000). Computational Methods for Flow and Transport in Porous Media, chapter Experimental and Numerical Investigation of Porosity Variations in Saline Media Induced by Temperature Gradients, pages 327–338. Kluwer Academic Publishers.

Clayton, D.J. and C.W. Gable (2009). 3-D Thermal Analyses of High-Level Waste Emplaced in a Generic Salt Repository, Advanced Fuel Cycle Initiative, AFCI-WAST-PMO-MI-DV-2009-000002, SAND2009-0633P. LA-UR-09-0089.

Clayton, D. J., Lee, M. Y., Holcomb, D. J., and Bronowski, D. R. (2010). Crushed salt reconsolidation at elevated temperatures. In 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium.

Coyle, A. J., J. Eckert, and H. Kalia (1987). *Brine Migration Test Report: Asse Salt Mine, Federal Republic of Germany*, BMI/ONWI---624, Office of Nuclear Waste Isolation, Battelle Memorial.

Czaikowski, O., Wieczorek, K., and Krohn, K. P. (2012). Compaction of salt backfill – new experiments and numerical modelling. In Mechanical Behavior of Salt VII, pages 155–160. MINES Paris Tech, Taylor & Francis.

Deal, D.E., R.J. Abitz, D.S. Belski, J.B. Case, M.E. Crawley, C.A. Givens, P.P.J. Lipponner, D.J. Milligan, J. Myers, D.W. Powers, and M.A. Valdivia (1995). *Brine Sampling and Evaluation Program, 1992–1993 Report and Summary of BSEP Data Since 1982*. Carlsbad, NM: U.S. Department of Energy, WIPP Project Office.

DOE (US Department of Energy) (2014), Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel, October 2014 (http://www.energy.gov/ne/downloads/assessment-disposal-options-doe-managed-high-level-radioactive-waste-and-spent-nuclear).

DOE (U.S. Department of Energy). (2013). *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*, http://energy.gov/downloads/strategy management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste. January 2013.

DOE (U.S. Department of Energy). (2012a). *Used Fuel Disposition Campaign Disposal Research and Development Roadmap*. FCR&D-USED-2011-000065, REV 1. U.S. Department of Energy, Used Fuel Disposition Campaign, Washington, D.C., September 2012.

DOE (U.S. Department of Energy) (2012b). A Management Proposal for Salt Defense Disposal Investigations (SDDI) for the Disposal of DOE---EM Managed Wastes, U.S. Department of Energy Carlsbad Field Office document, February 2012.

DOE (U.S. Department of Energy) (2011). A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP, DOE Carlsbad Field Office Report DOE/CBFO-11-3470.

DOE Carlsbad Field Office (DOE CBFO), (2012). A Management Proposal for Salt Defense Disposal Investigations (SDDI) for the Disposal of DOE-EM Managed Wastes, U.S. Department of Energy Carlsbad Field Office document, February 2012.

DOE (U.S. Department of Energy). (1996). *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant.* DOE/CAO-1996–2184, Washington, DC: U.S. DOE.

Doeven, I., P. P. Soullié, and L. H. Vons (1983). *Convergence measurements in the dry-drilled 300 m borehole in the Asse-II saltmine.* European Applied Research Reports – Nuclear Science and Technology Section, 5(2):267–324.

Empson, F.M. (1961). *Status Report on Waste Disposal in Natural Salt Formations: III.* ORNL-3053, Oak Ridge National Laboratory.

Freifeld, B.M., Doughty, C., and Finsterle, S. (2006). Preliminary Estimates of Specific Discharge and Transport Velocities near Borehole NC-EWDP-24PB, June 2006, LBNL-60740.

Freifeld, B. M ., Finsterle, S., Onstott, T. C., Toole P., and Pratt, L. M. (2008). Ground surface temperature reconstructions: using in situ estimates for thermal conductivity acquired with a fiber-optic distributed thermal perturbation sensor, Geophys. Res. Lett. 35, L14309, doi:10.1029/2008GL034762, LBNL-1755E.

Hammond, G. E. and Lichtner, P. C. (2010). Field-scale modeling for the natural attenuation of uranium at the Hanford 300 Area using high performance computing. Water Resources Research, 46: W09527. doi: 10.1029/2009WR008819.

Hammond, G. E., Lichtner, P. C., and Mills, R. T. (2014). Evaluating the performance of parallel subsurface simulators: An illustrative example with PFLOTRAN. Water Resources Research, 50. doi: 10.1002/2012WR013483.

Hansen, F. D., Howard, C., Kuhlman, K. L., & Holland, J. (2015a). Capturing Early Evolution of Salt Openings. American Rock Mechanics Association, 49th US Rock Mechanics / Geomechanics Symposium. San Francisco, CA.

Hansen, F. D., Leigh, C., Steininger, W., Bollingerfehr W., and von Berlepsch, T. (2015) Proceedings of the 5th US/German Workshop on Salt Repository Research, Design and Operation. FCRD-UFRD-2015-00514.

Hansen, F. Popp, T., Wieczorek, K., and Stuhrenberg, D. (2014) Granular Salt Summary Reconsolidation Principles and Applications. FCRD-UFD-2014-000590 Rev. 0, DOE Office of Nuclear Energy Used Fuel Disposition Campaign Report.Hansen, F.D. and Leigh, C.D. (2011). *Salt Disposal of Heat-Generating Nuclear Waste*. SAND2011–0161, Albuquerque, NM: Sandia National Laboratories.

Hansen, F. D. (2003). The disturbed rock zone at theWaste Isolation Pilot Plant. SAND2003-3407, Sandia National Laboratories, Albuquerque, NM.

Harp D.R., P.H. Stauffer, P.K. Mishra, D.G. Levitt, and B.A. Robinson (2014). Thermal Modeling of High-Level Nuclear Waste Disposal in a Salt Repository. Nuclear Technology, Volume 187, Number 3, September 2014, Pages 294-307.

Howard, C. (2014). Mechanical and Hydrological Characterization of the Near-field Surrounding Excavations in a Geologic Salt Formation. FCT-UFD-2014-000626, SAND2014-17822 R.

Hyoung-Choon, E., H. Park, and H.-S. Yoon (2010). Preparation of anhydrous magnesium chloride from ammonium magnesium chloride hexahydrate. Advanced Powder Technology, Volume 21, Issue 2, March 2010, Pages 125–130.

Jordan, A.B., Boukhalfa, H.; Caporuscio, F.A.; Robinson, B.A., Stauffer, P.H. (2015). Hydrous Mineral Dehydration around Heat-Generating Nuclear Waste in Bedded Salt Formations, Environmental Science & Technology, accepted pending revisions.

Jordan, A. B., P. H. Stauffer, D. Reed, H. Boukhalfa, F. A. Caporuscio, and B. A. Robinson (2014). *Draft Test Plan for Brine Migration Experimental Studies in Run-of-Mine Salt Backfill*, DOE Office of Nuclear Energy Used Fuel Disposition Campaign Milestone M4FT-14LA0818062.

Kessels, W., H.-K. Feddersen, D. Flach, I. Flentge, C. Frohn, H. Gies, G. Gommlich, J. Hahn, B. Hente, N. Jockwer, K. Klarr, S. Pfeifer, T. Rothfuchs, M. Schmidt, and P. Wieczorek (1986). *Results of Temperature Test 6 in the Asse Salt Mine*, 2 Vol. EUR 10827 EN, Commission of the European Communities.

Kim, J. (2010). Sequential Methods for Coupled Geomechanics and Multiphase Flow. PhD thesis, Stanford University.

Kostka, T. D. and Templeton, J. A. (2010). Coupled thermomechanical modeling using dissimilar geometries in Arpeggio. SAND2010–7746, Sandia National Laboratories, Albuquerque, NM.

Krause, W.B. (1983). *Avery Island Brine Migration Tests: Installation, Operation, Data Collection, and Analysis*. ONWI-190(4), Columbus, OH: Office of Nuclear Waste Isolation.

Krumhansl, J.L., Stein, C. L., Jarrell, G. D., and Kimball, K. M. (1991). Summary of WIPP Room B Heater Test Brine and Backfill Material Data, SANDIA REPORT SAND90–0626.

Kuhlman, K. (2014). *Summary Results for Brine Migration Modeling Performed by LANL, LBNL, and SNL for the UFD Program*, DOE Office of Nuclear Energy Report FCRD-UFD 2014-000071.

Kuhlman, K.L. and B. Malama (2013). *Brine Flow in Heated Geologic Salt*. SAND2013–1944, Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L. and S.D. Sevougian (2013). Establishing the Technical Basis for Disposal of Heat-Generating Waste in Salt. FCRD-UFD-2013–000233, US DOE, Used Nuclear Fuel Disposition Campaign.

Kuhlman, K.L., Wagner, S., Kicker, D., Kirkes, R., Herrick, C.G., and Guerin, D.C. (2012). *Review and Evaluation of Salt R&D Data for Disposal of Nuclear Waste in Salt*. FCRD-UFD-2012–000380, U.S. DOE, Used Nuclear Fuel Disposition Campaign.

Lichtner, P. C., Hammond, G. E., Lu, C., Karra, S., Bisht, G., Andre, B., Mills, R. T., and Kumar, J. (2014). PFLOTRAN user manual: A massively parallel reactive flow and transport model for describing surface and subsurface processes.

MacKinnon, R.J., Sevougian, S.D., Leigh, C.D., and Hansen, F.D. (2012). *Towards a Defensible Safety Case for Deep Geologic Disposal of DOE HLW and DOE SNF in Bedded Salt.* SAND2011–6032. Albuquerque, NM: Sandia National Laboratories.

Martinez, M. J., Stone, C. M., Notz, P. K., Turner, D. Z., Hopkins, P. L., Subia, S., Jove-Colon, C., Moffat, H. K., Bean, J. E., Dewers, T., Klise, K., Red-Horse, J., Field, R., Mesh, M., Davidson, S., Yoon, H., Carnes, B., Alger, N., Bishop, J., and Newell, P. (2011). Computational thermal, chemical, fluid, and solid mechanics for geosystems management. SAND2011–6643, Sandia National Laboratories, Albuquerque, NM.

Matalucci, R. V. (1987). In Situ Testing at the Waste Isolation Pilot Plant, Sandia Report, SAND87-2382.

McMahon, K. (2012) Update of the Used-Fuel Disposition Campaign Implementation Plan, DOE Office of Nuclear Energy Report FCRD-UFD-2012-000334.

Mestayer, J., S. Grandi Karam, B. Cox, P. Wills, A. Mateeva, J. Lopez, D. Hill, & A. Lewis (2012a). Distributed Acoustic Sensing for Geophysical Monitoring, 74th EAGE Conference & Exhibition incorporating SPE EUROPEC 2012 Copenhagen, Denmark, 4-7 June 2012

Mestayer, J., B. Cox, P. Wills, D. Kiyashchenko, J. Lopez, M. Costello, S. Bourne, G. Ugueto, R. Lupton, G. Solano, D. Hill, & A. Lewis (2012b). Field Trials of Distributed Acoustic Sensing for Geophysical Monitoring, SEG San Antonio 2011 Annual Meeting.

Miller, D., T. Parker, S. Kashikar, M. Todorov, and T. Bostick (2012). Vertical Seismic Profiling Using a Fiber-optic Cable as a Distributed Acoustic Sensor, 74th EAGE Conference & Exhibition incorporating SPE EUROPEC 2012 Copenhagen, Denmark, 4-7 June 2012.

Molecke, M. A. (1986) Measurement of hydrochloric acid vapors in WIPP from in situ experiments. Sandia National Laboratory, Memo of Record #303090, WP03146.

Molecke, M.A. (1984). *Test Plan: Waste Package Performance Technology Experiments for Simulated DHLW (WPP-DHLW-TE).* Albuquerque, NM: Sandia National Laboratories.

Molecke, M.A. and Matalucci; R.V. (1984). *Preliminary Requirements for the Emplacement and Retrieval of Defense High-level Waste (DHLW) Tests in the Waste Isolation Pilot Plant (WIPP).* SAND84–1444, Albuquerque, NM: Sandia National Laboratories.

Morgan, K.Z. (1959) Health physics division annual progress report for period ending July 31, 1959. ORNL-2806, Oak Ridge National Laboratory.

Munson, D.E., Hoag, D.L., Blankenship, D.A., Jones, R.L., Woerner, S.J., Baird, G.T., and Matalucci, R.V. (1997a). *Construction of the Thermal/Structural Interactions in situ Tests at the Waste Isolation Pilot Plant (WIPP).* SAND87–2685, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Hoag, D.L., Blankenship, D.A., DeYonge, W.F., Schiermeister, D.M., Jones, R.L., and Baird, G.T. (1997b). *Instrumentation of the Thermal/Structural Interactions in situ Tests at the Waste Isolation Pilot Plant (WIPP).* SAND87–2686, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Petney, S.J.V., Christian-Frear, T.L., Ball, J.R., Jones, R.L., and Northrop-Salazar, C.L. (1992) *18 W/m^2 Mockup for Defense High-level Waste (Rooms A): in situ Data Report, Vol. II – Thermal Response Gages (February 1985 – June 1990).* SAND90–2749, Albuquerque, NM:Sandia National Laboratories.

Munson, D.E., Petney, S.J.V., Clancy, R.M., Ball, J.R., Jones, R.L., and Northrop-Salazar, C.L. (1991). *18 W/m^2 Mockup for Defense High-level Waste (Rooms A): in situ Data Report: Vol. 1 – Mechanical response gages (February 1985 – June 1990), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program.* SAND90–2748, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Jones, R.L., Ball, J.R., Clancy, R.M., Hoag, D.L., and Petney, S.J.V. (1990). *Overtest forSimulated Defense High-level Waste (Room B): in situ Data Report (May 1984 – February 1988), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program.* SAND89–2671, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Jones, R.L., Hoag, D.L., and Ball, J.R. (1988). *Mining development test (Room D): in situ data report (March 1984 – May 1988): Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program.* SAND88–1460, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., Jones, R.L., Hoag, D.L., and Ball, J.R. (1987). *Heated Axisymmetric Pillar Test (Room H): in situ Data Report (February 1985 – April 1987), Waste Isolation Pilot Plant (WIPP) thermal/structural interactions program*. SAND87–2488, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E. and Matalucci, R.V. (1986). *Planning, Developing, and Fielding of Thermal/Structural Interactions in situ Tests for the Waste Isolation Pilot Plant (WIPP)*. SAND83–2048, Albuquerque, NM: Sandia National Laboratories.

Munson, D. E. and Dawson, P. R. (1979). Constitutive model for the low temperature creep of salt (with application to WIPP). SAND79–1853, Sandia National Laboratories, Albuquerque, NM.

NAS (National Academy of Sciences) Committee on Waste Disposal. (1957). *The Disposal of Radioactive Waste on Land*. Publication 519. Washington, DC: National Academy of Sciences–National Research Council.

Nelson, R. A., and N. Buschman (2012). Salt Disposal Investigations to Study Thermally Hot Radioactive Waste In A Deep Geologic Repository in Bedded Rock Salt – 12488, *proc. WM2012 Conference*, Phoenix, Arizona, February 26 --- March 1, 2012.

Notz, P. K., Subia, S. R., Hopkins, M. M., Moffat, H. K., and Noble, D. R. (2007). Aria 1.5: User manual. SAND2007–2734, Sandia National Laboratories, Albuquerque, NM.

Nowak, E. J., and McTigue, D. F. (1987). Interim Results of Brine Transport in the Waste Isolation Pilot Plant (WIPP), Sandia Report, SAND87-0880.

Olivella, S., S. Castagna, E. E. Alonso, and A. Lloret (2011). Porosity variations in saline media induced by temperature gradients: experimental evidences and modeling. *Transport in porous media* 90, no. 3, p 763---777.

Olivella, S., Carrera, J., Gens, A., and Alonso, E. E. (1994). Nonisothermal multiphase flow of brine and gas through saline media. Transport in Porous Media, 15:271–293.

Otto, S., and A. Miller (2013). Salt Instrumentation Research and Development Status Report. LA-UR-13-27467, Los Alamos National Laboratory, Los Alamos, NM.

Robinson, B. A., D. J. Weaver, P. H. Stauffer, R. A. Nelson, and N. Buschman (2014). The Salt Defense Disposal Investigations (SDDI): Current Status and Future Plans –14486, *proc. WM2014 Conference*, Phoenix, Arizona, March 2-6, 2014.

Robinson, B. A., N. Z. Elkins, and J. T. Carter (2012). Development of a U.S. Nuclear Waste Repository Research Program in Salt, *Nuclear Technology*, 180, 122-138.

Rothfuchs, T., J. Dittrich, J. Droste, J. Müller, and C.-L. Zhang (2003). *Final Evaluation of the Project "Thermal Simulation of Drift Emplacement" (TSDE-Project)*, GRS-194, Köln: Gesellschaft für Anlagenund Reaktorsicherheit (GRS) mbH.

Rothfuchs, T., L. Vons, M. Raynal, J.C. Mayor (1995). *The HAW Project: Test Disposal of Highly Radioactive Radiation Sources in the Asse Salt Mine*. EUR 16688 EN, Belgium:European Commission.

Rothfuchs, T., K. Wieczorek, H.K. Feddersen, G. Stupendahl, A.J. Coyle, H. Kalia, and J. Eckert (1988). *Brine migration test, Asse salt mine, Federal Republic of Germany: Final report*. GSF-Bericht 6/88, Munich:Office of Nuclear Waste Isolation and Gesellschaft fur Strahlen-und Umweltforschung.

Rutqvist, J., Blanco Martın, L., Mukhopadhyay, S., Houseworth, J., and Birkholzer, J. (2014). Modeling coupled THMC processes and brine migration in salt at high temperatures. FCRD-UFD-2014–000341, US Department of Energy Used Fuel Disposition Campaign.

Rutqvist, J. (2011). Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid flow and crustal deformations. Computers & Geosciences, 37:739–750.

Rutqvist, J. and Tsang, C.-F. (2003). TOUGH-FLAC: A numerical simulator for analysis of coupled thermal-hydrological-mechanical processes in fractured and porous geologic media under multiphase flow conditions. In Proceedings, TOUGH Symposium, 2003.

Sevougian, S. D. and R. J. MacKinnon (2014). *A Decision Methodology for Prioritizing R&D Supporting Geologic Disposal of SNF/HLW in Salt – 14030*, Waste Management 2014 Conference Proceedings, Phoenix, AZ, March 2-6, 2014.

Sevougian, S. D., R. J. MacKinnon, B. A. Robinson, C. D. Leigh, and D. J. Weaver (2013). RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes, FCRD-UFD-2013-000161, Rev. 0, SAND2013-4386P, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., May 31, 2013, http://www.energy.gov/ne/listings/document-library.

SIERRA Solid Mechanics Team (2011). Adagio 4.20 user's guide. SAND2011–1825, Sandia National Laboratories, Albuquerque, NM.

Stauffer, P. H., A. B. Jordan D. R. Harp, G. A. Zyvoloski, H. Boukhalfa, F. A. Caporuscio, T. A. Miller, and B. A. Robinson (2014a). *Thermo-hydrological and chemical (THC) modeling to support Field Test Design*, Used Fuel Disposition Campaign Milestone M4FT-14LA0818064.

Stauffer, P., B. Robinson, R. Nelson, D. Harp, A. Jordan, H. Boukhalfa, Y. Laybed, and J. Ten Cate (2014b). Simulations in Support of the Salt Defense Disposal Initiative (SDDI): Water and Salt Transport Driven by Heat Generating Nuclear Waste in Bedded Salt – 14512, *proc. WM2014 Conference*, Phoenix, Arizona, March 2-6, 2014.

Stauffer, P. H., D. R. Harp, A. B. Jordan, Z. Lu, S. Kelkar, Q. Kang, J. Ten Cate, H. Boukhalfa, Y. Labyed, P. W. Reimus, F. A. Caporuscio, T. A. Miller, and B. A. Robinson (2013). *Coupled model for heat and water transport in a high level waste repository in salt*, Los Alamos National Laboratory Document LA-UR-13-27584.

Stauffer, P., D. Harp, and B. A. Robinson (2012). Model Development and Analysis of the Fate and Transport of Water in a Salt-Based Repository, Used Fuel Disposition Campaign Milestone M2FT-12LA08180112, LANL Report LA-UR-12-25050.

Stickney, R.G. and Van Sambeek, L.L. (1984). *Summary of the Avery Island Field Testing Program.* RSI-0225, RE/SPEC, Inc., Rapid City, SD.

Stickney, R.G. (1987a). *Measured Data from the Avery Island, Louisiana, Heated Corejacking Tests.* BMI/ONWI-666, Columbus, OH: Office of Nuclear Waste Isolation.

Stickney, R.G. (1987b). *Results of an Accelerated Borehole Closure Testing Program at Avery Island, Louisiana.* ONWI-665, Columbus, OH: Office of Nuclear Waste Isolation.

Stone, C. M., Holland, J. F., Bean, J. E., and Arguello, J. G (2010). Coupled thermal-mechanical analyses of a generic salt repository for high level waste. In 44th US Rock Mechanics / Geomechanics Symposium and 5th US-Canadian Rock Mechanics Symposium, number ARMA 10180.

Tyler, L.D., Matalucci, R.V., Molecke, M.A., Munson, D.E., Nowak, E.J., and Stormont, J.C. (1988). *Summary Report for the WIPP Technology Development Program for Isolation of Radioactive Waste.* SAND88–0844, Albuquerque, NM: Sandia National Laboratories.

Van Sambeek, L.L., Stickney, R.G., and DeJong, K.B. (1983). *Avery Island Heater Tests: Measured Data for 1,000 Days of Heating.* ONWI-190(5), Columbus, OH: Office of Nuclear Waste Isolation.

Waldman, H. and Stickney, R.G. (1984). *Measured Data from the Avery Island Site C Heater Test.* BMI/ONWI-529, Columbus, OH: Office of Nuclear Waste Isolation.

Wieczorek, K., Forster, B., Rothfuchs, T., Zhang, C.-L., Olivella, S., Kamlot, P., Gunther, R.-M., and Lerch, C (2010). THERESA subproject MOLDAU: Coupled thermal-hydrological-mechanicalchemical processes in repository safety assessment. GRS-262, Gesellschaft fur Anlagenund Raktosicherheit (GRS).

Wolters, R., Lux, K.-H., and Dusterloh, U. (2012) Evaluation of rock salt barriers with respect to tightness: Influence of thermomechanical damage, fluid infiltration and sealing/healing. In Mechanical Behavior of Salt VII, pages 435–440. MINES Paris Tech, Taylor & Francis.

Zhang, K., Wu, Y.-S., and Pruess, K. User's guild for TOUGH2-MP - a massively parallel version of the TOUGH2 code. LBNL-315E, Lawrence Berkeley National Laboratory, Berkeley, CA, May 2008.

Zyvoloski, G. A., Robinson, B. A., Dash, Z. V., and Trease, L. L. Models and methods summary for the FEHM application. SC-194, Los Alamos National Laboratory, Los Alamos, NM, July 1999.

Enclosure 2

Project Plan: Salt in Situ Heater Test

Spent Fuel and Waste
Disposition

Project Plan: Salt in Situ Heater Test

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology

Sandia National Laboratories
Los Alamos National Laboratory
Lawrence Berkeley National Laboratory

April 30, 2018
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SUMMARY

This project plan gives a high-level description of the US Department of Energy Office of Nuclear Energy (DOE-NE) Spent Fuel and Waste Disposition (SFWD) campaign *in situ* borehole heater test project being planned for the Waste Isolation Pilot Plant (WIPP) site This plan provides an overview of the schedule and responsibilities of the parties involved. This project is a collaborative effort by Sandia, Los Alamos, and Lawrence Berkeley National Laboratories to execute a series of small-diameter borehole heater tests in salt for the DOE-NE SFWD campaign. Design of a heater test in salt at WIPP has evolved over several years. The current design was completed in fiscal year 2017 (FY17), an equipment shakedown experiment is underway in April FY18, and the test implementation will begin in summer of FY18.

The project comprises a suite of modular tests, which consist of a group of nearby boreholes in the wall of drifts at WIPP. Each test is centered around a packer-isolated heated borehole (5" diameter) containing equipment for water-vapor collection and brine sampling, surrounded by smaller-diameter (2" diameter) satellite observation boreholes. Observation boreholes will contain temperature sensors, tracer release points, electrical resistivity tomography (ERT) sensors, fiber optic sensing, and acoustic emission (AE) measurements, and sonic velocity sources and sensors. These satellite boreholes will also be used for plugging/sealing tests. The first two tests to be implemented will have the packer-isolated borehole heated to 120°C, with one observation borehole used to monitor changes. Follow-on tests will be designed using information gathered from the first two tests, will be conducted at other temperatures, will use multiple observation boreholes, and may include other measurement types and test designs.

This project plan satisfies SFWST milestone M3SF-18SN010303033, as part of the SNL "Salt Disposal R&D" work package.

REVISION HISTORY

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ACRONYMS

AE	acoustic emissions
BCP	baseline change proposal
CBFO	DOE-EM Carlsbad Field Office
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DRZ	disturbed rock zone
ERT	electrical resistivity tomography
EVMS	earned value management system
FY	fiscal year
IPT	integrated project team
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
M&O	Management and Operations
NWP	Nuclear Waste Partnership (WIPP M&O contractor)
PICS:NE	Project Information Collection System: Nuclear Energy
QA	quality assurance
RTD	resistive temperature device
SDI	salt disposal investigations
SNL	Sandia National Laboratories
SFWD	Spent Fuel and Waste Disposition
SFWST	Spent Fuel and Waste Science and Technology
TCO	test coordination office
THMC	thermal-hydraulic-mechanical-chemical
U.S.	United States
WBS	work breakdown structure
WIPP	Waste Isolation Pilot Plant

1. INTRODUCTION

1.1 Field Test Project Motivation

The long-term goals of the DOE-NE Spent Fuel and Waste Disposition (SFWD) campaign field-testing project for salt are related to the permanent isolation safety case for disposal of heat-generating radioactive waste in a generic salt repository concept. This borehole heater test is one component of the field-testing campaign, focused on the quantification of brine inflow and composition (Stauffer et al., 2015; Kuhlman et al. 2017; Johnson et al. 2017b). The transient evolution of brine inflow and the brine composition after excavating a drift or borehole are initial conditions relevant to the long-term performance assessment of a generic salt repository system. This field test is being conducted within the context of the larger testing program for generic salt systems, which includes laboratory testing and larger conceptual field testing. The goals of this field test are to:

1) improve understanding of brine availability and brine composition in bedded salt;
2) collect datasets for parameterizing numerical models, populating constitutive models, and generally improving process understanding;
3) improve understanding of bedded salt acid vapor generation mechanisms during heating; and
4) rebuild in-house expertise for implementing *in situ* experiments in salt.

The proposed borehole heater tests are comprised of relatively low-cost repeatable tests performed across a set of adjacent boreholes (one central heater borehole and multiple surrounding observation boreholes). Heated tests will be used to assess changes in physical-chemical properties associated with brine and vapor liberation and migration at elevated temperature. These borehole tests will include international collaboration on model prediction, validation, and follow-on test design.

The main focus of the first round of borehole heater tests is brine availability to better understand how much brine may flow into an excavation (e.g., borehole or room). Brine potentially leads to waste package corrosion, limits closure of brine-filled cavities, or facilitates radionuclide transport. In a generic salt repository for "hot" radioactive waste (e.g., above brine boiling temperature at the waste package surface) water vapor will in general be driven away from hot waste packages, while brine will still migrate towards the excavation. A convection process may set up around the waste, driving salts to precipitate near the waste package and creep closure will reconsolidate backfill and close gaps around the waste package to create a relatively dry, intact, low-permeability zone around the waste packages. As the radioactive decay heat decreases, the temperature will drop below the brine boiling temperature, and additional liquid may then migrate back toward the waste packages. However, the low-permeability salt surrounding the heater will minimize the amount of brine that can flow from the far field to the waste packages. Knowledge of brine availability and brine composition facilitates understanding long-term behavior of consolidated salt around waste packages and possible brine-radionuclide interactions that may affect transport.

In all salt disposal systems, the far-field ultra-low permeability of the salt provides the primary natural barrier that contains radioactive waste over performance assessment relevant time scales (10^4 to 10^6 years). Salt creep closes open excavations and fractures in the near field that could facilitate transport. This borehole heater project is focused on the quantification of inflow rates and brine composition in the near field (at scales of cm to m from heat source) at relatively short time scales (weeks to months). This is essentially to improve process understanding and to develop an initial condition in the long-term performance of a generic salt repository system, for which we have great confidence in its ability to provide isolation from the shallow geosphere.

1.2 Field Test Project Description

The project is primarily focused on brine availability to a small-diameter (10 to 15 cm [4" to 6"]) horizontal borehole. Understanding the amount of brine available to flow into such a borehole and a

relevant excavation in a generic salt repository involves understanding: 1) the sources of brine in salt, and 2) the mechanism of brine migration through the disturbed rock zone (DRZ) surrounding an excavation at ambient and elevated temperatures. Each test will collect unique data on the time-variable brine composition. Brine composition will reflect the transport of multiple types of brine present in a bedded salt formation (e.g., intragranular fluid inclusions, intergranular brine, water evolved from hydrous minerals). This horizontal borehole heater test will quantify relevant thermal-hydrological-mechanical-chemical (THMC) processes in salt, which will be upscaled to the drift scale. The main benefit of a horizontal test interval is avoidance of mapped clay or anhydrite layers. Temperature, brine inflow rate and composition, resistivity, acoustic emission, and gas samples will be collected to develop validation datasets for existing and future of numerical models. The project is designed to produce data for conceptual process validation, rather than as part of a more complex disposal demonstration (e.g., DOE CBFO 2011 & 2013).

Each test will have a central packer-isolated borehole with smaller-diameter satellite observation boreholes drilled around the heater borehole (Figure 1; Kuhlman et al. 2017). The heater borehole will be used to quantify brine inflow by circulating dry nitrogen gas through the packer-isolated borehole, while monitoring the humidity and temperature of the gas stream leaving the borehole. The observation boreholes will include the ability to monitor evolution of the salt resistivity, temperature, and strain through electrical resistivity tomography (ERT) and fiber optic sensing, and the salt mechanical properties through ultrasonic wave velocity and acoustic emission (AE) sensors. Both gas and liquid samples will be collected from the heated borehole to monitor brine composition and tracer (deuterated water) migration through the salt.

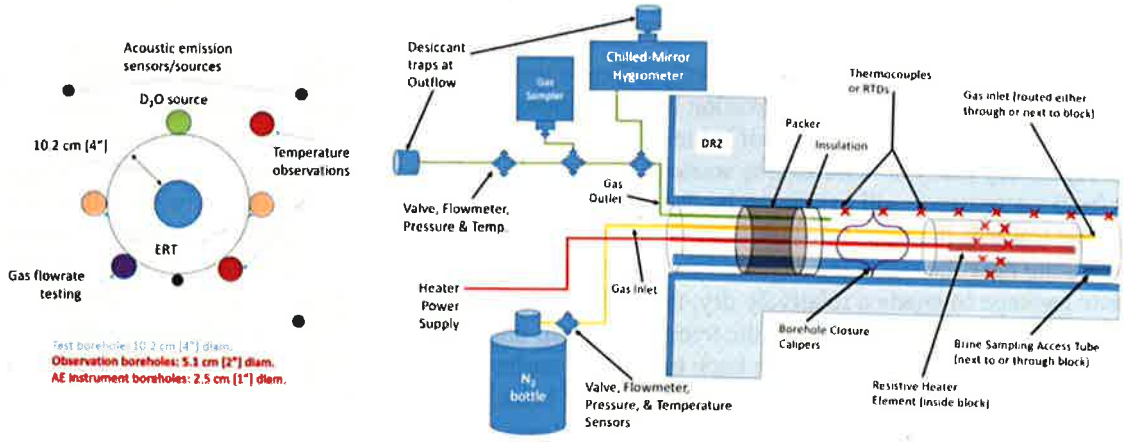

Figure 1. Borehole layout view (left) and longitudinal cross-section view (right) of typical heater test. Note: not to scale.

As of April 2018, equipment testing is underway in existing (> 4 yr old) horizontal WIPP boreholes in drift E-140, having started in February 2018 with test installation and pressurization of the packer system. This system was developed following the test plan as best as possible (Johnson et al. 2017b), but is being implemented with available materials, boreholes, and limited budget. The test will include: dry nitrogen gas circulation with a humidity gage (not a chilled-mirror hygrometer in the initial test) and gas sampling to measure water inflow, a heater at 120° C, and a sampling port for collecting liquid brine samples. The data collected from these existing boreholes will be preliminary compared to data collected from new boreholes, as the existing boreholes are no longer circular in cross-section and the potential initial pulse of brine inflow (~first year after drilling) has long passed. However, these serve well as the test bed for equipment assessment. A test of LBNL's ERT system will also be conducted before testing in newly drilled boreholes. Measurements of the internal borehole temperature, using thermocouples or resistance temperature detectors (RTDs), and closure, using a borehole closure caliper, will also be made. This

initial test in existing boreholes is mainly an equipment and personnel dry-run to maximize the likelihood of collecting useful data in new boreholes.

New groups of boreholes will be drilled at WIPP for executing the heater tests. Each group of boreholes will include a central 5" [12.7 cm] diameter collection borehole 10 to 20 feet [3 to 6.1 m] long, and several 2" diameter observation boreholes. Observation boreholes will be used to measure temperature; conduct ERT; measure temperature, acoustic, and strain using fiber-optic based sensors; and emplace tracers. These measurements are described in greater detail in Stauffer et al. (2015). Using new boreholes, two test will be instrumented around packers, boreholes closure instruments, and brine collection systems. One of the tests will set the central heater at (120° C) and the other test will be at ambient (~30° C). These tests will run concurrently to demonstrate the effects the heat has on brine availability, brine chemistry, borehole closure, acoustic emissions, and acid vapor generation.

2. MANAGEMENT STRUCTURE

The salt heater test project is relatively small in scope and, therefore, has a somewhat informal structure. It is managed as part of the DOE-NE Spent Fuel and Waste Science and Technology (SFWST) Program. Sandia National Laboratories (SNL) serves as the project management lead, while Los Alamos National Laboratory (LANL) Carlsbad serves as the underground testing coordinator. SNL, LANL, and Lawrence Berkeley National Laboratory (LBNL) are all contributing to test design and implementation. Site preparation work will be conducted by the WIPP management and operations (M&O) contractor Nuclear Waste Partnership (NWP). Additional staff from those listed below may be involved in aspects of the project, but the staff that have been working on the project to date are listed.

2.1 Roles and Responsibilities

Sandia National Laboratories (SNL) Project Manager

- Responsible and accountable to DOE for executing the Project within scope, cost, and schedule in a safe and responsible manner
- Provides Project technical guidance to collaborating team members
- Provides access to SNL resources, systems, and capabilities required to execute the Project
- Represents the Project in interactions with the DOE and international partners, participates in management meetings with DOE, and communicates Project status and issues
- Identifies and manages Project risks
- Designs and builds components of the Project related to borehole closure, acoustic emissions, ultrasonic wave velocity, and brine sampling
- Designs and builds engineered barrier system (EBS) components of the Project
- Performs laboratory analyses and characterization on salt and brine samples
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground
- Work within the controls established by the test plans and work authorization documentation to implement and operate the testing programs
- Provides personnel for underground installation of experimental equipment

Involved SNL staff: Kris Kuhlman, Melissa Mills, Courtney Herrick, Ed Matteo

Los Alamos National Laboratory Carlsbad Office (LANL-CO) WIPP Underground Test Coordination Office (TCO)

- Provides interface role between Project and US Department of Energy Office of Environmental Management (DOE-EM) Carlsbad Field Office (CBFO) and WIPP M&O contractor
- Provides implementation technical guidance to collaborating team members
- Designs and builds temperature sensing, data acquisition, and on-site control aspects of Project
- Provides access to TCO and WIPP resources, systems and capabilities required to execute the Project
- Provides the mechanism to deliver project funds to the WIPP M&O contractor for drilling new boreholes
- Collects and distributes data from the automated Data Acquisition Systems as coordinated with the National Laboratory project staff
- Provides on-site sample collection and sample control processes and resources as requested by

the National Laboratories project staff

- Develop (with the National Laboratories) appropriate work authorization and work control documentation for testing activities (for NWP review/acceptance), compliant with national laboratory and NWP requirements, to ensure the safe and consistent conduct of physical scientific work activities in the WIPP underground.

Involved LANL-CO staff: Doug Weaver, Shawn Otto, Brian Dozier

Los Alamos National Laboratory (LANL)

- Provides access to LANL resources, systems, and capabilities required to execute the Project
- Performs numerical modeling of thermal-hydrological-chemical system to design experiments, locate thermal measurement locations, and interpret results of the Project
- Designs and builds heater, gas handling, and packer components of the Project
- Performs laboratory analysis of brine and gas samples
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground
- Work within the controls established by the test plans and work authorization documentation to implement and operate the testing programs
- Provides personnel for underground installation of experimental equipment
- Participates in interactions with the DOE and international partners

Involved LANL staff: Phil Stauffer, Hakim Boukhalfa, Peter Johnson

Lawrence Berkeley National Laboratory (LBNL)

- Provides access to LBNL resources, systems, and capabilities required to execute the Project
- Performs numerical modeling of the thermal-mechanical-hydrological system to design the test and interpret results of the Project
- Design and build geophysical (ERT, fiber optics-based temperature, acoustics, and strain) monitoring components of the Project
- Conduct necessary laboratory tests to support field geophysical monitoring efforts in of the Project
- Work with the TCO for the development of job hazard analyses and work control documentation necessary to conduct work in the WIPP underground
- Work within the controls established by the test plans and work authorization documentation to implement and operate the ERT systems
- Participates in interactions with the DOE and international partners

Involved LBNL staff: Jonny Rutqvist, Yuxin Wu

Nuclear Waste Partnership (NWP) site M&O Contractor

- Works through the WIPP Underground Test Coordination Office
- Cores and prepares new horizontal boreholes for Project
- Prepares required underground infrastructure for Project including appropriate ventilation, ground control, lighting, communications, and electrical in accordance with applicable budget authorization and/or Contracting Officer direction.
- Provides axillary services required to conduct the Project including underground access, hoisting,

training, work control, lockout/tagout, environmental, safety and health, industrial hygiene, survey, and infrastructure maintenance.

2.2 Team Interfaces and Safety

It is mandatory that all WIPP underground science program participants and personnel performing work associated with the science and testing activities in the WIPP underground and on the WIPP site abide by the NWP guidelines and requirements referenced in the Integrated Project Team (IPT) Charter for Science and Testing Activities in the WIPP Underground (DOE 2016). Scientists and personnel associated with the underground test programs are not only responsible for their own health and safety, but are also responsible for the safety of fellow employees, and for the safe operation of the experiment, not precluding TCO and NWP oversight of the scientific work. The CBFO holds NWP accountable for safe operations at the WIPP and gives NWP authority to enforce safety rules and policies on all WIPP science participant organizations.

Work within the WIPP facility is strictly controlled to ensure safety and quality. This is accomplished primarily through an integrated work control and authorization process. All scientific testing activities conducted in the WIPP underground will be conducted under a work control package created in accordance with the process described in the IPT Charter (DOE 2016). The process ensures that planned science work scope is appropriately reviewed, authorized, scheduled, released for work, and integrated with the underground controller and field work supervisor for access and support in the underground.

3. INTEGRATED PROJECT BASELINE

3.1 Scope

The salt heater test project has the technical goals to 1) improve understanding of brine availability and brine chemistry in bedded salt; 2) collect datasets for parameterizing numerical models, populating constitutive models, and improving process model understanding; and 3) collect field data to improve understanding of acid vapor generation mechanisms. The project has the additional programmatic goal to rebuild in-house expertise at participating national laboratories in implementing *in situ* experiments in salt.

The technical justification and background relevant to these tests is laid out in Stauffer et al. (2015) and Kuhlman et al. (2017) and the design of the experiments is given in Johnson et al. (2017b). The following is a high-level summary of ongoing and planned activities in FY18 and FY19 work breakdown structure (WBS).

3.1.1 Instrumentation Dry Run (WBS 1.1)

The instrumentation dry-run is currently underway and is being conducted in existing boreholes in drift E-140 (see Figure 2 for location). This testing is being performed to test equipment and procedures, as well as getting personnel experience working in the WIPP underground. One of the existing boreholes is being instrumented with a packer, heater, borehole closure gage, temperature sensors, and gas flow system. The heater that will operate at 120°C. Both gas and liquid samples will be collected to monitor brine availability, composition, and migration through the salt. The test will include dry nitrogen gas circulation with a humidity gage and gas sampling to measure water inflow, and a sampling port for collecting liquid brine samples. An ERT system, to measure the change in salt resistivity, is being tested in a different, but nearby, location to minimize the effects of chain-link fencing and rock bolts that exist near the boreholes in the wall of drift E-140. Measurements of the internal borehole temperature, using thermocouples or resistance temperature detectors (RTDs), and closure, using a borehole closure caliper, are also being performed.

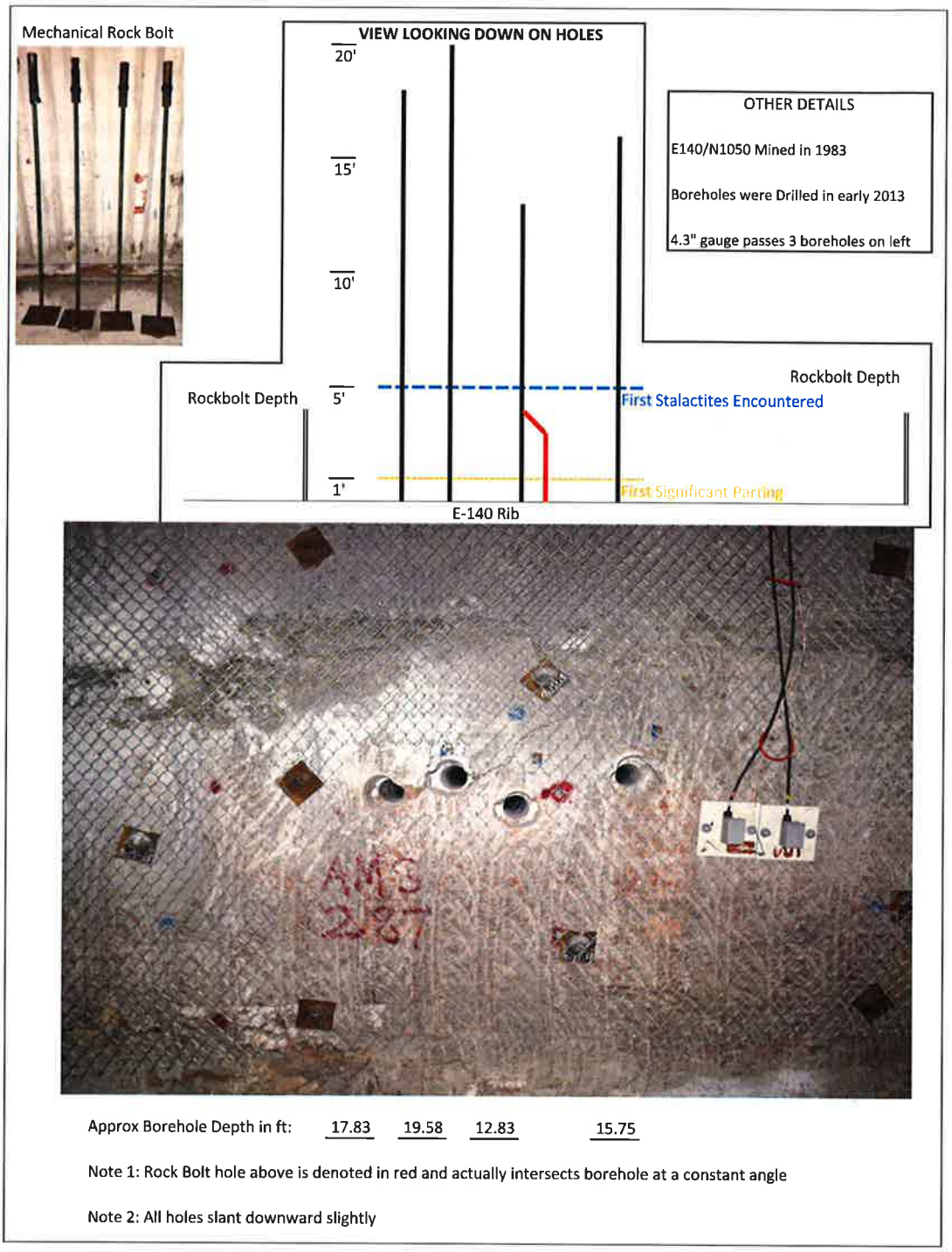

Figure 2. Configuration of existing boreholes in drift E-140 at WIPP (Johnson et al. 2017b)

3.1.2 Borehole Tests in New Boreholes (WBS 1.2)

Several groups of new boreholes will be cored, with preference for location in the salt disposal investigations (SDI) experimental area (see red shaded portion of "SDI AREA" on Figure 3), but this depends on NWP and the reconfiguration of ventilation to allow access to this area.

Initially, two parallel tests will be conducted using two sets of boreholes (as many as 5 sets of boreholes will be drilled to maximize utilization of drilling crew capabilities), where each set will consist of a larger-diameter borehole for sampling and heating, and a number of smaller-diameter observation boreholes. The tests in new borehole sets will follow the plan of Johnson et al. (2017b), while incorporating lessons learned from the instrumentation dry run test.

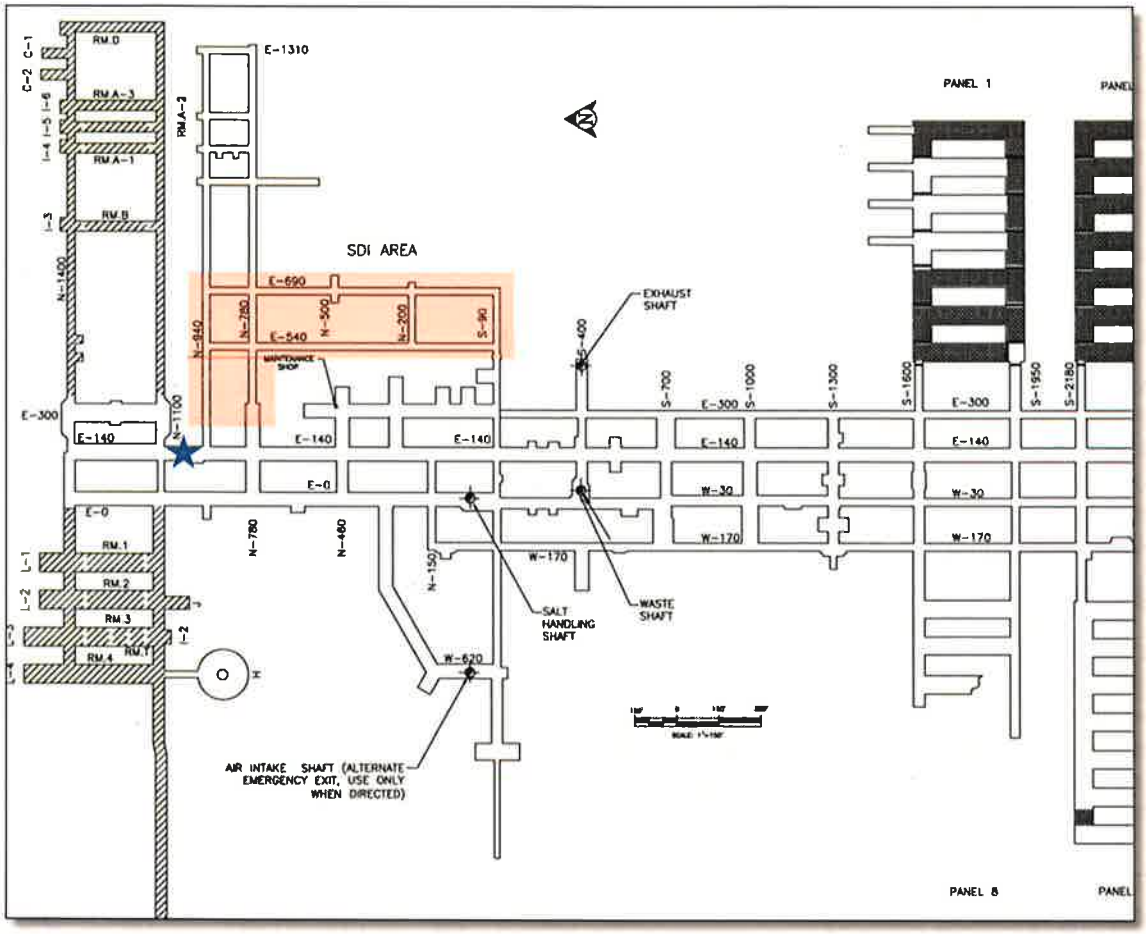

Figure 3. Preferred locations for new boreholes in red. Existing boreholes located at blue star.

3.1.3 Laboratory Analyses (WBS 1.3)

Salt samples (i.e., cores and salt precipitate samples from boreholes) will be analyzed to characterize the effect heating and brine flow have on the salt, and to characterize the salt geochemistry precipitated from brine entering the hole during the test. Brine samples will be analyzed for dissolved constituents, including isotopes and pH, and standard physical properties (e.g., density, electrical conductivity). Gas samples will be analyzed for composition (including isotopes). Salt cores taken before and after the tests will be analyzed to determine the change in electrical resistivity, ultrasonic wave velocity, frequency, amplitude, energy, and rate with increasing temperature. Sonic velocity changes are a sensitive method of assessing the degree of fracturing or healing that has occurred within the samples and will be used to interpret *in situ* data collected around the boreholes. Samples will be analyzed from salt cores to determine changes in porosity and salt mineralogy.

3.1.4 Pre- and Post-Test Modeling (WBS 1.4)

Numerical modeling has already been conducted (Johnson et al. 2017a; Rutqvist et al. 2017) and these models will continue to be updated to match the actual geometry and boundary conditions encountered during the tests. The numerical model predictions will be used to help locate sensors and design test durations, interpret the data, motivate additional model capability developments, and facilitate integrating the results in to the geologic disposal systems analysis program.

3.1.5 Follow-on Tests (WBS 1.5)

The instrumentation dry-run is being performed to provide experience to improve the first two heater tests in new boreholes for the Project. Results from these first two new borehole tests will lead to revised and improved test design for follow-on tests. While fielding multiple tests simultaneously increases equipment costs (i.e., multiple packer or data logger systems), waiting to begin additional tests until the first tests finish will allow the boreholes to age before the beginning of the experiments. This task includes planning for additional tests, and monitoring/preserving new boreholes until later tests are conducted in them, to increase their likelihood of producing good data (e.g., sealing boreholes from mine ventilation with plugs).

3.1.6 International Collaborations (WBS 1.6)

Working with existing foreign partners made through the US/German workshops (e.g., Institut für Gebirgsmechanik (IfG), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Germany, and Centrale Organisatie Voor Radioactief Afval (COVRA) in The Netherlands), we will strive to increase the impact of our work by seeking input and feedback during all aspects of the test development and implementation. International collaborations will involve participating in numerical model benchmarking exercises and sharing data with interested parties.

3.2 Schedule

The following schedule (Table 1) shows a high-level summary of planned execution of the first two parallel tests in new boreholes, which will be conducted in FY18 and FY19. The instrumentation dry-run is taking place in FY18, while new boreholes will be drilled as soon as possible in FY18, with implementation beginning in summer of FY18 and continuing into FY19. Planning and preparations for follow-on tests will begin in the second half of FY19. Laboratory analysis, modeling and international collaborations will continue throughout the life of the project.

Table 1. Projected Borehole Heater Test Schedule Components

		FY18		FY19			
WBS	**Work Scope Element**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
1.1	Instrumentation Dry Run						
1.2	First Two Tests in New Boreholes						
1.3	Laboratory Analyses						
1.4	Pre- and Post-Test Modeling						
1.5	Follow on Tests						
1.6	International Collaborations						

3.3 Costs

Lumped costs across all partners (including all the National Laboratories and NWP) for the different WBS elements of the program are given in Table 2.

Table 2 Projected Borehole Heater Test Costs ($K) across SNL, LANL & LBNL

WBS	Work Scope Element	FY18	FY19	FY20	Total
1.1	Instrumentation Dry Run	300			**300**
1.2	First Two Tests in New Boreholes	300	800	200	**1200**
1.3	Laboratory Analyses	200	300	200	**700**
1.4	Pre- and Post-Test Modeling	300	400	400	**1100**
1.5	Follow on Tests		100	400	**500**
1.6	International Collaborations	100	100	100	**300**
Total		1200	1700	1300	**4200**

3.4 Baseline Change Control

This project will be managed using the Project Information Collection System: Nuclear Energy (PICS:NE). The Baseline Change Proposal (BCP) process is managed within PICS:NE.

4. PROJECT MANAGEMENT

4.1 Project Reporting

The SNL Project Manager will report periodically to DOE-NE to provide updates on project progress and to discuss and resolve issues. Monthly status reports will be entered into the PICS:NE system as required. Each partner's financial system will provide required information related to project budget and costs to the PICS:NE system.

4.1.1 Earned Value Management System (EVMS)

SNL corporate EVMS, consistent with the PICS:NE EVMS guide, will be used, as necessary, to manage, control, analyze and report on the project. EVMS is not required for acquisition of commercial products that are designed and built from commercial off-the-shelf technology.

4.2 Risk Management

Risk Management is an essential element of this project. Risk assessments will be started early in the project lifecycle and will identify critical technical scope, cost, and schedule risks. Many risks can impact multiple aspects of the project. As risks are identified, they will be assessed, prioritized, and monitored by all the technical partners participating in the Project. Where necessary, risk mitigation strategies and actions will be developed, documented, and implemented to mitigate and disposition risks. Some general areas of risk that will be considered are listed below:

- **Technical Scope Risk** – The project includes significant research and development and thus has a high level of technical uncertainty. Independent technical reviews will be performed as appropriate, to minimize technical risks.
- **Cost/Budget Risk** – The funding and budgeting of a federal activity are subject to changes (e.g., availability of funds, continuing resolutions (CRs), congressional action, changes in Administration).
- **Schedule Risk** – As the project proceeds, delays can occur (e.g., equipment failure and technical development). There may also be schedule delays involved in the procurement process or impacts associated with changes in schedule driven by WIPP's disposal operations role.

4.3 Environmental and Regulatory Compliance

This work will operate under existing National Environmental Policy Act framework in place at WIPP and each of the participating laboratories. Additional permitting is not expected, beyond internal environmental safety and health requirements at WIPP.

4.3.1 Integrated Safety Management

Integrated Safety Management is addressed through the each participating partners' "Integrated Safety Management System." These activities will follow the guidelines and principles of integrated safety management. Section 2.2 discusses safety and training that is required by WIPP and will be coordinated through the TCO.

4.4 Configuration Management

A configuration management process will be established that controls changes to the physical configuration of project equipment, structures, and systems in compliance with DOE standards. This process ensures that the configuration is in agreement with the performance objectives identified in the technical baseline and the approved Quality Assurance (QA) plan.

A configuration management system will identify and document the configuration of the end products (e.g., samples and equipment) and control configuration changes during the life cycle.

4.5 Records Management/Document Control

Existing partner corporate processes will be utilized to control preparation, review, comment resolution, approval, issuance, use, and revision of documents that establish policies, prescribe work, and specify requirements.

The principle project controlled documents include contract documents, the Project Plan, Milestone reports, work authorizations, design specifications, compliance documents, QA and Environment, Safety, and Health Plans, and the BCP log including disposition.

4.6 Quality Assurance

QA is an integral part of effective project management and will be employed throughout the design, procurement, and construction of the project. The Project QA Plan will be based on each partner's corporate QA plan and the Spent Fuel Waste Science & Technology (SFWST) Program QA Plan (SNL 2018) and QA program document (DOE 2017). QA requirements will apply to all team members performing work on the project. A graded approach based on importance and significance of activities will be utilized in the application of standards.

In addition, national codes and standards will be followed throughout as applicable. Quality control will be required for the purchase, construction, and/or fabrication of essential components.

4.7 Project Closeout

When the project nears completion, project closeout activities will be identified and implemented. The following activities will be considered for project close out:

- Completion of contract obligations, products, services, and deliverables;
- Proper dispositioning of excess equipment and associated components;
- Determination for long-term use of boreholes; and
- Documentation of project lessons learned.

5. REFERENCES

DOE Carlsbad Field Office (CBFO), 2011. *A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP.* DOE/CBFO-11-3470. Carlsbad, NM: U.S. Department of Energy Office of Environmental Management.

DOE Carlsbad Field Office (CBFO), 2013. *Test Specification for the Salt Defense Disposal Investigations Thermal Test in WIPP.* DOE/CBFO-13-3510. Carlsbad, NM: U.S. Department of Energy Office of Environmental Management.

DOE Carlsbad Field Office (CBFO), 2016. *Interim Charge Notice #1 to DOE/CBFO-13-3515, Science and Testing Activities in the Waste Isolation Pilot Plant Underground Underground Integarated Project Team Charter.* DOE/CBFO-13-3515. Carlsbad, NM: U.S. Department of Energy Office of Environmental Management.

DOE Office of Nuclear Energy (DOE-NE), 2017. Nuclear Technology Research and Development (NTRD) Quality Assurance Program Document, Rev. 4 (Effective Date: 07/05/2017). U.S. Department of Energy Office of Nuclear Energy.

Johnson, P.J., S.M. Bourret, H. Boukhalfa, F.A. Caporuscio, G.A. Zyvoloski, D.J. Weaver, S.Otto, & P.H. Stauffer, 2017a. *Experiments and Modeling to Support Field Test Design.* SFWD-SFWST-2017-000102, LA-UR-17-27759. Los Alamos National Laboratory.

Johnson, P.J., H. Boukhalfa, D.J. Weaver, S. Otto, B.L. Dozier, P.H. Stauffer, M.M. Millis, E.N. Matteo, K.L. Kuhlman, J. Rutqvist & Y. Wu, 2017. *Test Plan Document for Thermal Testing in Salt.* SFWD-SFWST-2017-000043, LA-UR-17-30762. Los Alamos National Laboratory.

Kuhlman, K.L., M.M. Mills & E.N. Matteo, 2017. *Consensus on Intermediate Scale Salt Field Test Design.* SFWD-SFWST-2017-000099, SAND2017-3179R. Sandia National Laboratories.

Rutqvist, J., M. Hu, L. Blanco-Martin & J. Birkholzer, 2017. *Coupled THM Modeling in Support of a Phased Salt Field Test Plan.* SFWD-SFWST-2017-000103, LBNL-2001023. Lawrence Berkeley National Laboratory.

Sandia National Laboratories (SNL), 2018. *Sandia National Laboratories QA Program Interface Document for NTRD/SFWD Activities.* FCRD-TIO-2011-000032 Rev. 7 (Effective Date: 02/28/2018). Sandia National Laboratories, Albuquerque, NM.

Stauffer, P.H., A.B. Jordan, D.J. Weaver, F.A. Caporuscio, J.A. Tencate, H. Boukhalfa, B.A. Robinson, D.C. Sassani, K.L. Kuhlman, E.L. Hardin, S.D. Sevougian, R.J. MacKinnon, Y. Wu, T.A. Daley, B.M. Freifield, P.J. Cook, J Rutqvuist & J.T. Birkholzer, 2015. *Test Proposal Document for Phased Field Testing in Salt*, FCRD-UFD-2015-000077, LA-UR-15-23154. Los Alamos National Laboratory.

Enclosure 3

Consensus Scale on Salt Field Test Design

Spent Fuel and Waste Disposition

Consensus on Intermediate Scale Salt Field Test Design

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste
Science and Technology

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Sandia National Laboratories

March 28, 2017
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SUMMARY

This report summarizes the first stage in a collaborative effort by Sandia, Los Alamos, and Lawrence Berkeley National Laboratories to design a small-diameter borehole heater test in salt at the Waste Isolation Pilot Plant (WIPP) for the US Department of Energy Office of Nuclear Energy (DOE-NE). The intention is to complete test design during the remainder of fiscal year 2017 (FY17), and the implementation of the test will begin in FY18. This document is the result of regular meetings between the three national labs and the DOE-NE, and is intended to represent a consensus of these meetings and discussions.

The suite of tests is essentially modular, each test consisting of a central test borehole with water vapor collection and liquid brine sampling equipment, surrounded by satellite observation and instrumentation boreholes. Observation boreholes will be associated with temperature, electrical resistivity, and acoustic emission (AE) measurements. The first test of this modular design will be isothermal (no heating), and the second stage will be heated to a maximum borehole temperature of approximately 120°C. Later tests will be designed using information gathered from the first two boreholes, will be conducted at other temperatures, and may include other measurement types and test designs.

The suite of field tests is focused on the objectives of quantifying brine availability, brine migration, and brine chemistry under heat-generating-waste relevant conditions in bedded salt. To accomplish the first two objectives, we will quantify the mass flowrate of water and conservative tracer into the borehole while circulating out humidity inside the central test borehole. Brine chemistry will be monitored through brine and gas sampling during the experiment. To interpret water inflow data, we will use thermal-hydrologic (TH), thermal-hydrologic-chemical (THC), and thermal-hydrologic-mechanical (THM) modeling to estimate formation properties, given the applied boundary conditions and observed inflow data. To interpret observed chemistry data, we will use thermal-chemical (TC) and THC models to interpret observed changes in the chemistry of inflowing brine, from observations of precipitating minerals and samples of brine composition while constantly removing water vapor from the borehole.

Appendix A presents key components from historic heater tests in both bedded and domal salt. One motivation for this test is to "get back underground" and rebuild capabilities that have been lost with retiring staff since the bulk of *in situ* testing in salt was conducted in the 1980s. That being the case, this report presents key references and figures from previous tests as a first step in the design and implementation of the current suite of tests.

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ACRONYMS

AE	acoustic emissions
BPC	borehole pressure cell
CBFO	DOE-EM Carlsbad Field Office
CMH	chilled-mirror hygrometer
CRDS	cavity ring-down spectroscopy
D_2O	deuterated water
DOE	US Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DRZ	disturbed rock zone
EDS	energy dispersive X-ray spectography
ERT	electrical resistivity tomography
FCRD	DOE-NE Fuel Cycle Research and Development
FIB-SEM	focused ion beam-scanning electron microscopy
FY	fiscal year
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LVDT	linear variable differential transformer
MCC	Mississippi Chemical Company potash mine (in Salado Formation above WIPP)
MB139	Salado marker bed 139 (1.5 m below WIPP repository horizon)
MIIT	WIPP Materials Interface Interactions Test (1980s)
MU-0	WIPP Salado map unit zero
RH	relative humidity
RTD	resistance temperature device
SANS	small-angle neutron scattering
SCCM	standard cm^3/min
SDDI	CBFO Salt Defense Disposal Investigations (2013)
SDI	CBFO Salt Disposal Investigations (2011)
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
STEM	scanning transmission electron microscopy
TGA	thermogravimetric analysis
THMC	thermal, hydrological, mechanical, and chemical processes (also other subsets TC, TH, THM & THC)
TSI	WIPP Thermal/Structural Interactions tests (1980s)
US	United States of America
WIPP	DOE-EM Waste Isolation Pilot Plant
XRD	X-ray diffraction

CONSENSUS ON INTERMEDIATE-SCALE SALT FIELD TEST DESIGN

1. INTRODUCTION

The US desire to dispose of radioactive waste in geologic salt originated with Hess et al. (1957), and has motivated the development of our current extensive technical basis for waste disposal in salt. Salt has a low permeability to brine transport and a high thermal conductivity compared to other potential disposal media like clay or granite. This makes its thermal and hydraulic diffusivities the same order of magnitude (McTigue 1985; Cosenza & Ghoreychi 1993). Since these two diffusivities in salt are approximately equal, interplay between coupled thermal, mechanical, and hydrological processes is especially important. We can design salt repositories for heat-generating waste while understanding these coupled processes, taking advantage of salt's favorable thermal conductivity and permeability. Despite these favorable properties, geologic salt is a complex medium for which to quantitatively predict reconsolidation, room closure, brine migration, and solution chemistry because it creeps, is highly soluble, and contains saturated brines.

1.1 Field Test Goals

The long-range goals of the DOE-NE field-testing campaign for salt are related to the long-term isolation safety case for disposal of heat generating waste in salt. This intermediate-scale borehole heater test is one component of the field-testing campaign, focused on the quantification of brine inflow and composition. The transient evolution of brine inflow and the brine composition after excavating a drift or borehole can be thought of as initial conditions in the long-term performance assessment modeling of a salt repository system over long time scales. The high-level goals of this intermediate-scale field test (as opposed to the other parts of the overall testing campaign, such as small-scale laboratory tests or drift-scale emplacement demonstrations) are to:

1) improve understanding of brine availability and brine chemistry in bedded salt;
2) collect datasets for validating numerical models, populating constitutive models, and improving process model understanding;
3) collect field data to improve understanding of acid gas generation mechanisms; and
4) revitalize in-house expertise at participating national laboratories in implementing *in situ* experiments in salt at WIPP (Figure 1).

The proposed borehole heater test will be relatively low cost and performed at a small spatial scale. The test will be used to develop instrumentation and methods for further *in situ* testing, demonstrations, and characterization activities. A single-heater borehole test will be used to assess changes in physical-chemical properties associated with brine and vapor liberation and migration at elevated temperature. A follow-on to these borehole tests might include international collaborations for model prediction and validation (Hansen et al. 2016b).

The test is primarily focused on brine availability to a small-diameter (10 to 15 cm [4" to 6"]) horizontal borehole. This report provides a conceptual design of the borehole heater experiment, further specifying the recommendations of Hansen et al. (2016b). Brine availability quantifies how much natural brine flows into an excavation (borehole or room), and is thereby available to enhance waste package corrosion, limit the closure of brine-filled cavities, or to facilitate radionuclide transport. Understanding the amount of brine available to flow into a borehole or excavation in salt primarily involves understanding the mechanism of brine migration and the distribution of the disturbed rock zone (DRZ). As a secondary goal, the test will collect unique data on brine composition, which could change during the experiment due to transport of multiple types of water present in a bedded salt formation. Although the current disposal concept for heat-generating radioactive waste in salt does not necessarily include emplacing waste in

horizontal boreholes, this test is being designed as a horizontal borehole test to quantify relevant THMC processes in salt, which could be upscaled to the drift scale. The test will avoid mapped clay or anhydrite inter-layers. Data collected in response to the imposed constant-humidity and low-pressure conditions at the central borehole will hopefully allow more ready validation of numerical models, than data collected from a disposal demonstration that has less controlled conditions.

In addition to the two primary goals of brine availability and brine chemistry, we have identified lower-level goals that we will investigate in observation boreholes (if they do not interfere with the primary goals) or in later tests:

- Vapor flow in a partially saturated DRZ;
- Evolution of an unsaturated DRZ surrounding drifts and boreholes;
- Porosity and permeability changes in the DRZ surrounding boreholes;
- Acoustic emissions (AE) and other micro-mechanical processes during heating and cooling;
- Geophysical changes (e.g., electrical resistivity or ultrasonic wave propagation) in response to temperature changes, deformation, and brine transport;
- Tight coupling between mechanical, hydrological, and thermal processes in salt;
- Release of brine in response to sudden changes in borehole temperature (both increases and decreases);
- Long-term brine availability over multiple years (stability of steady-state inflow);
- Corrosion and degradation of materials (e.g., steel and cement).

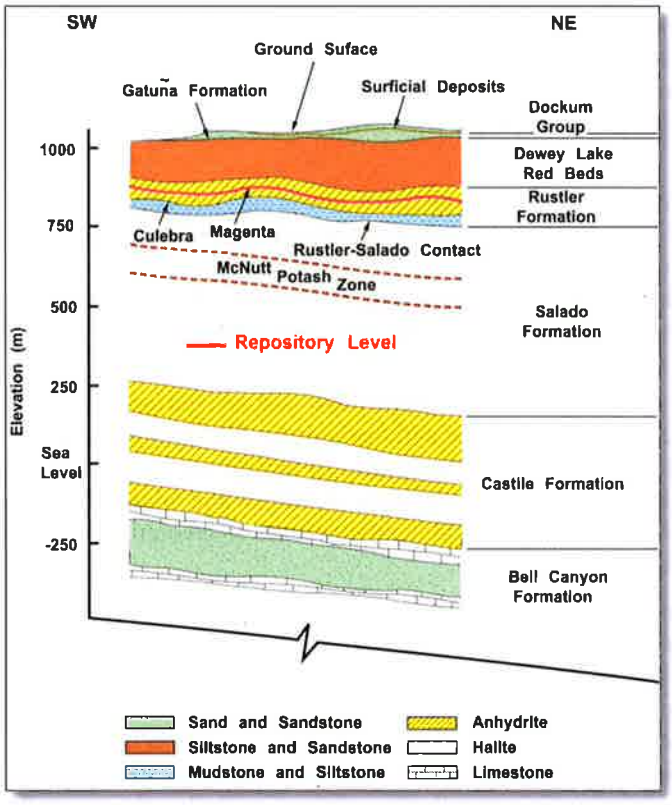

Figure 1. Generalized Waste Isolation Pilot Plant (WIPP) stratigraphy.

The data we plan to collect will require several analytical and numerical models to interpret. Some semi-analytical solutions may be used to assist in interpreting heat conduction (Carslaw & Jaeger 1953) and brine inflow (McTigue 1985, 1993), but there are few analytical solutions available to predict coupled THMC systems. Non-linear numerical solutions are needed when considering brine density and viscosity changes with temperature and composition, free thermal convection of brine and gas in a porous medium, brine chemistry at high ionic strength, salt dissolution and precipitation, or significant mechanical or chemical coupling. One of our goals is to collect data that may ultimately require a non-linear coupled numerical model to interpret, to provide a validation dataset for these numerical models.

The proposed suite of intermediate-scale borehole heater tests is modular and several arrangements of central test and satellite observation boreholes are planned at multiple maximum borehole wall temperatures, including ambient (unheated, ~30 °C), 50 °C, 120 °C, 160 °C, and 200 °C. The first two tests (ambient and 120 °C) are described in this report in more detail than the other three. The design of subsequent borehole tests will be revisited based on lessons learned executing the first two tests. In the first two tests, the central borehole will be the collection point for the brine inflow system, which builds upon a design used in several successful borehole heater tests in bedded and domal salt (see Appendices A-3, A-4, A-5, A-6, and A-7).

1.2 Relevant History

There have been several well-documented drift-scale borehole heater tests in bedded and domal salt that observed brine inflow including: Project Salt Vault (1965-1967), Avery Island (1978-1983), Carlsbad potash mines (1981-1983), WIPP Rooms A and B (1984-1990), and Asse (1983-1985). Heated borehole brine inflow tests have shown significantly less brine flows into boreholes completed in domal salt (Krause 1983; Rothfuchs et al. 1988) compared to bedded salt (10 to 100 times less). Heater tests in bedded salt have shown less brine inflow into boreholes that do not intersect clay or anhydrite layers (Bradshaw & McClain 1971; Nowak & McTigue 1987). These non-salt units have higher permeability than halite, often have higher brine-filled porosity, have markedly different mechanical responses compared to salt (e.g., salt creeps and heals, anhydrite is brittle, and clay allows shearing of sedimentary layers), and involve more hydrated mineral phases (e.g., clays, polyhalite, or gypsum that evolve water during heating) than halite.

Previous heated borehole tests at WIPP focused on thermal-structural interactions (i.e., WIPP TSI Rooms A and B – Tyler et al. 1988). These heated rooms included brine inflow observations in large-diameter vertical boreholes. These vertical boreholes at WIPP were at least 76 cm [30"] in diameter, and intersected Clay F below the floor of Rooms A and B. Non-salt layers encountered in these vertical boreholes contributed significantly to observed brine inflow, especially at temperatures above 100 °C (Figure 2). Borehole B042 in WIPP Room B operated at 130 °C and collected 35 liters of condensed water vapor over 600 days (Nowak & McTigue 1987). Deal et al. (1993) consolidated clays collected from the WIPP disposal horizon in oedometers at 13.8 MPa [2,000 psi]. They found them to have 25 to 29% brine content volumetrically (~12 wt-%), not including inter-layer or bound water that will be released during heating.

While a large number of previous salt heater tests exist, motivation for this proposed suite of borehole heater tests stems from a renewed US interest to conduct heater tests in salt related to disposal of heat-generating waste. Historic tests in salt are discussed in more detail in recent historical surveys: Kuhlman et al. (2012), Kuhlman & Malama (2013), and Kuhlman & Sevougian (2013). Sevougian et al. (2013) presented a summary of a workshop convened to discuss and prioritize research concepts related to heat-generating waste in salt. The US/German workshop on salt repository research has fostered and documented collaboration between salt researchers in the US, Germany, and the Netherlands (e.g., Hansen et al. 2016a; 2017). Recent DOE-NE funded laboratory and numerical modeling efforts at Sandia, Los Alamos, and Lawrence Berkeley National Laboratories have been summarized in Kuhlman (2014) and Stauffer et al. (2015).

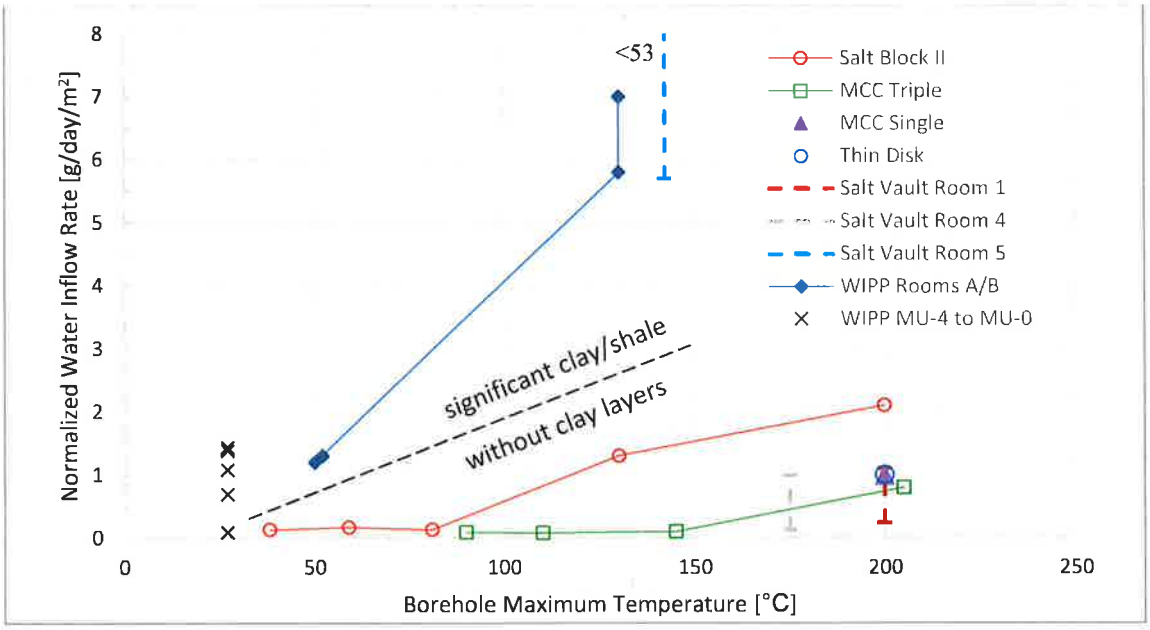

Figure 2. Normalized water production rate in bedded salt (data modified from Shefelbine 1982; Appendix A-10).

At WIPP, the US Department of Energy Office of Environmental Management (DOE-EM) Carlsbad Field Office (CBFO) began planning two large-scale heated disposal demonstrations: Salt Disposal Investigations (SDI; DOE CBFO 2011) and Salt Defense Disposal Investigations (SDDI; DOE CBFO 2013). The "SDI Area" at WIPP (Figure 3) was partially mined to accommodate these possible future tests. Stauffer et al. (2015) summarized modeling and instrumentation development carried out in planning for SDDI at WIPP. This report builds upon this recent background work (see Appendix A for discussion of relevant points from historic salt heater tests), and presents an initial consensus regarding a DOE-NE funded plan to begin field testing in salt related to heat-generating waste.

1.3 Proposed Field Test in Context of Performance Assessment

The main focus of these intermediate scale borehole heater tests is brine availability, since brine availability determines how much natural brine flows into an excavation (borehole or room), and is thereby available to potentially cause waste package corrosion, limit closure of brine-filled cavities, or to facilitate radionuclide transport. In a salt repository for "hot" radioactive waste (i.e., above brine boiling temperature at the waste package) moisture will be driven away from the waste packages. Salts will precipitate out of brine near the waste package, and thermally enhanced creep closure will reconsolidate any backfill and close any gaps or voids to create a dry low-permeability zone surrounding the waste packages. After tens to hundreds of years, depending on waste type, the waste radioactive decay heating rate will eventually decrease allowing temperatures to drop below the brine boiling temperature, and allowing liquid to migrate back toward the waste packages. However, low-permeability reconsolidated salt backfill and precipitated salt on the heater will minimize the amount of brine that contacts the packages.

In all salt disposal systems, the far-field ultra-low permeability of the salt formation and its proven stability over geologic time provides the primary natural barrier that contains radioactive waste over performance assessment relevant time scales (10^4 to 10^6 years). Salt creep closes open excavations, and closes fractures or other voids in the near field that could serve as transport pathways from the repository. While this intermediate-scale borehole heater test is focused on the quantification of inflow and

composition of brine, this is essentially the development of an initial condition in the long-term performance of a salt repository system, for which we have great confidence in its ability to provide isolation from the shallow geosphere.

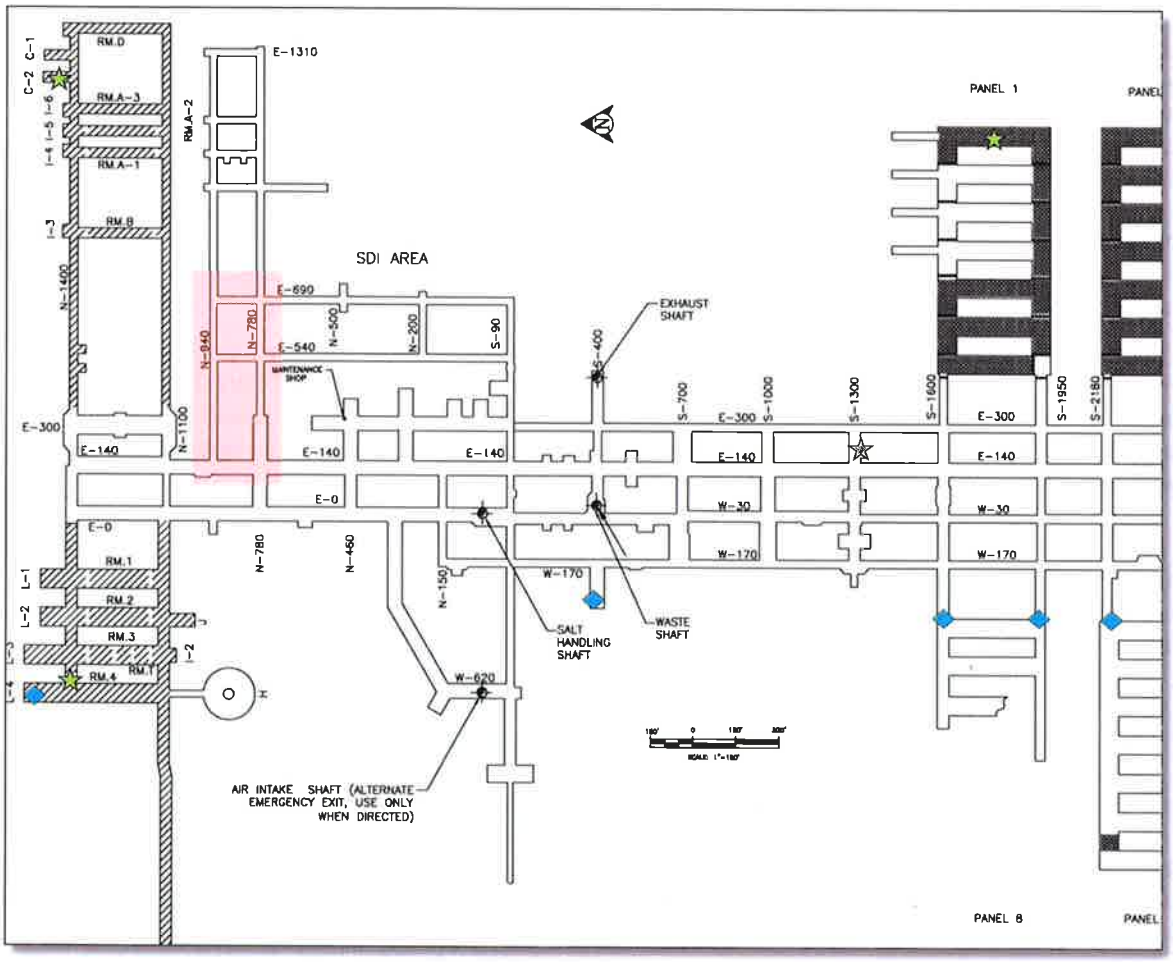

Figure 3. WIPP underground layout. Possible test location shaded red. MU-0 lithologic data locations marked with stars; MU-0 brine inflow observations marked with diamonds.

2. FIELD EXPERIMENTAL PROCESS DESCRIPTION

2.1 Location and Design Strategy

The field test will be conducted in a portion of the SDI Area of WIPP (e.g., the red shaded area in Figure 3). The precise location of the boreholes will be chosen to be at least two drift diameters away from a drift corner or intersection, to minimize edge effects and stress concentrations near tested intervals. Location will consider the dimensions of the access drift (smaller cross-section drifts being more favorable than larger, since they will have a smaller DRZ) and the time lag between drift excavation and deployment of the tests. We assume new drifts will not be available for testing in FY18, but if they were available for future tests, a test room should be constructed for multiple tests, with adequate room to limit end effects and test interference. From a purely geomechanical viewpoint, all the holes for multiple tests would be drilled and instrumented immediately upon mining a new test drift, and tests would be run in parallel.

This approach would capture more of the early-time room deformation, but would not allow performing tests sequentially and learning or improving methodologies from one test to another. This approach will not be taken with the first two boreholes, but may be possible for later borehole tests.

For the initial two tests, boreholes will be drilled immediately before the planned beginning of the test (as soon as is feasible), based on coordination with underground operations personnel. We will attempt to minimize accumulated pre-test borehole damage, and unmeasured early brine inflow (when brine inflow is expected to be largest). Both phenomena are associated with boreholes being open for extended periods before tests begin. Testing and instrumentation installation will begin immediately after borehole construction, to minimize the uncertainty associated with unmeasured early boreholes conditions. Drilling the boreholes immediately before the tests and running the tests serially, rather than in parallel, may lead to higher costs associated with drilling boreholes. Both this cost and any possible impacts to the data should be considered when coordinating test interval construction and instrumentation. Running tests in parallel will require multiple sets of packers, heaters, and instrumentation to be installed simultaneously and would preclude re-using equipment across tests.

The central borehole of each test will be cored or drilled sub-horizontally at 10.2 cm [4"] or 15.2 cm [6"] diameter and 6.1 m [20'] in length, at a horizontal level 60 to 90 cm [2' to 3'] from the floor in a typical room on the WIPP disposal horizon. This orientation places the test elevation sufficiently far from mapped clay or anhydrite layers, targeting Map Unit 0 (MU-0); see Figure 5 and discussion of previous isothermal brine inflow boreholes in MU-0 in Appendix A-1.

2.1.1 Test Interval Location to Avoid Interbeds and DRZ

A sub-horizontal test borehole orientation (i.e., with a downward dip to accumulate brine for collection at end of the borehole) will minimize crossing major lithologic changes or interbeds (e.g., see mapped clay and anhydrite layers in Figure 4 and Figure 5). This orientation will keep test intervals within a single mapped unit. MU-0 is the target unit, and is an "argillaceous halite" with minor dispersed clay and polyhalite (Figure 5). The reasons for choosing this stratigraphic location and orientation include making the test results more transferrable to other bedded salt formations, ease of access from existing WIPP excavations, and controlling the influence of Clay F that contributed large amounts of brine in Rooms A and B (Figure 2). A horizontal borehole orientation was also chosen because there have been fewer historical heater tests focusing on brine production in bedded salt with a horizontal orientation (e.g., Bradshaw & McClain 1971, Ewing 1981b, Shefelbine 1982). Previous heater tests at WIPP were in vertical boreholes, except the 300 W horizontal borehole heater tests in Room T that did not monitor brine inflow (Molecke 1992). Figure 2 shows normalized brine production rate from boreholes in bedded salt, as a function of the borehole maximum temperature. Boreholes in WIPP Rooms A and B, and Project Salt Vault Room 5 intersected significant clay or shale layers. These boreholes produced much more brine than other bedded salt deposits at similar temperatures (The 1-m diameter Salt Block II sample came from the Mississippi Chemical Company (MCC) potash mine near WIPP). There are large uncertainties on results from Project Salt Vault, due to the way brine collection was performed and reported.

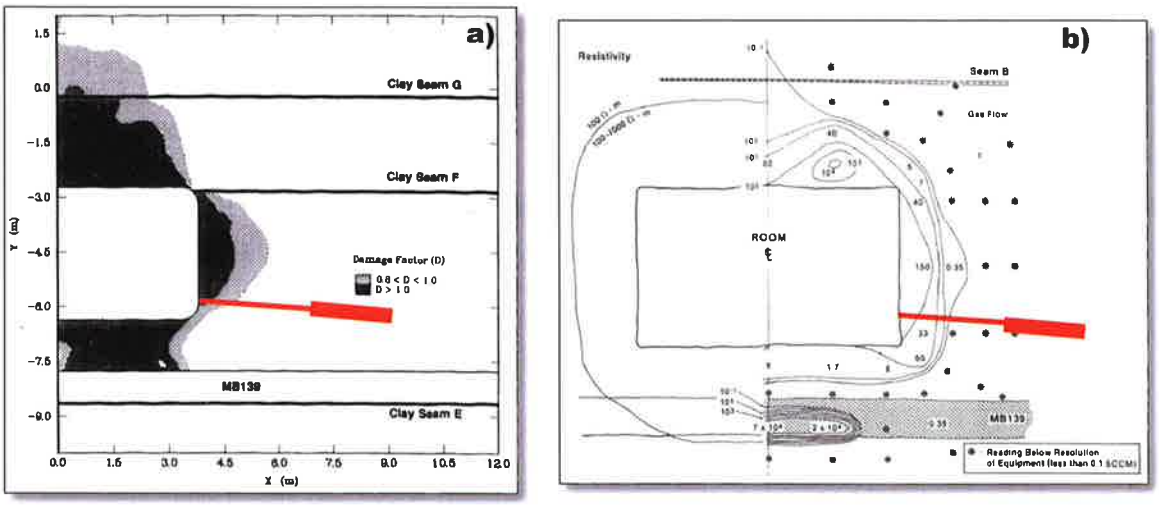

Figure 4. Model-predicted and observed DRZ at WIPP, with approximate borehole and test interval indicated (a: Figure 2-10 from Van Sambeek et al. 1993, b: Figure 5 of Stormont 1997b).

Each heated test interval will be located at the end of its borehole, and it will use a combination of plugs and packers for isolation between the access drift and the test portion of the borehole. The length of the borehole will be long enough to place the test interval beyond the access drift DRZ to the extent practical, but placing the test interval too deep will complicate the setup. See the 4.5 m borehole and test interval locations indicated on Figure 4. "Cartoon" representations of typical accumulation of damage surrounding drifts at Asse and WIPP are illustrated in Figure 6. The major DRZ with significant open fractures will likely be confined to the first 1.5 m [5'] of the borehole; see the $D > 1.0$ area in Figure 4a and gas flowrates > 1 standard cm^3/min (SCCM) in Figure 4b. Lesser damage may extend 3 m [10'] into the wall, based on geophysical and petrographic analysis of cores and boreholes (Holcomb et al. 2001; Hansen 2003). The testing interval should be at least 3 to 4.5 m [10' to 15'] away from the access drift wall, and 4.5 to 6.1 m [15' to 20'] if practical.

Low-pressure gas flowrate testing will be conducted in the boreholes after drilling (Figure 4b; Section 2.4.6), before installing brine collection equipment, to identify the extent of the damage zone using an approach similar to that of Stormont et al. (1987). Borehole packers or seals will be installed deep enough to get beyond most of the observed damage, but not too deep to complicate borehole equipment installation and monitoring.

2.1.1 Expected MU-0 Lithology

Appendix D of Finley et al. 1992 (see Appendix A-1.2 this document) shows the types of insoluble residues found in Room L4 borehole samples from MU-0. The insoluble hydrous minerals from these samples include smectite, gypsum, and polyhalite (see Figure 17 in Appendix A-1). Soluble hydrous minerals (e.g., magnesium chloride salts) are not believed to exist in large quantities in MU-0.

Powers (2017) described the non-halite components in WIPP argillaceous halite:

> "…appear to average ~1% but are higher in coarser halite. The clay proportion dominates in the coarser halite intervals, and sulfate dominates in the fine halite intervals. Clay is not uniformly distributed. Some occurs as irregular blebs between crystals, but clay also forms thin (e.g., 2-3 mm; 0.08-0.12 inch), irregular curved discontinuous stringers."

Saulnier et al. (1991) described MU-0, encountered in vertical boreholes C2H01-A, B, and C drilled from Room C2 (see Figure 3 for borehole locations), as "Medium to coarse argillaceous halite, clay decreases downsection, polyhalite increases downsection." They described MU-0 in vertical borehole N4P50 drilled from SPDV Room 4, as "coarse, colorless, trace polyhalite, argillaceous halite." They described MU-0 in vertical borehole S0P01-A (S1300 drift), as "Coarsely crystalline clear halite." They described MU-0 in vertical borehole, S1P71 drilled from Room 7 of Panel 1, as "Coarse, colorless halite, minor intercrystalline brown clay."

Deal et al. (1989) described MU-0 in their generalized stratigraphy (their Appendix H) as:

> "Clear to moderate reddish orange/brown, moderate brown and grayish brown. Medium to coarsely crystalline. <1 to 5% argillaceous material. Predominantly brown, some gray, intercrystalline argillaceous material and discontinuous breaks and partings. Upper 0.6 meters of unit is argillaceous halite decreasing in argillaceous material content downward. None to <1% polyhalite. Contact with lower unit is gradational based on polyhalite content."

Boreholes will be logged upon drilling by inspecting core. A remote video or photo inspection process to will be used look for discontinuous (i.e., unmapped) clay stringers which may significantly affect test results. If significant unanticipated discontinuous clay is encountered during drilling the central test borehole at a test site, a different location or horizon will be chosen.

Based solely on geological observations of MU-0 at WIPP, the packer-isolated portion of the borehole should be located away from the upper portion of MU-0, in the deeper (i.e., stratigraphically lower) portions of MU-0 if possible, to minimize clay content. This could be achieved by lowering the collar height of the borehole (i.e., starting at a lower elevation in the room), or by drilling the borehole at a slightly steeper angle down.

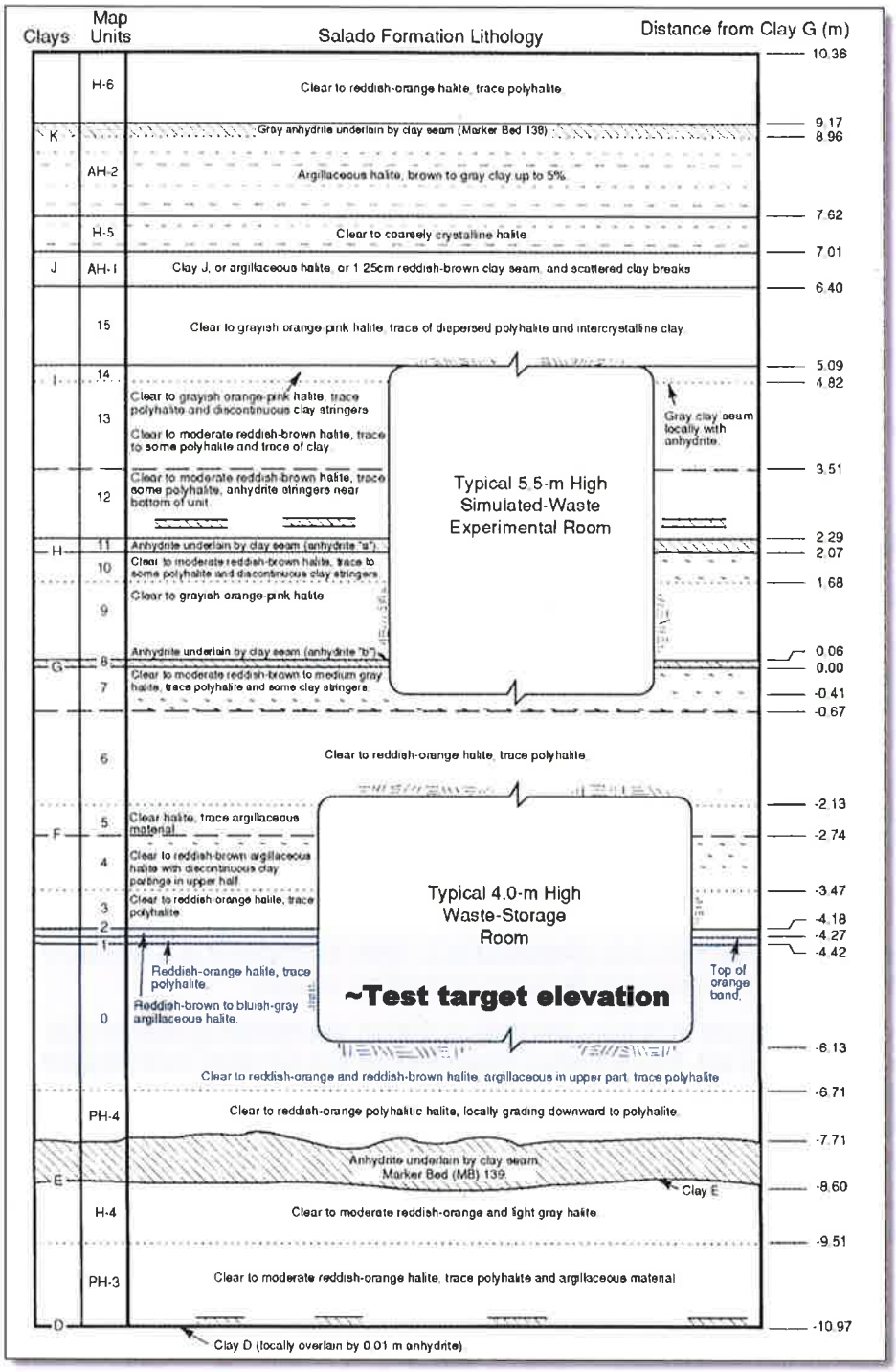

Figure 5. Generalized WIPP stratigraphy (Figure 2-3 of Roberts et al. 1999); MU-0 shaded blue.

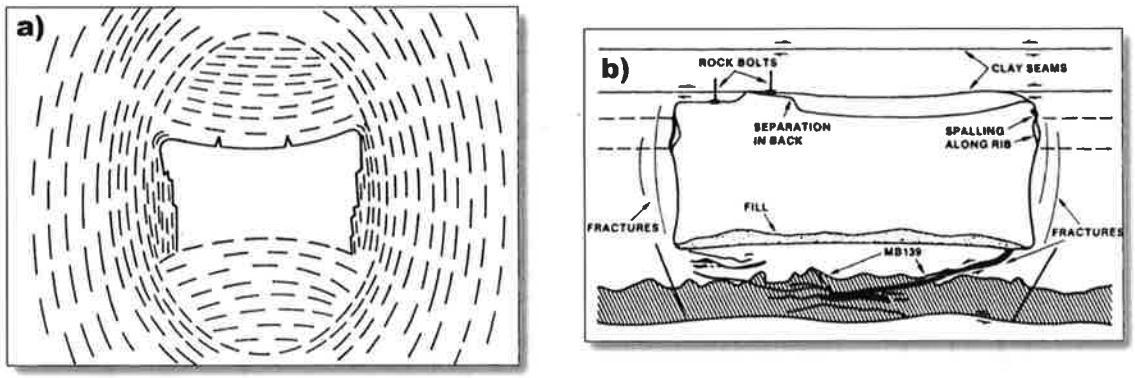

Figure 6. Fractures around mined openings at Asse (a) and WIPP (b) (Figures 3 and 11 of Borns & Stormont 1988).

2.2 Heated Borehole Backfill Considerations

For the first two tests, a central test borehole configuration without backfill is preferred to:

- Allow simpler implementation. It is difficult to fill a horizontal borehole completely with granular backfill, especially in an annular space around a heater. WIPP Room T involved partially backfilling canisters in horizontal remote-handled waste boreholes; the boreholes were not completely backfilled (Molecke 1992);
- Minimize material added to the test interval that may increase the complexity of the chemical and hydrological response. Run-of-mine backfill would contribute to the observed brine inflow and composition, and could have significant anhydrite or clay components, depending on its source;
- Allow straightforward sampling of gases and liquids from the borehole. Backfilled boreholes have included vapor sampling (Westinghouse 1987; Rothfuchs et al. 1988) and permeability estimation using gas flow tests (Bechthold et al. 1999; Rothfuchs et al. 1999), but backfill would make it more difficult to collect liquid brine chemistry samples;
- Allow easier removal of heaters, sampling equipment and monitoring devices after the completion of the test. This will allow possible re-use and will allow more straightforward collection of salt core from near the heater (i.e., coring would not require over-coring the entire heater in a single pass using a very large core barrel, core can instead be collected in pieces or just along one side of the borehole); and
- Allow possible use of radiative heaters and borehole-wall imaging of efflorescence development during the test (Shefelbine 1982).

The primary reason for considering backfilling the borehole is to minimize heat transfer complications from thermal radiation and free convection of air in the borehole. Free convection of hot air within the borehole would alter the applied distribution of temperature in the borehole, complicating simulation of proper boundary conditions using porous medium THMC models. This effect will be minimized by enclosing the heater element in a block of solid material, to provide a "thermal ballast" and displace low heat capacity air. This approach adds foreign material to the borehole, so the chemical stability of added materials in hot brine will be considered. A secondary reason to backfill the borehole is that disposal drifts would likely be backfilled in typical configurations.

The heater should be roughly centered in the borehole either by using centralizing arms or rings (e.g., Appendix A-7, Figure 40), or by simply filling all or most the borehole with the heater. The latter could be done by either making the heater borehole small diameter (same as the heater), or by making the heater or heater/block combination large diameter (same as the boreholes with centralizers or spacers attached to the heater block).

If there is only a small clearance between the heater and the borehole at the beginning of the test, the combination of salt creep and salt precipitation from brine inflow could make the heater removal very difficult (e.g., see WIPP Room B heater removal in Appendix A-2, Figure 21). A tight clearance may also preclude sampling of liquid brines from the borehole during the test. Conversely, borehole closure or rock pressure measurements could be made on the surface of the heater block, if it is made of rigid material and the clearance is tight.

Another heater/borehole configuration option is to place strip heaters along the surface of the borehole and backfill inside of them. While it would be easier to backfill a cylindrical cavity than an annular cavity, the top of the borehole would still be difficult to backfill completely. If heaters are placed against the intact salt, the inner backfill is not located in the primary path for the energy transfer between the heater and the far field, like it is when the heater is in the center of the borehole.

2.3 Test Interval and Observation Boreholes

Around the central test interval boreholes, several smaller-diameter satellite observation boreholes will be drilled and instrumented. The number and size of satellite boreholes depends on the needs of the test. Observation boreholes can be oriented and located in a variety of ways around the test borehole. One suggested layout is shown in Figure 7, with a 10.2 cm [4"] test borehole and multiple 5.1 cm [2"] observation boreholes. The observation holes are at different orientations and distances away from the test interval. The arrangements of boreholes in Avery Island tests, described in Appendix A-3 (Figure 27), suggest alternatives. The total number of observation holes could be reduced by sharing some observation holes between neighboring test locations, but drilling small-diameter observation boreholes is not difficult or expensive. For the first two boreholes, we foresee only executing one test from the test suite at a time, therefore only one test borehole and associated observation boreholes will be drilled to minimize any creep closure effects and missed observations of brine inflow or borehole closure in boreholes before the test begins. The importance of possible impacts due to leaving boreholes open before instrumenting tests should be weighed against the logistical and financial implications of drilling boreholes in multiple efforts, rather than drilling all boreholes in one mobilization of the drilling crew.

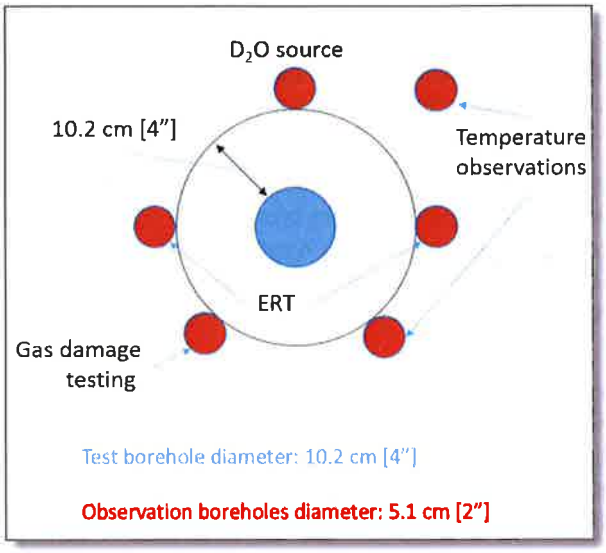

Figure 7. Possible configuration of test borehole and observation boreholes.

2.4 Test Conditions and Features

2.4.1 Test Matrix

Table 1 provides a proposed set of conditions for the suite of borehole tests. The overall intermediate-scale field-testing campaign will have at least five sets of boreholes as different components or stages of the experiment. Each set of central borehole and satellite observation boreholes will be associated with different maximum borehole wall temperatures. The isothermal test will take at least 200 days, based on observations from previous isothermal boreholes at WIPP (Appendix A-1, Figure 14). The exponential decay of borehole inflow rate is related to the permeability of the salt and the geometry of the borehole (McTigue 1993).

Table 1. Proposed test matrix.

		Test Target Temperature (°C)	Step Heating	Cement	Drift Closure Observations	Acoustic Emission Sensors	Duration (days)
Initial tests	1	Ambient (~30)	No	No	No	None	200
	2	120	No	No	No	1-2	100
Follow-on tests	3	50	No	Yes	Yes	1-2	100
	4	160	Yes	TBD	Yes	4-6	200
	5	200	No	TBD	Yes	4-6	100

Test target temperatures will be chosen to straddle different temperature thresholds associated with sources of water to the borehole (Table 2). Based on these estimated key dehydration and phase-change temperatures (and the estimated presence of these minerals in MU-0), the borehole heater tests should be conducted at the target maximum temperatures of 50 °C, 120 °C, 160 °C, and 200 °C. This should keep the maximum temperature well below the decrepitation temperature (where fluid inclusions will fracture the salt), and will straddle either side of the lowest gypsum and smectite (corrensite) clay dehydration temperatures (65 and 100 °C), and the lower (possibly "contaminated") polyhalite and bischofite

dehydration temperatures (150-155 °C). Krumhansl et al. (1991b) indicate the range of temperatures required to dry out the borehole walls in WIPP Room B heaters was 120-130 °C.

Table 2. Expected MU-0 sources of brine sorted by minimum dehydration temperature (data from Powers et al. 1978 and Roedder & Bassett 1981)

Component	Formula	wt% water	Dehydration/release temp [°C]	wt% in MU-0
Smectite	$Al_2Si_4O_{10}(OH)_2 \cdot n(H_2O)$	5-18	65[#] & 100-400	≤ 2% [§]
Gypsum	$CaSO_4 \cdot 2(H_2O)$	21	75-175	≤ 2%
Polyhalite	$Ca_2K_2Mg(SO_4)_4 \cdot 2(H_2O)$	6	150-160[+] & 340-360	≤ 2% [¥]
Bischofite	$MgCl_2 \cdot 6(H_2O)$	53	155-220*	None[^]
Carnallite	$KMgCl_3 \cdot 6(H_2O)$	39	180-224*	None[^]
Fluid Inclusions	(Brine inclusion chemistry variable)	74[@]	240-250	0.1-0.75

\+ Lower dehydration temperatures for polyhalite may be due to "contamination" (Roedder & Bassett 1981).

@ Weight % water in saturated NaCl brine.

\# Caporuscio et al. (2013) Figure 32, likely due to corrensite clay dehydration.

^ Little or no magnesium chloride salt is expected to exist before the test in the salt, but the brine is expected to evolve to a Mg-Cl brine and these salts will precipitate (see Krumhansl et al. (1991b) and figures in Appendix A-2).

§ Clay content in MU-0 is observed to increase going stratigraphically up in the interval.

¥ Polyhalite content in MU-0 is observed to increase going stratigraphically down in the interval.

* Dehydration temperatures for hydrated Mg-Cl salts are such that lower RH → lower dehydration temperatures.

For the initial heated test (120 °C), it is expected ~1,000 Watts of power will be required to maintain the maximum wall temperature at an approximate steady-state in the middle of the 1.5 m [5'] heated test interval. For the planned radial test geometry, a true steady-state temperature distribution will not develop, but the rate of change in temperature with time is expected to stabilize. This estimate is based on analytical solutions to the heat conduction problem (McTigue 1985; Eqn. 83) and numerical TH solutions (e.g., FEHM or TOUGH2). The analytical solution has simplified geometry and only takes into account linear heat conduction in the intact salt. Analytical solutions do not take into account a cooling effect that may occur due to removal of heated air and evaporation of brine from the borehole into the dry N_2 circulating through the borehole. Heat will also be lost through the packer assembly and into the access drift.

Table 3 lists the planned tests, data measurements, and other observations and where they will be made.

Table 3. Borehole test components (all 5 tests).

	Packer/plug equipment	Internal equipment	External equipment	Data collected
Borehole Test Interval	Inflow/outflow gas lines		Dry N_2 gas Gas flowmeters Data collector and power Chilled-mirror hygrometer Two-ended sample container	RH Gas composition
	Pass-through	RTDs	Data collector and power	Temperature
	Brine sampling access tube		One-use samplers	Liquid brine samples
	Pass-through	Heater / heater block	Power	Power applied, T on heater block
	Pass-through	LVDTs on heater block	Data collector and power	Borehole closure
		Cement plug near borehole end	Over-core after test to retrieve samples	Cement/salt interface characteristics
Satellite Observation Borehole	Inflow/outflow gas lines		Gas source (w/ Ar & Xe tracers) Gas flowmeters Gas pressure & T Data collector and power	Characterization of DRZ extent and permeability of damaged regions
		RTDs	Data collector and power	Temperature
		Deuterated water tracer	In-drift sampling to assess leakage	Tracer breakthrough to test borehole and distribution
		AE sensors / sources	Data collector and power	Passive monitoring of AE events and damage mapping via active sources
		ERT electrodes	ERT controller	Salt resistivity in space and time

Instruments are described in Section 4, and a summary of testing chronology is given in Appendix B.

2.4.2 Access Drift Monitoring

Power applied to the heater through time will be monitored. The heater power controller will be set to a target temperature (rather than a target power level), using a temperature sensor on the outside of the heater block.

Access drift barometric pressure, air temperature, and relative humidity (RH) will be monitored at high frequency. These parameters are important to monitor because they are essentially the boundary conditions applied in the access drift DRZ. Air pressure, air temperature, and RH will be monitored with sensors sensitive enough to discern expected differences in these variables between the drift air and the borehole test interval.

Air in equilibrium with Na-Cl brine has a RH of 75%, but Mg-Cl brines have equilibrium RH of 40% or lower, depending on the precise composition (Appendix A-2.1, Figure 21). Mine ventilation at WIPP often contains more or less humidity than this, but the differences are moderated as ventilation air moves through the underground. The moderation effect may depend on the ventilation flowrate. RH of the air in the access drift will provide a measure of dis-equilibrium with respect to the salt formation, and the potential for moisture to exchange between ventilation air and the tested rock mass. Atmospheric data from the central WIPP "mine weather station" or other WIPP ventilation datasets, including the flowrate, will be monitored during the test for comparison with test location data.

To the extent possible, the ventilation in the access drift should be limited or controlled. Doors or bulkheads could be used to route ventilation around the active test area. Controlling and limiting the transients in the ventilation system will help simplify future modeling of the test results.

2.4.3 Salt Temperature Monitoring

Temperature will be monitored very close to, or in contact with, the heater surface, to determine the hottest point in the borehole (e.g., between the heater block and heater). Temperature will be measured along a line parallel to the borehole axis, and along one circumferential ring around the heater. Temperature will also be monitored through time in satellite boreholes at two different radii away from the heated borehole (Figure 7). Section 4.3 discusses temperature monitoring devices.

Heat conduction should be the primary heat transfer mechanism in the intact salt, as opposed to radiation and convection. It will be important to characterize the distribution of temperature in the heated borehole since this is the source of heat flux (i.e., the boundary condition) for the THMC problem. Observations of temperature in satellite boreholes will only require monitoring along the length of the boreholes. The observation hole diameter will be small compared to the heated borehole, and there should not be a significant temperature gradient across the diameter of the observation holes.

Spatial and temporal distribution of temperature data will be used with TH(MC) models to estimate thermal transport properties of the salt (thermal conductivity and heat capacity). The temperature distribution must be well characterized because it drives brine flow (i.e., thermal expansion of brine; McTigue 1985) and enhances creep closure.

2.4.4 Vapor Collection and Gas Sampling

Water vapor extraction will be monitored at high frequency. Data collection frequency will be approximately minutes or seconds between observations to resolve temporal fluctuations in brine inflow as a function of changes in temperature, access drift air pressure and humidity, and creep closure of the borehole and access drift (see high-frequency lab data in Figure 34 of Appendix A-4). The primary method for high-frequency monitoring of brine inflow will be monitoring water vapor production. Water vapor production will be determined by measuring the mass flowrate of gas circulation through the test interval, and estimating its absolute humidity. Periodic measurements of weight gain in downstream desiccant traps will be performed as a secondary lower-frequency method for estimating brine inflow. The traps will provide a cumulative estimate of moisture production, and help prevent re-cycling of

deuterated water (D_2O) tracer that would otherwise be release to the access drift air and potentially migrate back into the test interval.

The flowrate of gas (other than water) going into and out of the borehole will be measured to quantify the mass balance, and estimate the leakiness of the borehole system (i.e., packers, plug, and near-borehole DRZ).

Figure 8 illustrates the layout and connection of borehole equipment. The equipment will allow for multiple configurations:

1) gas flowrate damage testing (upstream constant pressure, downstream outflow closed, observe upstream pressure – Section 2.4.6);
2) water vapor inflow measurement (upstream constant flowrate, downstream open, measure upstream/downstream gas flowrate and downstream humidity);
3) gas sampling (upstream constant pressure, downstream sampler attached, outflow closed); and
4) liquid brine sampling (downstream closed, possibly applying upstream pressure to lift out brine samples).

For water vapor sampling, an inflow line will be connected to a dry nitrogen gas supply (with as little water content as practical) by a flowmeter valve that will measure a range of flowrates relevant to the flowrates controlled by the upstream valve on the N_2 tank. The end of the N_2 inlet tubing will be positioned near the back of the borehole. An outflow line will be branched to outputs such as a flowmeter valve (that must tolerate possibly hot, acidic moisture in the outflow stream) through a downstream set of desiccant canisters to the exhaust. The end of the N_2 outlet tubing will be near the packer, to encourage the gas to sweep through as much of the heated borehole interval as possible.

An inline chilled-mirror hygrometer (CMH), and a double-ended sample container will be connected downstream of the borehole. Since humidity measurements are important, the exhaust line will also have a redundant hygrometer gauge taking higher-frequency humidity readings throughout the test (e.g., a lower-cost resistive or capacitive hygrometer sensor). The CMH will take readings for more accurate estimates of RH (Section 4.8). Appendix B presents a bounding calculation illustrating a that typical a N_2 gas cylinder would last no longer than 53 days, removing the expected amount of brine flowing into an isothermal horizontal borehole at WIPP.

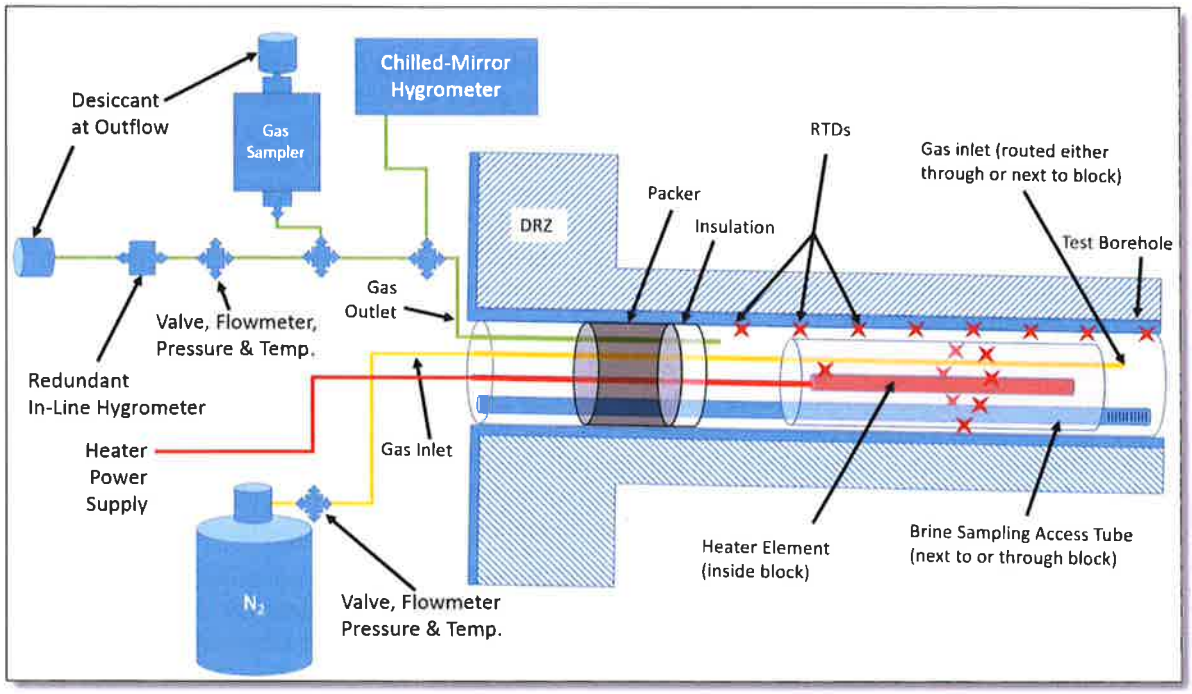

Figure 8. Schematic of test borehole equipment.

The water vapor sampling system will be operated at multiple N_2 flowrates to investigate the efficiency of the moisture removal from the borehole. This data should inform the choice of optimal rate for moisture removal in future tests, or may illustrate any effects of depressing the humidity in the borehole below its equilibrium value with the salt (i.e., a N_2 flowrate that is too high).

Gas samples will be collected using a double-ended sampling vessel attached to a sampling port in the downstream tubing. Humid borehole gas will first flush through the sample container (both valves open), then the downstream sample container valve will be closed, and finally the upstream sample container valve will be closed. A desiccant canister will be installed downstream of the sample outlet to minimize recycling of D_2O in the access drift. The gas sample composition will be tested using gas chromatography. The distribution of isotopes of water (e.g., deuterated water tracer – see Section 2.4.10) will be analyzed using a cavity ring-down spectrometer (CRDS).

The observed water inflow rate through time will be used with the applied constant-humidity boundary condition to estimate the flow and transport properties of the salt via parameter fitting TH(MC) models to the data (e.g., FEHM, PFLOTRAN, or TOUGH2). Gas and liquid samples will be used to monitor the breakthrough of deuterated water tracer from the observation borehole, which will provide a measure of transport velocity, related to the permeability, effective saturation, and effective porosity of the salt – although these parameters might not each be uniquely estimable. Interpretation of tracer data may require a THC model accounting for the fractionation of deuterated water during flow from the source to the evaporation in the central test borehole (heated or isothermal). Gas sample data would provide information on the transport of inert gas tracers (i.e., Ar and Xe) introduced in the observation boreholes, to the test borehole. Tracer transport may require a two-phase TH(MC) flow model to interpret, since the system could be mostly brine-saturated, although salt that is mostly gas-saturated could behave like a single-phase gas system (Stormont et al. 1987).

2.4.5 Brine Composition Sampling

The packer isolation system will also be equipped with a brine sampling access tube to collect liquid brine samples from the test borehole (Figure 8). The composition of the fluid in the borehole will evolve due to two competing processes. One is the possibly changing source of brine flowing into the borehole. Brine collected in the borehole would include components of intergranular brine, intragranular fluid inclusions, water vapor released from dehydration of minerals, and brine from condensation of steam that dissolves salt and then flows into the borehole. A second effect would be the evaporation and concentration brine in the borehole, due to constant removal of moisture (see Appendix A-2). The superposition of these two competing processes may make it difficult to discern the source of any observed changes in liquid brine chemistry during the test.

The design of the brine sampling tool is not complete, but it will include the ability to collect samples of liquid brine for laboratory compositional analysis. The tool should use a robust approach not subject to plugging (e.g., small-diameter tubing would likely become plugged between sampling events by crystallizing salt as the hot salt-saturated brine is cooled). Sampling would be done through a slotted or perforated access tube. This sampling access tube and its openings to the borehole should be large enough diameter so it does not become plugged after repeated sampling events. Possible approaches include:

- Use capillary tubes to wick up standing brine at the end/bottom of the sampling tube. These capillaries would each lift up a small amount of brine. This approach does not require pumping, but might not capture a large volume of brine, which could make some laboratory analyses difficult or less accurate.
- Samplers could comprise fiberglass wool or fine-sand material to wick up brine from the end/bottom of the sampling access tube. This would be analogous to using a giant "Q-tip" to wick up brine. This approach also would not require pumping, but may not acquire large enough sample volumes and samples would require additional processing steps (e.g., centrifugation or rinsing of samples from sampler).
- A small diameter tubing (larger than a capillary) could be used to pump brine up from the bottom of the borehole. Pumping requires either syphoning brine up or using applied gas pressure from the moisture extraction system, but could potentially acquire larger-volume samples.

Samples of liquid brine acquired during testing will be used in conjunction with post-test samples of precipitated salts for calibrating transient thermal-chemical models (e.g., EQ3/6 or PHREEQC). It may be possible to treat the borehole system as a beaker-type mixing experiment, with a stream of inflowing brine, outflowing moisture, and precipitation of solids through time. These models will be used to estimate any discernable changes in the temporal composition of brine flowing into the borehole from the observed changes in borehole brine chemistry.

2.4.6 Gas Flowrate Damage Testing

Gas flow in packed-off intervals can be used to estimate the damage in borehole intervals to assess the extent of the DRZ. An interval of a borehole is isolated (either between two packers or behind a single packer), and gas pressure is applied to the interval. In the constant-pressure test, a low pressure (e.g., 70 kPa [10 psi gauge]) is applied and the resulting gas flowrate is observed. The test runs until a steady state is achieved (which is on the order of a few seconds or minutes). In the falling-pressure test, a pressure is applied to the interval, and the interval is closed in, followed by monitoring the decay of pressure in the interval. Falling-pressure tests are typically more useful on lower-permeability intervals. The tests can be repeated in different intervals of the borehole to assess damage along the length of the borehole. These tests have been run at WIPP (Appendix A-9 and Figure 4b) and at Avery Island (Appendix A-3.2) with success. The tests performed at WIPP (Stormont et al. 1987; data from gas flowrate damage testing listed in their Appendix C) applied 70 kPa [10 psi gauge] across a 1-m section of

13 cm-diameter borehole and had a lower limit of 0.1 SCCM (standard cm^3/min), which corresponds to a gas permeability of approximately 3×10^{-6} darcy [3×10^{-18} m^2]. The configuration used at Avery Island (Appendix A-3.2, Figure 31) involved grouting the borehole above the mechanical packer and was able to interpret gas permeability down to 10^{-21} m^2 (~1 nanodarcy). The minimum interpretable permeability is related to the sealing ability of the packer system.

Since the moisture inflow system (Section 2.4.4) also uses gas flow, the N_2 flow system will be plumbed to allow the downstream outlet to be closed, while maintaining the upstream pressure and monitoring the flowrate. This will allow an estimation of the gas-accessible permeability of the borehole during the bine inflow test. This test could observe changes in the DRZ surrounding the access drift or boreholes, or change in the gas saturation in the test interval. Low pressure gas will likely not displace brine in a partially saturated DRZ during testing. It will be difficult to differentiate changes in total porosity (i.e., either damage or healing) from changes in gas saturation, due to the existence of two-phase brine and gas flow (i.e., brine flowing in to the DRZ surrounding boreholes, reducing the gas-accessible porosity).

The gas used to conduct the damage test should include different tracer gas in each borehole, which would be analyzed for in the gas samples collected from the test borehole. This would provide a measure of gas transport in the salt. The tracer gas should be inert, stable at elevated temperatures, and naturally rare in the testing environment (e.g., Ar and Xe at $\leq$10% concentrations in a N_2 carrier gas). Gas tracers will provide information regarding their earliest breakthrough (or lack or breakthrough) during a brine collection test. This could be related to an advective gas porosity of the salt, for a gas-only pathway. The magnitude of gas concentrations in the test borehole samples (especially under two-phase flow conditions) may not be uniquely interpretable. Therefore, this type of measurement is considered to be of secondary importance.

WIPP site pressure-safety regulations require a pressure-safety plan be prepared for any system involving high-pressure gas (i.e., connected to a N_2 cylinder). Strategies to meet these requirements and achieve test are being explored and addressed in FY17 laboratory and preliminary field testing.

Stormont et al. (1987) discuss gas tracer experiments using SF_6, conducted in vertical boreholes in drift N1420 at WIPP. These tracer tests showed there was significant gas-saturated porosity in the marker bed and in the DRZ of the access drifts. Any gas tracer experiments as part of this plan would not be in Marker Bed 139 (MB139), and would likely not have gas-saturated connected porosity between the boreholes.

2.4.7 Geomechanical Monitoring

Borehole closure will be monitored in the test borehole using multiple linear variable differential transformer (LVDT) gauges or possibly other less-accurate displacement monitoring devices. These will monitor closure of the borehole throughout the test due to creep. These may be mounted on the heater block, if it is manufactured from material with well-known mechanical properties (i.e., thermal expansion coefficient). Borehole closure observations will help constrain THM models and predict borehole closure effects during the test. There is a large amount of existing drift and borehole closure information for comparison, gathered from the TSI experiments in the WIPP North Experimental Area (Tyler et al. 1988; Munson et al. 1991, 1992a, 1992b, 1997a). Borehole strain was measured in brine inflow boreholes at WIPP in Rooms A and B (Nowak & McTigue 1987).

Extensometers could be installed in observation boreholes, with wires or rods used to monitor relative motion of an anchor point in the salt and the collar at the access drift (Section 4.4). Extensometers provide observations of relative displacement between two or more fixed points, which could also be used to constrain THM models that include creep closure and deformation of the access drift.

Borehole pressure cells (BPC) could be installed into a grouted observation borehole to measure changes in stress due to thermal effects and creep closure of the heated borehole (Section 4.5). They are typically installed in pairs, giving data about the changes in vertical and horizontal stress during the test.

Observations of stress or pressure in the salt are difficult to make reliably (Bechthold et al. 2008) but can be used to constrain THM models that include creep closure and deformation of the access drift.

Large-scale geomechanical observations of drift closure are not the primary goal of the first two tests, and will be deferred to later tests. Borehole closure observations may be included in the first two tests if they do not complicate the observations related to the primary goals of the test.

2.4.8 Cement Exposure Test

A short plug of Class G or H cement or variant concrete will be placed in the back of at least one borehole in a follow-on test. The point of the test is not to create a solid sealing plug of cement, so a small amount of cement can be emplaced to the end of the borehole with a long "pusher" rod. Cement and concrete are ubiquitous in construction and have been proposed as repository sealing materials. Although some studies have been conducted on the topic of cements in a salt repository (e.g., WIPP Plugging and Sealing Program; Tyler et al. 1988), it would be valuable to take exposed samples from the salt and cement interface, and to help understand how the interface between the cement, salt, and aggregate behaves in contact with a hot, acidic brine. This test may impact brine composition samples and even inflow rates of moisture to the vapor collection system, so cement exposure tests should be deferred to follow-on tests.

Samples of cement and the cement/brine interface would be recovered from the borehole after the end of the test. They would be examined quantitatively using scanning electron microscopy (SEM)/energy dispersive X-ray spectography (EDS) and X-ray diffraction (XRD) for elemental compositions, and porosimetry (multi-beam SEM, nitrogen adsorption) for pore-alteration. The aim would be to quantify the effects that heat, brine, and acid gas have on the chemical and structural properties of the cement.

2.4.9 Electrical Resistivity Surveys

Electrical resistivity surveys will be conducted within and between satellite boreholes on either side of the test borehole (Figure 7) to estimate the evolution of brine content in the salt surrounding the boreholes. Appendix A-8 shows some resistivity vs. brine content relationships used in previous salt work in electrical resistivity. Typically, the higher brine content in bedded salt (compared to domal salt), means the resistivity of the formation will be lower than in domal salt.

Salt resistivity is expected to change by orders of magnitude due to changes in brine content (see Appendix A-8), while changes in temperature should only result in changes in resistivity of only a few percent. Electrical resistivity tomography (ERT) is the process of estimating formation resistivity from multiple sets of applied current and measured voltage electrode pairs. It is not clear whether ERT could distinguish between difference in brine content due to changes in porosity (i.e., damage or healing) or equivalent changes in brine saturation, due to flow of brine into or out of gas-saturated salt. Distinguishing between these two interpretations may require jointly interpreting results from the ERT surveys and a seismic or active AE survey (Section 2.4.11).

Electrical geophysical methods often have problems with metal located in or near the test interval. WIPP drifts include extensive rockbolts and chain-link fencing, while the test borehole will include tubing, packers, and wires associated with the test (Figure 8). ERT may still produce usable results in the presence of these metal components, since it is the change of resistivity through time (i.e., between individual surveys) that is being interpreted.

2.4.10 Deuterated Water Tracer

A deuterated water (D_2O) tracer will be added to one of the observation boreholes above the test borehole. A small amount (e.g., 10 mL to 100 mL) of liquid D_2O will be added to an isolated section of one of the observation boreholes. Leakage of D_2O from the source borehole should be reduced by using multiple packers or plugs to isolate it from the access drift, and air samples should be taken during the test to assess the level of leakage directly from the source borehole into the access drift. Limiting the source to a short interval at the back of the borehole would make behave it more like a point source. Samples of

water vapor and liquid brine from the test borehole will be analyzed with CRDS to quantify hydrogen isotopes in the water. Quantifying the breakthrough of tracer from the D_2O source in an observation borehole to the test borehole will be used to estimate brine transport velocities, including the effective porosity of the salt.

The D_2O could be added to the observation borehole by saturating a small sponge with the traced water. The RH of a sealed observation borehole in equilibrium with Na-Cl brine will be 75%. The D_2O will evaporate into the borehole air, elevating it above 75% RH (since it is pure water and therefore wants to equilibrate to 100% RH), and leading to deliquescence (dissolution of salt by condensation of moisture in the air).

Fractionation of the D_2O will occur in the test borehole during evaporation or boiling of the brine from a liquid into a vapor phase (Appendix A-3.1 and Stauffer et al. 2015, p. 73), as well as during the precipitation of any hydrous minerals in the borehole. The RH is equal to the activity of water, which primarily controls fractionation during evaporation, with less fractionation happening in a more humid environment. Evaporation into air with RH above 95% results in essentially no fractionation (Kendall & Caldwell 1998).

As with gas tracers, the initial breakthrough of liquid tracer can be related to transport velocities and effective porosity. Unlike the gas tracers, we can attempt a mass balance of D_2O distribution after the completion of the test. The sampling would need to estimate:

1) net loss of in D_2O in the source borehole,
2) mass of D_2O collected in vapor form in the test borehole during the length of the test,
3) mass of the D_2O precipitated in hydrous minerals in the test borehole, and
4) D_2O left in the formation (less the background concentration – estimated to be 3 ppm per gram of salt at Avery Island).

Post-test samples of salt will be cored between the source and test boreholes (adequately preserving the salt samples for evaporative losses and possible further fractionation during handling and transport to the laboratory), to estimate the spatial distribution of D_2O left in the formation (done at Avery Island, Appendix A-3.1).

Observed spatial and temporal distributions of D_2O will be used to calibrate THC models of flow and transport in the salt. This data will provide a unique calibration and validation dataset regarding brine transport through salt under both isothermal and heated conditions.

2.4.11 Acoustic Emission Monitoring

During heating and cooling, salt produces acoustic emissions (AE) related to micromechanical brittle deformation. AE sensors (i.e., sensitive piezoelectric microphones) will be installed into observation boreholes with grout or epoxy to ensure a good connection between the rock and sensors. A minimum of four sensors is required to estimate source locations of emissions in three dimensions, but due to effects of ambient noise six or more are preferred. The second borehole test will have one or two sensors emplaced in observation boreholes, to assess the ability to monitor and discriminate AE from the heating and cooling of salt, in the presence of ambient WIPP noise. Piezoelectric sensors will be placed in boreholes deep enough to be located beyond the access drift DRZ, where ultrasonic velocities are slower (Hardy & Holcomb 2000; Holcomb et al. 2001). If sufficient AE events are observed during the 120°C test, an arrangement of six or more AE sensors and higher-frequency observations may be justified for subsequent tests, to allow estimate source location estimation, especially with repeated heating and cooling episodes (Section 2.8.1).

AE would be useful for characterizing brine release micromechanical processes during heating and cooling (e.g., failure of fluid inclusions or micro-crack damage accumulation). Most macroscopic

mechanical or THMC models would not be able to use AE observations (timing or source locations) directly, but this dataset might be useful for building a physical understanding of the THMC processes going on in salt, especially during a rapid heating or cool-down period. This is not one of the primary goals of the test series, so these observations are lower priority than those directly related to brine availability, but the data may improve understanding of micromechanical and hydrological coupling in salt.

Piezoelectric sensors can double as ultrasonic sources to survey the distribution of wave velocities between sensor boreholes in the salt (i.e., cross-hole wave propagation tests). Estimating the distribution of faster and slower travel-time regions in the salt could help to estimate the distribution of the DRZ (Holcomb et al. 2001), and to better estimate the source locations of AE. Alkan et al. (2007) have used AE in the laboratory to investigate the onset of permeability enhancement in salt during triaxial compression tests. Active velocity surveys could be conducted before, during, and after heating, since the applicable wave propagation characteristics in the salt may change with temperature, damage, or healing.

If ambient WIPP noise levels are favorable, AE testing will collect full-waveform data for possible analysis of wave attenuation and dispersion. This data would also be useful for quality control, since the observations will change in character if the sensors de-bond from the salt in their boreholes. For subsequent tests, the sensor and source network should be installed to allow automatic execution of the velocity survey frequently during the test. As the bulk salt deforms and fractures the changes in seismic propagation can be significant, and associating the changes with AE events would be helpful, in place of more traditional geomechanical observations. Salt creep may complicate the survey process, because movement of the source relative to the receivers will appear just like changes to the speed of propagation between the sensors.

2.5 Expected Test Conditions and Processes

The following bulleted list summarizes important processes and conditions we expect to observe during the first two borehole tests (isothermal [~30°C] and 120°C) at WIPP. The expected conditions necessarily motivate the sequence of activities that will be conducted in the borehole (Appendix B), and the types of sensors to be used (Section 4).

- Boreholes will be drilled through the access room DRZ (gas flowrate testing will be used to delineate the extent of the DRZ surrounding the access room). If borehole test intervals are located deep enough into the salt to be outside the access drift DRZ, the salt will be low porosity, low permeability, and brine saturated as an initial condition.
    - Boreholes will each develop a small DRZ of approximately the same radius as the borehole.
        - Salt porosity will increase in the borehole DRZ due to dilation associated with stress redistribution from creating the borehole.
        - Salt permeability will increase in the borehole DRZ due to increased porosity.
        - Brine saturation of salt will decrease in the borehole DRZ due to increased porosity.
- Intergranular brine will flow to the test borehole down a pressure gradient (up the temperature gradient in the heated borehole). High brine pressure (~lithostatic) exists in the undisturbed far field, while the borehole will be maintained at nearly atmospheric pressure and constant humidity. There are porosity and permeability gradients, also (porosity and permeability of the salt are lowest in the far field and highest near the borehole). The brine inflow rate will be highest at first, and will decay exponentially with time (Figure 11).
- Brine will flow towards the borehole driven by thermal expansion of the brine in the pores (i.e., thermoporoelasticity, McTigue 1985), with slight changes in composition along the way. Salt

permeability will simultaneously decrease with expansion and accelerated creep deformation of the salt grains due to heating (Figure 32).

- Tracer (deuterated water) will be added in an observation borehole.
    - Tracer will travel through the brine-saturated porosity of the salt via diffusion (down a concentration gradient), and advection (down a pressure gradient towards the larger borehole).
    - Tracer may travel through the gas-saturated porosity of the salt (if a continuous gas-saturated path exists) as water vapor.
- Water will evolve in vapor form as hydrous minerals in the salt dehydrate at different temperatures. As different minerals dehydrate, there is typically a volume change associated with the dehydration, which may lead to additional porosity and permeability in the salt.
- Water vapor from mineral dehydration will migrate down minor air pressure and water vapor concentration gradients to the borehole, but it may condense and dissolve additional salt *en route*, depending on the temperature.
- Brine will evolve from the salt as fluid inclusions (i.e., intragranular brine) by migrating to grain boundaries and becoming "free" intergranular brine. Fluid inclusion composition is often different from intergranular brine (Figure 25) with higher concentrations of typically minor ionic species.
- Water vapor will be removed in the isothermal test borehole because dry N_2 will be circulated through the borehole.
    - Salts (mostly halite and sylvite, initially) will precipitate out of the brine as water vapor is removed, since the brine flowing into the borehole is at or near saturation already. Activity of H_2O will decrease below the 75% RH associated with saturated Na-Cl brine as the concentration of Mg increases (Figure 18).
    - The brine remaining in the borehole will evolve to a more Mg-rich brine, and hydrous magnesium chloride salts will precipitate as the system loses more water. This is brine evolution due to enrichment and salt precipitation (Appendix A-2.1).
    - Additional brine will flow into the borehole, which may or may not differ in composition from brine that will already have flowed into the borehole at that point. This may be a change in source composition (Appendix A-2.3).
    - Samples of gases collected from the borehole will include water vapor and the added deuterated water (D_2O) tracer. The D_2O may have fractionated in several ways (Appendix A-3.1):
        - D_2O will fractionate at the source, where it will migrate from the source into the salt via deliquescence and mixing with native formation brine.
        - D_2O will mix during flow through the salt via diffusion and dispersion with native brine (with concentration levels of D_2O).
        - D_2O will fractionate predictably after flowing into the test borehole, where the heavier D_2O will preferentially stay in the borehole and lighter H_2O will evaporate and be removed by the dry N_2 stream. The fractionation will be harder to predict if the temperature is above boiling, but there will be minimal fractionation if there is complete boiling. The volume of residual moisture may be small enough in a hot borehole to make fractionation less important in the overall mass balance of D_2O.
        - D_2O will fractionate, as precipitation of hydrous minerals in to borehole may take up D_2O at different rates than H_2O.
        - Microbial effects on fractionation should be small, since there are not significant communities of halophiles known to be viable in WIPP salt, especially heated salt.

  - The CMH and any downstream flow meters may require flushing or cleaning due to deposition of salt dust or precipitation of any condensable gases besides H_2O (e.g., $HCl_{(g)}$).
- Acid gas ($HCl_{(g)}$) will exist in equilibrium with the heated brine, especially as the brine evolves to become magnesium-rich. The effective pH of any condensate in the borehole will be low due to the presence of acid gas, and the reduced partial pressure of steam (availability of liquid water) from circulating dry N_2 gas (Appendix A-2.2).
- Acid gas will be generated in the heated borehole environment from a combination of:
  - decomposition of hydrous Mg salts (thermodynamically favored at higher temperatures and in presence of adequate oxygen), and
  - directly from a liquid brine by equilibrating $HCl_{(g)}$ above a strong chloride brine (Na-Cl or Mg-Cl) and moving that partial pressure of acid gas over distilled water.
- Magnesium chloride minerals will evolve differently depending on the humidity of the borehole environment. If the N_2 flowrate is too high and RH is low, minerals will dehydrate at lower temperatures than if the RH is in equilibrium with the salts (i.e., 75% RH for Na-Cl brine or lower for other brines – Greenspan 1976).
- In a heated borehole, the brine will evolve differently than in the isothermal borehole, since minerals have different stabilities with respect to temperature and RH (Wollmann 2010).
- In a heated borehole the fractionation of D_2O will be different than in the isothermal borehole, since fractionation between liquid and vapor and hydrous minerals is temperature dependent.
- The resistivity of the salt will change in space and time due to (Appendix A-8):
  - Resistivity of salt is a function of brine saturation
  - Resistivity of the brine is a function of temperature
  - Metal tools (including the heater, its power cables, rockbolts and chain-link fencing) in the boreholes and access drift will influence the effective resistivity (but this effect shouldn't change through time) – the magnitude of this effect will be examined in the initial isothermal test
  - Presence of brine-saturated clay layers outside the near field of the test interval could strongly affect the response, but should also not change significantly with time
  - Resistivity of the salt near the access drift, in the room DRZ, may fluctuate with the RH of the ventilation system air (i.e., dry vs. moist).
  - Formation factor may be a function of temperature due to temperature-driven changes in surface conductance, causing an apparent change in brine-saturated resistivity with temperature. This effect is stronger in clays, but the disseminated clays in MU-0 may produce a similar effect.
- Material added to the borehole may generate vapor, and may react with the brine and acid vapor evolving in the borehole. These materials may generate $HCl_{(g)}$ vapor and may interact with the acid brine, and may produce corrosion products and further change the system composition. Key system materials should be tested in the laboratory at expected temperatures to monitor their degradation and any byproducts they may produce. The materials in the borehole and directly exposed to the borehole will include:
  - Packer or plug seal materials (e.g., neoprene, viton, or silicone rubber). Neoprene may generate HCl vapor when heated; viton may genereate HF vapor when heated.
  - Gaskets or seals between packer and tubing (e.g., neoprene, silicone, or filler foam). Organic components could produce unexpected chemical results when heated.
  - Insulation on the heater side of the plug or packer (e.g., fiberglass).
  - Metal components of packers, brine sampling equipment, valves, and gas tubing (e.g., stainless steel or nickel-chromium based corrosion-resistant materials) will corrode.
  - Heater element and any "thermal ballast" added to surround the heater element will corrode.

  - Any cement samples added to the borehole will react with brine, acid gas, and heat.
- The test and observation boreholes will deform and creep closed.
  - Heating the test borehole will speed up borehole closure and creep closure of the access drift.
  - If the salt closes in on the heater or packers to prevent their removal, they will need to be overcored or destroyed to be removed.
  - The drift will only be heated from one side; it will creep closed asymmetrically.
- Acoustic emissions (AE) will be generated in the salt.
  - They may be difficult to discern faint emissions from background WIPP noise.
  - Rapid heating or cooling will cause micro-cracking due to extension or contraction, and will lead to AE.
  - Macroscopic cracking, spalling, and failure related to drift closure will cause AE.
  - Ultrasonic wave velocities are a function of the amount of damage in salt, with waves traveling faster in intact salt (Holcomb et al. 2001).
  - Ultrasonic wave velocities are more function of temperature and less a function confinement, with waves traveling slower in hot salt and faster in more strongly confined salt (Yan et al. 2014).
  - Both the travel times (i.e., first arrival) and the full observed waveforms from man-made cross-hole AE contain useful information for understanding changes to the salt and the sensor network.
  - Salt creep may change the relative positions of the AE sensors and sources with time. It may be difficult to discern the difference between changes in sensor network geometry from changes in material properties (including both damage and temperature effects).
- During cool-down of heated salt, a surge of brine will flow into the borehole.
  - At least two weeks of cool-down brine inflow data will be collected after the end of heating, with high-frequency data collected at changes in heater power (up or down).
  - Any unplanned fluctuations in heater power (i.e., power surges or brownouts) may lead to changes in brine inflow.
- Salt precipitate (i.e., efflorescence) will form on the borehole wall under isothermal and heated conditions. Salt will also precipitate in the formation once the boiling isotherm moves out into the formation. Precipitates will be collected from the test borehole during post-test sampling, to quantify the D_2O mass incorporated in hydrous minerals, and to determine its mineral makeup.

2.6 First Borehole Test Objectives

The first borehole test will be performed at ambient or isothermal (~30 °C) conditions. We will choose instrumentation and methods with high likelihood of success. A goal of this test will be not to over-complicate techniques or try too many new methods or equipment. Another important objective will be to enhance the test organization's experience with testing in the underground environment, with organizing and arranging activities, and assessing the efficacy methods and equipment at the conclusion of the test. The isothermal test will allow debugging of the data collection setup without the complication of the heater.

The isothermal test will provide a baseline of data to compare brine inflow, tracer transport, and brine chemistry against data collected from the second heated borehole. The main activities during this test will include gas flowrate testing for damage evaluation, installation of electrodes to gather ERT data, monitoring water vapor mass flowrate using recovery by circulation of dry N_2 gas, sampling liquid brine flowing into the test interval borehole, and observing migration of D_2O through the system. The first test will also assess the effectiveness of measures to control D_2O source containment and possible contamination of the access drift with deuterium. Table 4 is modified from Table 3 to only include practices utilized in the first test.

Features of the initial isothermal test include:

- Interval gas-flowrate rock damage testing sequence (constant pressure and falling-pressure tests with gas tracers) will be conducted in the borehole to evaluate damage along the length of the borehole by testing repeatedly and moving the packer deeper into the borehole (Appendix A-9). These tests should be conducted as quickly as possible, to install the borehole seal and quantify brine inflow before losing too much brine to the mine ventilation.
- Adding D_2O source to a packed-off portion of one observation borehole.
- The isothermal brine inflow test using dry N_2 may take 200 days or more to reach an approximate steady-state condition (e.g., see data reported in Appendix A-1).
- Experiment with multiple N_2 gas flowrates, to estimate the optimal gas flowrate for subsequent tests. Test should flush water vapor from the borehole, but N_2 flowrate should not be too high, which may create an artificially dry environment that might complicate the boundary condition applied at the borehole during model interpretation of data.
- Sample gases collected from the borehole, test water vapor samples from the borehole and the access drift air with CRDS for stable water isotopes.
- Sample liquid brine from borehole during test. Isothermal test may allow some sampling approaches not possible in heated boreholes (i.e., hot brine will precipitate salt in sampling tubes as it cools).
- After the test, gas flowrate damage testing will be conducted along the borehole (no need for tracer gases) to evaluate damage along the length of the borehole, to compare to the pre-test results.
- After the test, salt precipitate will be removed from the test borehole and tested for D_2O content and mineral identification.
- After the test salt cores will be examined in the laboratory to compare samples from before testing, to discern change that occurred to the salt pore network from the test.
- After the test, salt cores will be collected between the tracer and test boreholes to tests for D_2O content in the salt. Samples should be preserved to minimize evaporative losses and additional fractionation of D_2O in the cores.

Appendix B presents a proposed testing sequence for the first two tests.

Table 4. First borehole test components.

	Packer/plug equipment	Internal equipment	External equipment	Data collected
Borehole Test Interval	Inflow/outflow gas lines		Dry N_2 gas Gas flowmeters Data collector and power Chilled-mirror hygrometer Two-ended sample container	RH Gas composition
	Brine sampling access tube		One-use samplers	Liquid brine samples
Satellite Observation Borehole	Inflow/outflow gas lines		Gas source (w/ Ar & Xe tracers) Gas flowmeters Gas pressure & T Data collector and power	Characterization of DRZ extent and permeability of damaged regions
		Deuterated water tracer	In-drift sampling to assess D_2O leakage	Tracer breakthrough to test borehole and distribution
		ERT electrodes	ERT controller	Salt resistivity in space and time

2.7 Second Borehole Test Objectives

The objectives of the second (120 °C) borehole are to perform essentially the same tests conducted in the first borehole, but with the effects of added heat. This temperature was chosen to be above the lower-end gypsum and clay dehydration temperatures but below the lower polyhalite and bischofite dehydration temperatures (Table 2). Heat will speed up most processes in the salt (i.e., borehole closure, brine inflow, brine evaporation). Test activities will include the same measurements: gas flow tests, electrical resistivity tomography, brine and vapor sampling from the test interval borehole, and observations of D_2O tracer. This test will include preliminary deployment of a limited AE sensor network to quantify the timing of AE events in the presence of ambient WIPP noise. The initial deployment will not include enough sensors or high-frequency data acquisition rate to estimate source locations or conduct active surveys.

For comparison, tests 1 and 2 should be nearly identical right up to turning on the heater, including: 1) same borehole layout, especially in relation to access drift geometry; 2) borehole sealing system with pass-throughs and fixtures for heaters in the isothermal test; and 3) an initial baseline monitoring period without heating, in the second test. Appendix B lists a proposed chronology of tests in the first two boreholes.

2.8 Follow-on Borehole Test Objectives

Further tests will be conducted using the modular borehole plan, but we intend to take a break between tests two and three to re-assess the testing goals, instrumentation, and sampling strategies. Lessons learned from the first two boreholes may result in changes to instrumentation, heater design, or testing schedule (e.g., parallel *vs.* serial tests). We only present possible test ideas for boreholes 3-5 and possible subsequent tests, with the intention of updating the plan after the first two boreholes are complete.

2.8.1 Stepwise Heating

A follow-on experiment could include stepwise heating. In such a test the power would be increased in steps and cycled on and off several times, to monitor the brine inflow during repeated episodes of heating and cooling. The typical response of salt (both bedded and domal) is to produce large amounts of brine at the first significant decrease in temperature (i.e., beginning of cool-down; Avery Island Figure 28, Salt Block II Figure 34, and Asse – Rothfuchs et al. 1988). Previous field tests have sought to minimize this effect by stepping down the heater power gradually, but even the first minor decrease in heater power results in a large increase in brine inflow. At Avery Island, gas permeability tests were conducted during the cool-down period. Results showed the permeability of the salt increased during cool down (Appendix A-3.2, Figure 32).

We do not expect the "power" level of radioactive waste to drop suddenly, but no salt heater test (lab or *in situ*) has yet reduced heater power slowly enough to prevent this surge of cool-down brine inflow. The Asse brine migration test spread the cool-down phase out over a month (Appendix A-5.3, Figure 38) and it still produced half of the total brine inflow during the cool-down period. If the brine surge is due to cool-down tensile forces cracking the salt and increasing its permeability, the cool-down rate must be slow enough to allow salt creep (which does not produce damage to the salt) to dissipate any stresses due to cooling before they lead to tensile cracking.

This proposed follow-on test will generate data for validating the coupled hydromechanical mechanisms in THMC models. We will cycle one of the tests through multiple hot/cold cycles and multiple temperature steps to collect a dataset for investigating the physical mechanism behind this widely observed (but still yet un-modeled) behavior. During this temperature cycling test, it will be important to measure borehole closure (and possible expansion), measure high-frequency brine inflow (including collecting samples of brine and gases), monitor AE, conduct active ultrasonic surveys to characterize DRZ development, and estimate the gas permeability of satellite boreholes through time.

2.8.2 Sealed Borehole Test

Another follow-on test of interest would involve conducting a hotter borehole heater test (i.e., above the brine boiling point), but under sealed conditions, without flowing dry N_2 through the borehole to remove brine. This test would be more representative of the conditions around a waste package. The cool-down phase would have to be quite drawn out (i.e., like radioactive decay) to reduce damage and brine release at the end of heating from completely wiping out the evidence left in the system that evolved during heating. The main information from this type of test would be the post-test coring and sampling to determine the final distribution of moisture and estimation of salt permeability and porosity surrounding the heater. This type of test would reveal information about the fate of brine in a sealed heated borehole or drift, where water is not continually removed. The interaction of brine migration down a pressure gradient, thermal expansion of brine, and water vapor recirculation and heating may be significantly different from in tests where the water is removed.

Brady et al. (2013) prepared their survey of remaining equipment as part of a re-entry plan to collect cores and heater samples from still-in-place Room A and B heaters in WIPP (emplaced in the 1980s). Most of these WIPP heaters were sealed (i.e., did not have N_2 circulated through them) and achieved temperatures above boiling.

2.8.3 Long-term Brine Availability

Once the brine collection and borehole packer system designs have been tested, a follow-on low-temperature heated (~50 °C) test could be conducted for a longer period of time (≥3 years) in a deeper borehole (≥20 m [65']). The point of this type of experiment would be to monitor the availability of brine over a longer time scale, to possibly see boundary effects associated with the edge of the DRZ for the repository excavation (i.e., a decline in the production of brine). The initial planned tests are short duration and are expected to reach an essentially steady-state brine production rate. The reservoir of brine and permeable salt that these shorter tests will draw from appears infinite in previous *in situ* tests. From the point of view of long-term performance of a salt repository, it would be useful to quantify the extent of the DRZ associated with the excavation of the repository facility and possibly assess the ultimate quantity of brine that could flow into a repository excavation.

2.8.4 Other Follow-on Measurement Types

Cement and brine interaction tests will be conducted in later borehole tests (possibly during tests listed above), as they will likely affect brine chemistry. Geomechanical observations beyond possibly simple borehole closure will also be conducted in subsequent tests.

3. LABORATORY INVESTIGATIONS

Along with in-situ testing, laboratory experiments and laboratory investigations of samples from the test intervals will also be coordinated. These include microscopic observational studies and flow properties on cores, estimating the coefficient of thermal expansion of salt and brine, and analyzing captured brine and gas samples from the boreholes. These experiments require preservation of samples. All core should be sealed to prevent dry-out. If samples are properly preserved, analyses can be run in subsequent years, based on the availability of funding.

3.1 Pre-Field Test Materials Interaction Experiment

Materials to be utilized in the elevated temperature field tests should be tested first in the laboratory to monitor for significant produced gases or liquids. Neoprene rubber gaskets or seals may produce HCl vapor, and silicone or fiberglass may produce silane (SiH_4) vapor. These by-products should be evaluated to assess whether they will meaningfully interfere with the planned measurements, including: CRDS interference, CMH condensate, and tracer gas detection via gas chromatography.

Laboratory exposures of cement and metal samples in heated brine would also help to better understand their impacts on brine composition, but would not require laboratory testing before execution of the field test.

3.2 Core Analysis

Classical microscopic observational studies will include examination of thin sections to determine mineral distributions and microstructural features. Mineral distributions will require accurate descriptions of hydrous minerals that influence brine and gas samples collected during the test, as well as deformation mechanisms. Microstructural features provide details of deformation characteristics ongoing in salt structures before and after testing. The evolution of micro-mechanical processes is important to the long-term performance of heat-generating repositories and model validation (Hansen 2014). Pressure solution processes, dislocation creep, and plasticity are micro-mechanical processes that are sensitive to thermal exposure and have a direct impact on the structural state of salt. The effects from hot brine or steam on these micromechanical processes have not been explored directly. Exposed samples from the near-borehole region can be analyzed for precipitated salts or damage associated with heat and vapor transport.

Flow and pore properties of the intact salt are also desired. Laboratory analyses will be conducted on samples obtained before and after heating. Laboratory analyses will include total porosity (e.g., He

porosimetry), and pore size distribution (i.e., Hg-injection porosimetry). The three-dimensional pore morphology, connectivity, pore-grain dihedral angle (Ghanbarzadeh et al. 2015), and elemental composition will be investigated using serial imaging methods, including: micro –CT scanning, focused ion beam-scanning electron microscopy (FIB-SEM), multi-beam SEM, and scanning transmission electron microscopy (STEM). Small-angle neutron scattering (SANS) will be used to characterize pore network and brine distribution. These methods have been used to classify pore types and reconstruct pore networks in shales (Dewers et al. 2012), and may reveal microstructural changes to the salt due to heating not revealed by more classical methods. FIB-SEM digital reconstructions can have resolution of 10 nm/voxel and allow quantification of pore structure and topology.

Sandia's automated robotic polishing and imaging instrument, the Robo-Met.3D, has multiple options for polishing and etching of samples (Madison et al. 2017). The Robo-Met.3D can obtain optical bright or dark field image resolutions of 2.1 micron/pixel (at 5×) to 0.21 micron/pixel (at 50×). Automated polishing, etching, and imaging may achieve new understanding of 3D micro-structural deformation in salt and the connectivity of associated pore networks. The combination of FIB-SEM, STEM, SANS, and Robo-Met.3D will allow for multiscale examination of the coupled deformation and flow properties of the salt samples and the effects heating and in situ salt precipitation has on the network.

The water and EDTA-insoluble fractions of salt samples will be estimated. Dissolving away the water-soluble portions of the salt samples reveals the silicate, sulfate, and carbonate fraction of the salts. Boiling this water-insoluble residue from salt in 0.25 molar EDTA for 4 hours further removes the sulfate and carbonate minerals (Stein 1985). These methods allow rapid estimation of bulk silicate, carbonate, and sulfate composition of the salt. The insoluble fractions isolated from water dissolution will be tested via TGA and SEM to further quantify their composition.

3.3 Brine Evaporation Experiment

To provide relevant data for TC model validation, samples of brine collected from MU-0 will be concentrated in the lab via evaporation (both at 30 °C and 120 °C). Fluid samples will be collected from the experiment for compositional analysis during their dry-out process to confirm predictions of numerical TC models, and confirm field observations. Krumhansl et al. (1991a) essentially performed this experiment at room temperature, using fluid collected from a vertical borehole across MB139 (Appendix A-2.1).

The heated sample will be held at a constant temperature and the RH will be monitored during the evaporation process, rather than increasing temperature through time, typical to TGA. Especially at higher temperatures, thermochemical database entries for relevant salts have significant uncertainty (Jové Colón et al. 2013). The minerals in equilibrium with brine are strongly a function of temperature, and the behavior of multi-component brine systems at elevated temperatures is complex (Wollmann 2010). Precipitation of different salts at different temperatures will lead to different pathways along which the brine will evolve.

3.4 Gas and Brine Analysis

Gas samples will be analyzed in the laboratory for major gases and key noble gases (e.g., He and Ar) using gas chromatography. Sampling and analysis will need to account for condensate that may form in gas sample containers, once the high-RH warm gas moves into the relatively cold container. Some gases will dissolve into the condensate (e.g., HCl), and should be accounted for in the analyses. Individual gases of concern (e.g., HCl) could be tested directly in the field using gas-specific detection equipment.

The distribution of brine in sub-samples from cores will be examined by thermal-gravimetric analysis (TGA) before and after the borehole test. This will allow for the estimation of inter- and intra-granular brine as well as moisture associated with different minerals and their phases. Multiple sub-samples will be analyzed to characterize the heterogeneity of the salt. Based on available capabilities, a gas

chromatograph can be connected to the TGA to provide information on the composition of gases released during heating. This can also be used to confirm any gases observed during field test sampling.

Brine samples will be analyzed by ion chromatography and inductively coupled plasma mass spectrometry for major ions (i.e., Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, Br^-, SO_4^{2-}, CO_3^{2-}, and BO_3^{3-}) and minor substituting ions (NH_4, I, F, Fe, and Rb), based on analysis of data from previous samples collected from WIPP boreholes. Samples tested for ionic composition will require significant dilution (>1,000×) before analysis, but chloride levels can be tested without dilution using a chlorimeter. Stable water isotopes will be tested via CRDS. Brine electrical conductivity, pH, alkalinity, total dissolved solids, and density will be measured in the laboratory using appropriate methods. Meaningful estimates of pH are difficult in brines, requiring development of pH standards with similar salinity of the brine (Marcus 1989; Nir et al. 2014). Quantitative analysis will be done on precipitated salts, including X-ray diffraction, X-ray fluorescence, and TGA to quantify the composition and minerology of salts precipitated in the borehole. CRDS analysis will be used to estimate the isotopic composition of hydrated minerals.

Preserved salt samples will be dissolved in the laboratory using de-aerated water inside a sealed container put under an initial vacuum. The gases that develop in the head space will be analyzed using gas chromatography to estimate the gases that exist dissolved in the brine and trapped in the salt crystal structure (e.g., He, Ar and other noble gases). This data will help explain some observations during the field test. Some gases will come from the rock directly, while other gases will evolve from thermal decomposition of various materials in the borehole.

4. TESTING AND MEASURING EQUIPMENT

4.1 Plug and Packer Types

Sealing the borehole from the access drift and its DRZ, and isolating discrete borehole intervals is important to the success of several of the proposed tests and observations.

A wide variety of plugs or packers for borehole applications exist. However, there are several factors to consider for this field test. Factors include: ease of implementation, seal effectiveness, cost, dimensions, and corrodibility. The ideal packer system would be easy to implement with multiple ports, good sealing against a possibly creeping borehole wall, diameter close to the borehole diameter, low cost, and constructed of non-corrosive material that can withstand the saline environment, elevated temperature, and acidic vapors.

Sewer plugs are made from aluminum or plastic plates that sandwich a neoprene membrane. They are commonly used in industry and are straightforward to implement. They are relatively inexpensive and come in an assortment of sizes and materials. Sewer plugs seal a short interval (2" to 3") and have a limited capacity to seal when the borehole wall is even slightly irregular. Because their plates must be turned against one another to expand the neoprene membrane, they are difficult to install at more than an arm's length into the borehole. This twisting can also create complication for tubing and power cords running through the ports. Neoprene may also emit HCl vapor when heated above ~100 °C.

Commercial inflatable and mechanical packers are being investigated and would create a much better seal than sewer plugs for a reasonable increase in price. Inflatable packers require pumps or gas cylinders to apply and maintain fluid pressure to create a seal. Packers come in various sealing lengths and can create a good seal against most borehole conditions. Packer elements can be made of different types of rubber; all packer construction materials should be compatible with heat, brine, and acidic vapor.

Packers or plugs must have inflow, outflow, instrumentation, and heater pass-throughs to accommodate a variety of measurements and the heater. In inflatable packers, packer inflation pressure would be monitored throughout the test, and in mechanical packers/plugs, the torque associated with the closure of the tools would be monitored through the test. It would be more straightforward to monitor pressure automatically during the test than to monitor torque.

The test program is currently considering both inflatable packers and mechanical packers. Mechanical packers could be based on the design used by Blankenship & Stickney (1983) at Avery Island (see drawing in Figure 31b), or a commercially available equivalent. A mechanical packer is simpler to install than an inflated packer (no need for pumps to apply or maintain pressure), but the seal may not be as good in an irregular borehole. In a mechanical packer, the sealing rubber is shortened axially, and the sealing is provided by its radial expansion. In inflatable packers, a fluid is used to radially expand the seal directly. The sealing element on a mechanical or inflatable packer would be several times longer than a sewer-type plug, and allow simpler installation of the packer at depth into the borehole (not just within arm's reach). Since the gas flowrate damage testing is not planned at high operating pressures, or to estimate permeability of salt below approximately a microdarcy (similar to the approach of Stormont et al. 1987), a relatively simple mechanical or inflatable packer would likely be sufficient for the project's needs.

4.2 Heater Element

For the heated borehole test intervals, a resistive heater element is proposed. Resistive heater elements have better thermal properties and require less on/off cycling to maintain a specified temperature if the heater element is embedded in a block of thermally conductive and chemically inert material. Quartz lamp type heaters have been used successfully in bedded and domal salt (Appendix A-7.1), but resistive heaters are familiar to the WIPP testing organization and they are simple. Curved flat resistive heater elements could be installed directly on the surface of the borehole and backfilled inside, but this arrangement would be more difficult to test in the laboratory and set up.

The heater element and surrounding heater block should be non-corrosive in a wet, briny, acidic, hot environment. The heater block should isolate the heater element from the borehole environment. The temperature sensor for control of the power should be on the outside of the heater block (assuming the heater block is made of reasonably conductive materials), but temperatures at the heater element should also be monitored to record the hottest temperatures experienced in the borehole. The hottest temperature in the borehole may have significant ramifications on the stability of some mineral phases (e.g., Krumhansl 1986).

The test borehole heater assembly will be put together in a pipe on a lab bench with all instruments, wiring, pass-throughs and packers. The assembly will be tested in the laboratory before being inserted into the borehole in the field.

WIPP site electrical standards require electrical components to be listed with a testing laboratory (e.g., UL listed) or have an electrical safety inspection and plan developed. These aspects of heater and electrical component design are being considered in laboratory and preliminary field testing being conducted in FY17.

4.3 Thermocouples/Resistance Temperature Devices

Previous WIPP thermal experiments used premium grade, Type-E thermocouples with ungrounded junctions, high purity magnesium oxide insulation, and Inconel 600 sheathing (Munson et al. 1997b). A lesson learned from use of this type of thermocouple at WIPP involved numerous unidentified sensor failures (i.e., a break or short in the lead wires). It was not always clear the gauges failed until looking at the sensors after the experiment. A robust option for temperature sensors is the resistance temperature device (RTD), which relies on resistance being a function of temperature in a specific element of the circuit. It is more obvious during testing when these types of sensors have failed. It will be imperative the temperature detectors are well sealed to prevent brine from invading the insulation.

Thermal gauges will be installed by mounting them on a non-conducting rod to be inserted into the borehole as part of the heater/packer system. In the heated borehole it would be informative to also measure temperature at different angular locations around the borehole, at a given radius (e.g., thermal

gauges attached to an expandable non-conductive ring). This would provide some information regarding the development of convection or thermal stratification of the air during the test.

4.4 Multi-Point and Single-Point Borehole Extensometers

Used previously in Asse and WIPP thermal tests (Bollingerfehr et al. 2004; Munson et al. 1997b), rod or wire borehole extensometers monitor rock mass deformation by measuring relative displacement between anchors in a borehole, and the borehole collar. This can be done with a single anchor or multiple anchors set at different depths. Borehole extensometers are typically installed in an array around the room or access drift, with anchors set at varying depths up to 15 m [50'].

Room closure is important for calibrating drift-scale creep closure models, but is deferred to subsequent tests because these measurements would complicate setup of the initial testing boreholes. During later tests it would be useful to install a single extensometer set in a recently mined access drift between multiple borehole locations, so the response of the salt surrounding the access drift can be observed across multiple tests.

4.5 Borehole Pressure Cells

BPCs have been used to measure stress change in a wide variety of rock types (Bechthold et al. 2004). A BPC typically consists of a flat metal chamber filled with incompressible fluid connected to a transducer by a tube; the transducer converts fluid pressure into a measurable electrical output. The cell is grouted into the borehole, and pumped up to create contact with the material in which stress changes are to be measured. The BPC responds primarily to stresses acting perpendicular to the plane of the fluid chamber, but also has small sensitivity to stress changes in the perpendicular direction. 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 the borehole.

The evolution of stress redistribution around the rooms is not a measurement of primary importance and is deferred to subsequent test. It would provide useful information to corroborate extensometry, characterize the evolution of salt deformation around the access drift, and how it responds to heating.

4.6 Acoustic Emission Monitoring

The deformation induced by heating and cooling the salt will likely result in some brittle failure in the surrounding salt. 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 AE. As heating progresses, large-scale fracturing can occur in the access drift walls, roof, and floor. Data from these events can be used to characterize the development of the DRZ, including the extent of fracturing and information about the fracture mechanism. A passive AE monitoring system will provide insight into the presence and source of brittle phenomena. The brine migration test at Asse recorded AE at multiple locations through time (Appendix A-5.3).

Only one AE sensor is needed to get the timing of events (but data can be interpreted jointly from multiple sensors to eliminate some noise). Observation of natural AE could be made in conjunction with observations of a known active source to assist in interpretation of the data, and to estimate the distribution and evolution of the DRZ. More than four (likely six) sensors recording at a high frequency (higher than the inverse of the expected travel time from the source or heated interval to the closest sensor) would be required to accurately estimate event location. Beyond the minimum, the number of sensors is tied to the objective. What volume of salt needs to be characterized? How many boreholes are present?

4.7 Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) will be used to infer water content from electrical measurements made between electrodes in two observation boreholes. An electric current is induced into the test bed through two electrodes, and voltage is monitored between other pairs of electrodes. The data from a collection of measurements are then processed tomographically 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 to electrical resistivity has about 1% precision in saturation levels below 40% (Appendix A-8). ERT has been successfully used to monitor brine injection in the DRZ at Asse, Germany (Jockwer & Wieczorek 2008) and the distribution of damage around drifts at WIPP (Skokan et al. 1989).

4.8 Air Humidity Sensors/Chilled Mirror Hygrometers

Whereas air humidity sensors (i.e., capacitive thin-film polymer sensors) are reliable, stable, and accurate in most applications, past experience using them in salt has resulted in early failures of the instrument and erroneous readings resulting from salt dust buildup on the sensor (e.g., a constant reading of ~75% RH). CMHs will likely be a more robust and accurate measurement in these underground conditions for measuring the humidity of the dry N_2 circulating through the test borehole. 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 is reflected from the surface into a photo-detector. 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. However, salt dust deposition on polished surfaces can lead to erroneous CMH measurements, and may require periodic inspection and cleaning.

4.9 Other Sensors and Instruments

Linear variable differential transformer (LVDT) gauges are high-resolution linear displacement sensors that have been used to observe isothermal borehole closure at WIPP (Roberts et al. 1999). LVDTs could be placed at three locations (spaced 120°) around the heater block, or attached to a centralizer to allow initial contact with the borehole wall. Alternative emplacement strategies and measurement approaches are also being investigated.

Gas flowrate will be measured accurately upstream and downstream of the test borehole to develop a water mass balances. The upstream gas flowmeter will only need to measure flow of dry N_2 from a cylinder at ambient temperature, while the downstream gas flowmeter will need to measure flow of humid, hot gas, with acidic vapor components. Flowmeters that depend on the composition of the gas remaining constant (i.e., mass or density-based flowmeters), or depend on a dry gas stream will not work for the downstream gas flowrate measurement. Rotameter or turbine-style flow meters are economical, robust, tolerant of water vapor content, and work with a compositionally variable stream of gases. The instantaneous flowrate measurement will be used with the estimate of absolute humidity to estimate the total water inflow rate, so the accuracy of the downstream gas flowrate is important (i.e., should be better than 1%).

Gas pressure will be measured upstream and downstream of the test borehole. Gas pressure will be measured at the same time and locations with gas temperature, to allow estimation of the gas budget going into and coming out of the borehole. Gas pressure should be measured with accurate gauges that will be able to resolve expected differences in air pressure expected during the test (i.e., a few tens of kPa [few psi] higher gas pressure upstream of the borehole compared to downstream). Like the downstream gas flowmeter, the downstream gas pressure transducer should be tolerant of a hot, humid, acidic environment. Rather than differencing two pressure transducers measured relative to an atmospheric or vacuum standard, a differential pressure transducer could be used to accurately measure the pressure

difference between the upstream and downstream gases. Downstream gas pressure and temperature observations should be close to one another and at or very near the CMH, to allow accurate estimation of the absolute humidity of the gas stream. Pressure, temperature, and RH measurements should be collocated, because the pressure and temperature of the downstream gas may be changing rapidly as the gas leaves the borehole environment.

Sensors are available to quantify concentrations of individual specific gases (e.g., HCl vapor) directly via sampling. This analyte can be added to the downstream sampling system, but water vapor will tend to condense as the temperature of the outflow gas drops. HCl vapor will tend to go into the condensate, rather than stay in the gas phase.

4.10 Instrumentation Lessons Learned in a Salt Environment

Munson et al. (1997a, 1997b) presented lessons learned and details of instruments used in the drift-scale defense high-level waste mockup heater tests in Rooms A and B at WIPP. They detailed room closure gauges, extensometers, stress gauges, inclinometers, borehole strain gauges, thermocouples, thermal flux meters, and power meters used in WIPP. They present experience learned during testing and maintenance of the gauges over 10 years. Several instruments types had issues with corrosion of particular metal parts.

Howard et al. (1993) detailed much of the instrumentation used in the Room Q large-scale brine inflow and mine-by experiment. This test notably included multiple types of slim-hole packer test tools for both brine and gas permeability testing of the salt. Hydraulic test intervals contained LVDT borehole closure and thermocouple observations.

Roberts et al. (1999) detailed the instrumentation used in brine permeability packer testing, and brine/gas sampling from MB140. These instruments included multipacker systems with thermocouples and LVDT borehole closure observations, differential pressure measurements, and a fracture dilation test tool to observe fracture opening and closing during hydraulic testing.

Brady et al. (2013) presented an analysis of the heaters and canisters used in the Room A and B WIPP experiments, illustrating what heater and sample materials were left in place and still exist underground at WIPP.

Krumhansl et al. (1991b) analyzed precipitated salts and metal corrosion products observed in vertical heaters retrieved from WIPP Room B. They found stainless steel and nickel-based metals corroded readily in the acidic environment. Krumhansl (1986) discussed heater failures in brine-filled vertical boreholes as part of the Materials Interface Interactions Test (MIIT) test at WIPP.

Bechthold et al. (2004) and Bollingerfehr et al. (2004) presented observations about corrosion of instrumentation during the 10 years of the Asse drift-scale heater test. Krause (1983) included an appendix discussing issues and adjustments made while implementing the brine collection test plan at Avery Island (Appendix A-3). The Project Salt Vault report (Bradshaw & McClain 1971) presented a large amount of information learned during the first set of large-scale *in situ* heater tests in salt (Appendix A-6).

5. SUMMARY AND NEXT STEPS

This report presents the background and an initial conceptualization of the proposed FY18 DOE-NE intermediate-scale heater test at WIPP. This report summarizes relevant previous tests and data collected at salt research sites around the world, to support the design of the test, and is intended to represent an initial consensus on test design. The scientific focus of the tests is on brine availability, brine transport, and brine chemistry. The technical goals of the project are to create a validation dataset for coupled THMC numerical models of salt, as well as to provide the means for a new generation of salt science researchers to build upon the long successful history of underground testing in salt.

There have been several heater tests with brine collection in both bedded and domal salt, but the proposed suite of tests is unique because:

- the horizontal heater will not intersect major clay or anhydrite layers;
- the test will track deuterated water to better quantify intergranular brine transport in salt;
- liquid brine samples will be collected during progression of the test; and
- a straightforward test design is chosen to be executed at both ambient and elevated temperatures;
- the test of a modular design to facilitate adding similar, future tests with different test conditions (e.g., maximum temperature and thermal cycling and sealed or long-duration tests) and data collection activities (e.g., more intensive studies of AE, geomechanical observations, and cement exposure tests).

Proposed tests will be designed in more detail through FY17, to allow FY18 implementation, including the development of cost estimates, procedures, and quality assurance/quality control documentation as required. The tests should provide a better understanding of the relevant THMC processes in salt under controlled circumstances, which may better allow numerical model predictions before testing and validation after testing. Hopefully, the data collected from these proposed field and laboratory tests will result in further DOE and international collaboration on numerical model benchmarking and validation.

6. REFERENCES

Alkan, H., Y. Cinar and G. Pusch, (2007). Rock salt dilatancy boundary from combined acoustic emission and triaxial compression tests, *International Journal of Rock Mechanics and Mining Sciences* 44(1):108-119.

Beauheim, R.L. and R.M. Holt, (1990). "Hydrogeology of the WIPP Site" *in* Powers, Holt, Beauheim and Rempe, [eds.] *Guidebook 14*, pp. 131-179. Dallas, TX: Geological Society of America (Dallas Geological Society).

Beauheim, R.L. and R.M. Roberts, (2002). Hydrology and hydraulic properties of a bedded evaporate formation, *Journal of Hydrology* 259(1):66-68.

Beauheim, R.L., A. Ait-Chalal, G. Vouille, S.-M. Tijani, D.F. McTigue, C. Brun-Yaba, S.M. Hassanizadeh, G.M. van der Gissen, H. Holtman and P.N. Mollema, (1997). *INTRAVAL Phase 2 WIPP 1 Test Case Report: Modeling of Brine Flow Through Halite at the Waste Isolation Pilot Plant Site*. SAND97-0788. Albuquerque, NM: Sandia National Laboratories.

Bechthold, W., T. Rothfuchs, A. Poley, M. Ghoreychi, S. Heusermann, A. Gens, and S. Olivella, (1999). *Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS Project)*. EUR 19124 EN, Commission of the European Communities.

Bechthold, W., E. Smailos, S. Heusermann, W. Bollingerfehr, B. Bazargan Sabet, T. Rothfuchs, P. Kamlot, J. Grupa, S. Olivella and F.D. Hansen, (2004). *Backfilling and Sealing of Repositories for Radioactive Waste in Salt (BAMBUS II Project)*. EUR 20621 EN, Commission of European Communities.

Blankenship, D.A. and R.G. Stickney, (1983). *Nitrogen Gas Permeability Tests at Avery Island*. ONWI-190(3), Rapid City, SD: RE/SPEC, Inc.

Bollingerfehr, W., S. Heusermann, J. Droste, and T. Rothfuchs, (2004). "Reliability and accuracy of geotechnical instruments during 10 years of in situ application" in *EURADWASTE '04. EUR 21027* EN, Brussels, Belgium: Commission of the European Communities.

Borns, D.J. and J.C. Stormont, (1988). *An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone.* SAND87-1375, Albuquerque, NM: Sandia National Laboratories.

Bradshaw, R.L. and W.C. McClain [Eds.], (1971). *Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines*. ORNL-4555. Oak Ridge, TN: Oak Ridge National Laboratory.

Brady, P., C. Herrick, K. Kuhlman, B. Malama, M. Schuhen, and B. Stenson, (2013). *Sandia Experimental Programs Background and Targeted Activities for Forensic Investigation of Rooms B and A1*. Carlsbad, NM: Sandia National Laboratories.

Caporuscio, F.A., H. Boukhalfa, M.C. Cheshire, A.B. Jordan and M. Ding, (2013). *Brine Migration Experimental Studies for Salt Repositories*, LA-UR-13-27240, FCRD-UFD-2013-000204. Los Alamos, NM: Los Alamos National Laboratory.

Carslaw, H.S. and J.C. Jaeger, (1959). Conduction of Heat in Solids, Second Edition, Oxford.

Clynne, M.A., R.W. Potter, and L.D. White, (1981). *Analytical Results of Tagged Synthetic Brine Migration Experiments at Avery Island, Louisiana*. USGS Open File Report 81-1137. Menlo Park, CA: US Geological Survey.

Cosenza, Ph., M. Ghoreychi, (1993). "Coupling between mechanical behavior and transfer phenomena in salt" in *Proceedings of the Third Conference on the Mechanical Behavior of Salt*, September 14-16, 1993, Ecole Polytechnique Palaiseu, France, pp. 271-293.

Coyle, A.J., J. Eckert, and H. Kalia, (1987). *Brine Migration Test Report: Asse Salt Mine, Federal Republic of Germany*, BMI/ONWI-624, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Deal, D.E., R.J. Abitz, D.S. Belski, J.B. Case, M.E. Crawley, R.M. Deshler, P.E. Drez, C.A. Givens, R.B. King, B.A. Lauctes, J. Myers, S. Niou, J.M. Pietz, W.M. Roggenthen, J.R. Tyburski, and M.G. Wallace, (1989). *Brine Sampling and Evaluation Program 1988 Report*. DOE-WIPP-89-015, Carlsbad, NM: Westinghouse Electric Corporation.

Deal, D.E., R.J. Abitz, J. Myers, D.S. Belski, M.L. Martin, D.J. Milligan, R.W. Sobocinski and P.P.J. Lipponer, (1993). *Brine Sampling and Evaluation Program 1991 Report*. DOE-WIPP 93-026, Carlsbad, NM: Westinghouse Electric Corporation.

Deal, D.E., R.J. Abitz, D.S. Belski, J.B. Case, M.E. Crawley, C.A. Givens, P.P.J. Lipponer, D.J. Milligan, J. Myers, D.W. Powers and M.A. Valdivia, (1995). *Brine Sampling and Evaluation Program 1992-1993 Report and Summary of BSEP Data since 1982*. DOE-WIPP 94-011, Carlsbad, NM: Westinghouse Electric Corporation.

de Bakker, J., J. Lamarre, J. Peacey and B. Davis, (2012). The phase stabilities of magnesium hydroxychlorides, *Metallurgical and Materials Transactions B*, 43:758.

Dewers, T.A., J.E. Heath, R. Ewy, and L. Duranti, (2012). Three-dimensional pore networks and transport properties of a shale gas formation determined from focused ion beam serial imaging. *International Journal of Oil, Gas and Coal Technology*, 5(2):229-248.

DOE Carlsbad Field Office (CBFO), (2011). *A Management Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP*. DOE/CBFO-11-3470. Carlsbad, NM: US Department of Energy Office of Environmental Management.

DOE Carlsbad Field Office (CBFO), (2013). *Test Specification for the Salt Defense Disposal Investigations Thermal Test in WIPP*. DOE/CBFO-13-3510. Carlsbad, NM: US Department of Energy Office of Environmental Management.

Ewing, R.I. (1981a). *Test of a Radiant Heater in the Avery Island Salt Mine*. SAND81-1305, Albuquerque, NM: Sandia National Laboratories.

Ewing, R.I. (1981b). *Preliminary moisture release experiment in a potash mine in southeastern New Mexico*. SAND81-1318, Albuquerque, NM: Sandia National Laboratories.

Finley, S.J., D.J. Hanson, and R. Parsons, (1992). *Small-scale brine inflow experiments – data report through 6/6/91*. SAND91-1856, Albuquerque, NM: Sandia National Laboratories.

Ghanbarzadeh, S., M.A. Hesse, M. Prodanovic and J.E. Gardner, (2015). Deformation-assisted fluid percolation in rock salt, *Science*, 350(6264):1069-1072.

Greenspan, L., (1976). Humidity fixed points of binary saturated aqueous solutions. *Journal of Research of the National Bureau of Standards – A. Physics and Chemistry*, 81A(1):89-96.

Hansen, F.D., (2003). *The Disturbed Rock Zone at the Waste Isolation Pilot Plant*. SAND2003-3407, Albuquerque, NM: Sandia National Laboratories.

Hansen, F.D., (2014). "Micromechanics of isochoric salt deformation" in *American Rock Mechanics Association 48th Annual Meeting*, ARMA14-7012.

Hansen, F.D., T. Popp, K. Wieczorek, and D. Stührenberg, (2014). *Granular Salt Summary: Reconsolidation Principles and Applications*. SAND2014-16141R, FCRD-UFD-2014-000590. Albuquerque, NM: Sandia National Laboratories.

Hansen, F.D., W. Steininger and W. Bollingerfehr, (2016a). *Proceedings of the 6th US/German Workshop on Salt Repository Research, Design, and Operation*. SAND2016-0194R, FCRD-UFD-2016-000069. Albuquerque, NM: Sandia National Laboratories.

Hansen, F.D., S. Sobolik and P.H. Stauffer, (2016b). *Intermediate Scale Testing Recommendation Report*, SAND2016-9041R, FCRD-UFD-2016-000030, Albuquerque, NM: Sandia National Laboratories.

Hansen, F.D., W. Steininger and W. Bollingerfehr, (2017). *Proceedings of the 7th US/German Workshop on Salt Repository Research, Design, and Operation*. SAND2017-1057R, SFWD-SFWST-2017-000008. Albuquerque, NM: Sandia National Laboratories.

Hardy, R.D., and D.J. Holcomb, (2000). "Assessing the Disturbed Rock Zone (DRZ) around a 655 meter vertical shaft in salt using ultrasonic waves: An update" in *4th North American Rock Mechanics Symposium*. American Rock Mechanics Association. SAND2000-0668C.

Hess, H.H., J.N. Adkins, W.B. Heroy, W.E. Benson, M.K. Hubbert, J.C. Frye, R.J. Russell, and C.V. Theis, (1957). *The Disposal of Radioactive Waste on Land, Report of the Committee on Waste Disposal of the Division of Earth Sciences*. Publication 519, Washington, D.C.: National Academy of Sciences - National Research Council.

Hohlfelder, J.J., (1979). *Salt Block II: Description and Results*. SAND79-2226, Albuquerque, NM: Sandia National Laboratories.

Hohlfelder, J.J., A.G. Beattie, and H.C. Shefelbine, (1981). *Water Release and Mechanical Failure in Heated Geologic Salt*. SAND81-1488. Albuquerque, NM: Sandia National Laboratories.

Holcomb, D.J., T. McDonald, and R.D. Hardy, (2001). "Assessing the disturbed rock Zone (DRZ) at the WIPP (Waste Isolation Pilot Plant) in salt using ultrasonic waves" in *DC Rocks 2001, The 38th US Symposium on Rock Mechanics (USRMS)*. American Rock Mechanics Association. SAND2001-13055C.

Howard, C.L., A.L. Jensen, R.L. Jones, and T.P. Peterson, (1993). *Room Q Data Report: Test Borehole Data from April 1989 through November 1991*. SAND92-1172, Albuquerque, NM: Sandia National Laboratories.

IT Corporation, (1995). *Summary of Brine Investigations at the Waste Isolation Pilot Plant, Southeastern New Mexico*. DOE/WIPP 96-2161. Carlsbad, NM: Westinghouse Electric Corporation.

Jockwer, N. and K. Wieczorek, (2008). *ADDIGAS: Advective and Diffusive Gas Transport in Rock Salt Formations Final Report*. GRS-234, Cologne, Germany: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS).

Jové Colón, C.F., P.F. Weck, T. Hadgu, J.E. Bean, M.J. Martinez, J.G. Argüello, C.D. Leigh, and F.D. Hansen, (2012). *Thermomechanical, Hydrological and Chemical (THMC) Model Development*. SAND2013-1412P, FCRD-UFD-2013-000064, Albuquerque, NM: Sandia National Laboratories.

Kendall, C. and E.A. Caldwell, (1998). "Fundamentals of Isotope Geochemistry" in *Isotope Tracers in Catchment Hydrology*, C. Kendall and J.J. McDonnell [Eds.], Elsevier, Amsterdam pp. 51-86.

Krause, W.B., (1979). *Avery Island Test Site Procedure for Installation and Operation of Brine Movement Experiments and Prototype Test Site*. RSI-0090. ONWI/SUB-79-E512-02200/10, Rapid City, SD: RE/SPEC, Inc.

Krause, W.B., (1983). *Avery Island Brine Migration Tests: Installation, Operation, Data Collection, and Analysis*. ONWI-190(4). Rapid City, SD: RE/SPEC, Inc.

Krumhansl, J.L., (1986). *MIIT Heater Failure: Geochemical Analysis*. April 1, 1986 Memo to M.A. Molecke (Obtained as attachment to Molecke 1986; ERMS-303090), Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

Krumhansl, J.L., K.M. Kimball, C.L. Stein, (1991a). *Intergranular Fluid Compositions from the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico*. SAND90-0564, Albuquerque, NM: Sandia National Laboratories.

Krumhansl, J.L., C.L. Stein, G.D. Jarrell, and K.M. Kimball, (1991b). Summary of WIPP Room B Heater Test Brine and Backfill Material Data. SAND90-0626, Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L., (2014). *Summary Results for Brine Migration Modeling Performed by LANL, LBNL, and SNL for the UFD Program*. SAND2014-18217R, FCRD-UFD-2014-000071. Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L. and B. Malama, (2013). *Brine Flow in Heated Geologic Salt*. SAND2013-1944, Carlsbad, NM: Sandia National Laboratories.

Kuhlman, K.L. and B. Malama (2014). *Assessment of Contaminated Brine Fate and Transport in MB139 at WIPP*. SAND2014-16153, Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L. and S.D. Sevougian, (2013). *Establishing the Technical Basis for Disposal of Heat-Generating Waste in Salt*. SAND2013-6212P, FCRD-UFD-2013-000233. Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L., S. Wagner, D. Kicker, R. Kirkes, C. Herrick, D. Guerin, (2012). *Review and Evaluation of Salt R&D Data for Disposal of Nuclear Waste in Salt*. SAND2012-8808P, FCRD-UFD-2012-000380, Carlsbad NM: Sandia National Laboratories.

Lambert, S.J., (1979). *Mineralogical Aspects of Fluid Migration in the Salt Block II Experiment*. SAND79-2423, Albuquerque, NM: Sandia National Laboratories.

Lambert, S.J., (1992). Geochemistry of the Waste Isolation Pilot Plant (WIPP) site, southeastern New Mexico, U.S.A., *Applied Geochemistry*, 7(6):513-531.

Lappin, A.R., (1988). *Summary of Site-Characterization Studies Conducted from 1983 through 1987 at WIPP, Southeastern New Mexico*, SAND88-0157. Albuquerque, NM: Sandia National Laboratories.

Madison, J.D., O.D. Underwood, G.A. Poulter and E.M. Huffman, (2017). Acquisition of real-time operation analytics for an automated serial sectioning system. *Integrating Materials and Manufacturing Innovation, 224.*

Marcus, Y., (1989). Determination of pH in highly saline waters. *Pure and Applied Chemistry*, 61(6):1133-1138.

McTigue, D.F., (1985). *A Linear Theory for Porous Thermoelastic Materials*. SAND85-1149. Albuquerque, NM: Sandia National Laboratories.

McTigue, D.F., (1993). *Permeability and Hydraulic Diffusivity of WIPP Repository Salt Inferred from Small-Scale Brine Inflow Experiments*. SAND92-1911, Albuquerque, NM: Sandia National Laboratories.

McTigue, D.F. and E.J. Nowak, (1987). *Brine Transport Studies in the Bedded Salt of the Waste Isolation Pilot Plant (WIPP)*. SAND87-1274C, Albuquerque, NM: Sandia National Laboratories.

Molecke, M.A., (1983). *A Comparison of Brines Relevant to Nuclear Waste Experimentation*. SAND83-0516, Albuquerque, NM: Sandia National Laboratories.

Molecke, M.A., (1986). *Measurement of Hydrochloric Acid Vapors in WIPP from In Situ Experiments – SAFETY ASPECTS.* ERMS-303090, May 8, 1986 Memo of Record. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

Molecke, M.A., (1992). *Results from Simulated Remote-Handled Transuranic Waste Experiments at the Waste Isolation Pilot Plant (WIPP).* SAND92-1003C, Albuquerque, NM: Sandia National Laboratories.

Morgan, K.Z., (1963). *Health physics division annual progress report for period ending July 31, 1963.* ORNL-3492, Oak Ridge, TN: Oak Ridge National Laboratory.

Munson, D.E., S.J.V. Petney, R.M. Clancy, J.R. Ball, R.L. Jones and C.L. Northrop-Salazar, (1991). *18 W/m^2 Mockup for Defense High-level Waste (Rooms A): In situ Data Report: Vol. 1 – Mechanical response gages (February 1985-June 1990), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program.* SAND90-2748, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., R.L. Jones, C.L. Northrop-Salazar and Woerner, S.J. (1992a). *Multipass Mining Sequence Room Closures: In situ Data Report. Waste Isolation Pilot Plant (WIPP) Thermal-Structural Interactions Program.* SAND87-2687, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., S.J.V. Petney, T.L. Christian-Frear, J.R. Ball, R.L. Jones and C.L. Northrop-Salazar, (1992b). *Geomechanical Evaluation (Room G): in situ Data Report (December 1984-November 1990), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program.* SAND92–0582, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., D.L. Hoag, D.A. Blankenship, R.L. Jones, S.J. Woerner, G.T. Baird and R.V. Matalucci, (1997a). *Construction of the Thermal/Structural Interactions in situ Tests at the Waste Isolation Pilot Plant (WIPP).* SAND87-2685, Albuquerque, NM: Sandia National Laboratories.

Munson, D.E., D.L. Hoag, D.A. Blankenship, W.F. DeYonge, D.M. Schiermeister, R.L. Jones, and G.T. Baird, (1997b). *Instrumentation of the thermal/structural interactions in situ tests at the Waste Isolation Pilot Plant (WIPP).* SAND87-2686, Albuquerque, NM: Sandia National Laboratories.

Nir, O., E. Marvin, and O. Lahav, (2014). Accurate and self-consistent procedure for determining pH in seawater desalination brines and its manifestation in reverse osmosis modeling, *Water Research*, 64:187-195.

Nowak, E.J., and D.F. McTigue, (1987). *Interim Results of Brine Transport Studies in the Waste Isolation Pilot Plant (WIPP).* SAND87-0880. Albuquerque, NM: Sandia National Laboratories.

Powers, D.W., S.J. Lambert, S.E. Shaffer, L.R. Hill, W.D. Weart, (1978). *Geological Characterization Report: Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* (2 Volumes) SAND78-1596, Albuquerque, NM: Sandia National Laboratories.

Powers, D.W., (2017). *Reference Stratigraphy Applied to Rock Mechanics Studies for the Waste Isolation Pilot Plant: A Review – Jan 11, 2017.* ERMS-567705. Carlsbad, NM: Sandia National Laboratories WIPP Records Center.

Roberts, R.M., R.L. Beauheim, P.S. Domski, (1999). *Hydraulic Testing of the Salado Formation Evaporites at the Waste Isolation Pilot Plant: Final Report.* SAND98-2537, Albuquerque, NM: Sandia National Laboratories.

Roedder, E., and R.L. Bassett, (1981). Problems in determination of the water content of rock-salt samples and its significance in nuclear-waste storage siting, *Geology*, 9:525-530.

Rothfuchs, T., K. Wieczorek, H.K. Feddersen, G. Staupendahl, A.J. Coyle, H. Kalia, and J. Eckert, (1988). *Brine Migration Test: Asse Salt Mine Federal Republic of Germany Final Report*, GSF-

Bericht 6/88, Joint project between Office of Nuclear Waste Isolation (ONWI) and Gesellschaft für Strahlen- und Umweltforschung Munchen (GSF).

Rothfuchs, T., H.-K. Feddersen, K.-P. Krohn, R. Miehe, and K. Wieczorek, (1999). *The DEBORA Project: Development of Borehole Seals für High-Level Radioactive Waste – Phase II Final Report*. GRS-161, Braunschweig, Germany: Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH.

Saulnier, Jr., G.J., P.S. Domski, J.B. Palmer, R.M. Roberts, W.A. Stensrud, and A.L. Jensen, (1991). *WIPP Salado Hydrology Program Data Report #1*. SAND90-7000, Albuquerque, NM: Sandia National Laboratories.

Sevougian, S.D., R.J. MacKinnon, B.A. Robinson, C.D. Leigh, and D.J. Weaver, (2013). *RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes*. FCRD-UFD-2013–000161, Albuquerque, NM: Sandia National Laboratories.

Shefelbine, H.C., (1982). *Brine migration: A summary report*. SAND82-0152, Albuquerque, NM: Sandia National Laboratories.

Skokan, C.K., M.C. Pfeifer, G.V. Keller, and H.T. Andersen, (1989). *Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico*. SAND87-7174, Albuquerque, NM: Sandia National Laboratories.

Sonnenfeld, P. and J.-P. Perthuisot, (1989). *Brines and Evaporites*, American Geophysical Union.

Stauffer, P.H., A.B. Jordan, D.J. Weaver, F.A. Caporuscio, J.A. Ten Cate, H. Boukhalfa, B.A. Robinson, D.C. Sassani, K.L. Kuhlman, E.L. Hardin, S.D. Sevougian, R.J. MacKinnon, Y. Wu, T.A. Daley, B.M. Freifeld, P.J. Cook, J. Rutqvist and J.T. Birkholzer, (2015). *Test Proposal Document for Phased Field Thermal Testing in Salt*. LA-UR-15-23154, FCRD-UFD-2015-000077. Los Alamos, NM: Los Alamos National Laboratory.

Stein, C.L., (1985). Mineralogy in the Waste Isolation Pilot Plant (WIPP) Facility Stratigraphic Horizon. SAND85-0321, Albuquerque, NM: Sandia National Laboratories.

Stein, C.L. and J.L. Krumhansl, (1986). *Chemistry of Brines in Salt from the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico: A Preliminary Investigation*. SAND85-0987, Albuquerque, NM: Sandia National laboratories.

Stein, C.L. and J.L. Krumhansl, (1988). A model for the evolution of brines in salt from the lower Salado Formation, southeastern New Mexico, *Geochemica et Cosmochimica Acta*, 52:1037-1046.

Stickney, R.G. and L.L. Van Sambeek, (1984). *Summary of the Avery Island Field Testing Program*. RSI-0225, Rapid City, SD: RE/SPEC, Inc.

Stormont, J.C., (1988). *Test Plan: WIPP Horizon Gas Flow/Permeability Measurements*. Albuquerque, NM: Sandia National Laboratories.

Stormont, J.C., E.W. Peterson, P.L. Lagus, (1987). *Summary and Observations About WIPP Facility Horizon Flow Measurements Through 1986*. SAND87-0176, Albuquerque, NM: Sandia National Laboratories.

Stormont, J.C., (1997a). Conduct and interpretation of gas permeability measurements in rock salt. *International Journal of Rock Mechanics and Mining Sciences*, 34(3–4):303.e1–303.e11.

Stormont, J.C., (1997b). In situ gas permeability measurements to delineate damage in rock salt. *International Journal of Rock Mechanics, Mineral Science & Geomechanics Abstracts*, 34(7):1055-1064.

Sugimoto, K., R.E. Dinnebier, and J.C. Hanson, (2007). Structures of three dehydration products of bischofite from in situ synchrotron powder diffraction data ($MgCl_2 \cdot nH_2O$; n=1,2,4), *Acta Crystallographica Section B*, 63(2):235-242.

Tyler, L.D., R.V. Matalucci, M.A. Molecke, D.E. Munson, E.J. Nowak, and J.C. Stormont, (1988). *Summary report for the WIPP technology development program for isolation of radioactive waste.* SAND88-0844, Albuquerque, NM: Sandia National Laboratories.

Ucok, H., I. Ershaghi, and G.R. Olhoeft, (1980). Electrical resistivity of geothermal brines. *Journal of Petroleum Technology*, 32(04), 717-727.

Van Sambeek, L.L., D.D. Luo, M.S. Lin, W. Ostrowski, and D. Oyenuga, (1993). *Seal Design Alternatives Study*. SAND92-7340, Albuquerque, NM: Sandia National Laboratories.

Westinghouse Electric Corporation, (1987). *Brine Migration Test for Asse Mine, Federal Republic of Germany: Final Design Report*, BMI/ONWI-651, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Wollmann, G., (2010). *Crystallization Fields of Polyhalite and its Heavy Metal Analogues*, PhD. Dissertation, Technische Universität Bergakadamie Frieberg, Frieberg, Germany.

Yan, F., D.-H. Han, Q. Yao, and H. Li, (2014). "Seismic Velocities of Halite Salt: Anisotropy, Dispersion, Temperature, and Stress Effects." in *SEG Denver Annual Meeting Technical Program Expanded Abstracts.* (pp. 2783-2787). Society of Exploration Geophysicists.

Appendix A RELEVANT HISTORICAL TESTS

A-1. Horizontal Boreholes in MU-0 at WIPP

A series of horizontal boreholes was monitored for brine inflow at WIPP in the late 1980s and early 1990s. The relevant aspects of these data include:

1) Isothermal brine inflow observations were made over several years at WIPP in MU-0 salt
2) Modeling was done to match brine inflow fluxes observed with time
3) Non-salt components of MU-0 samples were characterized from Room L4

Finley et al. (1992) reported brine inflow measured in vertical and horizontal boreholes at WIPP. Brine was manually sampled from boreholes by technicians who breached the borehole seal, and used a vacuum pump to remove brine from the borehole. Humidity was monitored in the boreholes with capacitance-type hygrometers, but this data was only used to assess the quality of the borehole seal.

The horizontal boreholes in room L4 (L4B01 and L4X01) of the North Experimental Area were completed in MU-0 (Figure 9). Vertical boreholes near room Q (QPB0{1,2,3,4,5}) intersected MB139, while vertical boreholes from the higher-elevation experimental drifts (DBT1{0,1,2,3,4,5} and DBT3{1,2}) intersected Clay F. Nearly horizontal boreholes completed in Map Unit 9 (DBT16 and DBT17) would be difficult to reach from currently accessible excavations within WIPP (i.e., the North Experimental Area is currently inaccessible).

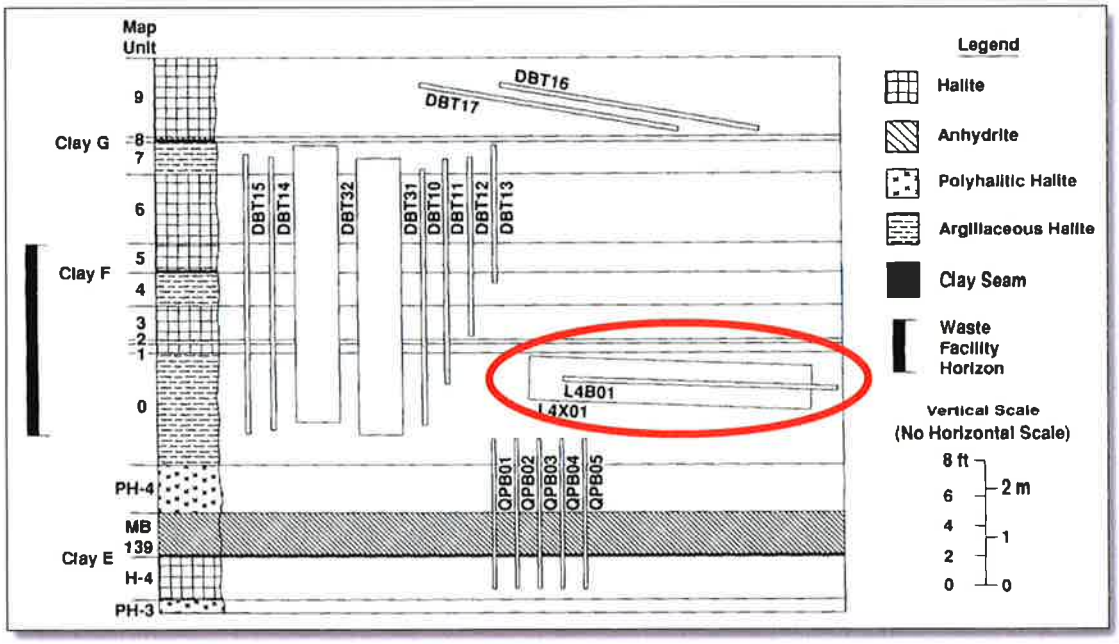

Figure 9. Boreholes at WIPP monitored for isothermal brine inflow and idealized stratigraphy (Figure 2 of Finley et al. 1992).

The boreholes in Room L4 were similar in stratigraphic location to the planned intermediate-scale heater test boreholes, and the smaller borehole is similar in diameter (10.2 cm) and length (5.8 m) to the planned boreholes.

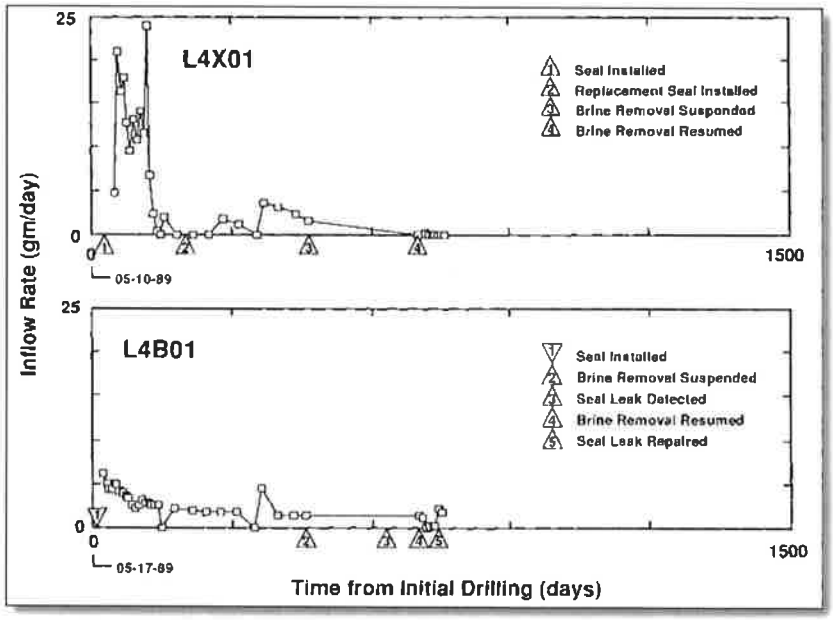

Figure 10. Brine inflow to horizontal boreholes in Room L4. (Figure 11 of Finley et al. 1992).

A-1.1 Isothermal Brine Inflow into Horizontal MU-0 Boreholes

Brine inflow data (Figure 10) indicate boreholes L4B01 collected approximately 2 to 5 grams of brine per day over approximately 2 years, with the largest amount collected in the first few months after drilling the borehole. The larger-diameter borehole L4X01 collected more brine and the pattern of inflow was less regular. Scaling the inflow data in Figure 10 by the borehole surface area reveals the normalized inflow into L4X01 was less than L4B01 (Figure 14). This difference might be due evaporative losses through a larger DRZ existing around the larger borehole, since the borehole DRZ should be proportional in size to the borehole diameter.

This brine inflow data was used in the INTRAVAL model validation exercise. Multiple analytical solutions and numerical models tried to match observed data (Beauheim et al. 1997). McTigue (1993) developed a pressure-gradient driven analytical flow solution, which was fit to observations (Figure 11 and Figure 12).

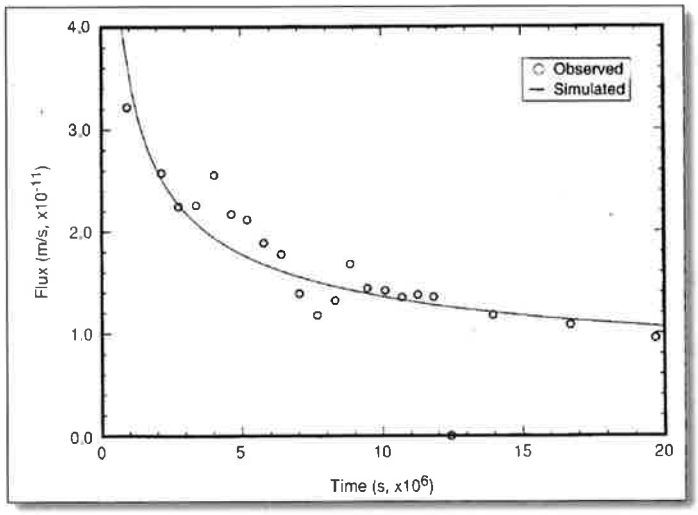

Figure 11. Comparison of McTigue (1993) model to data from L4B01 over 230 days (Figure 4-31 of Beauheim et al. 1997).

Table 4-4. Parameters Derived from Fits to Flux through January 1990

Hole	Perm. x Press. kp_∞ (m^2Pa, x 10^{-15})	Permeability* k (m^2, x 10^{-21})	Diffusivity c (m^2/s, x 10^{-10})	Specific Capacitance* C_s (Pa^{-1} x 10^{-9})
DBT10	3.84 ± 0.24	0.380 ± 0.024	0.47 ± 0.078	3.870 ± 0.69
DBT11	14.92 ± 0.55	1.490 ± 0.055	35.09 ± 6.29	0.200 ± 0.037
DBT12	8.40 ± 0.94	0.840 ± 0.094	101.73 ± 65.33	0.039 ± 0.025
DBT13	2.29 ± 0.35	0.230 ± 0.035	0.59 ± 0.23	1.850 ± 0.77
L4B01	0.88 ± 0.56	0.088 ± 0.056	0.58 ± 0.91	0.730 ± 1.24
	—	—	—	—

* Assumes p_∞ = 1.0 x 10^7 Pa, μ = 2.1 x 10^{-4} Pa s, ρ = 1200 kg/m^3.

Figure 12. Results from model-data fit for borehole L4B01 (Table 4-4 of Beauheim et al. 1997).

The WIPP management and operations contractor (initially Westinghouse) monitored brine inflow to WIPP for several years, and the inflow rates and brine composition data are available from Deal et al. (1995). Figure 13 shows brine inflow data for a period of approximately 1,700 days in 46-m long horizontal boreholes completed in MU-0 at the entrances to Panels 7 and 8, and OH45 was completed in S400 (see Figure 3 for borehole locations). The first 15 m of these boreholes are completed above the orange marker band (MU-1, Figure 5), but the boreholes dip down, and the back 2/3 of these boreholes are completed in MU-0. Deal et al. (1993) hypothesized the brine collected in these boreholes originated mostly from thin clay layers above MU-1.

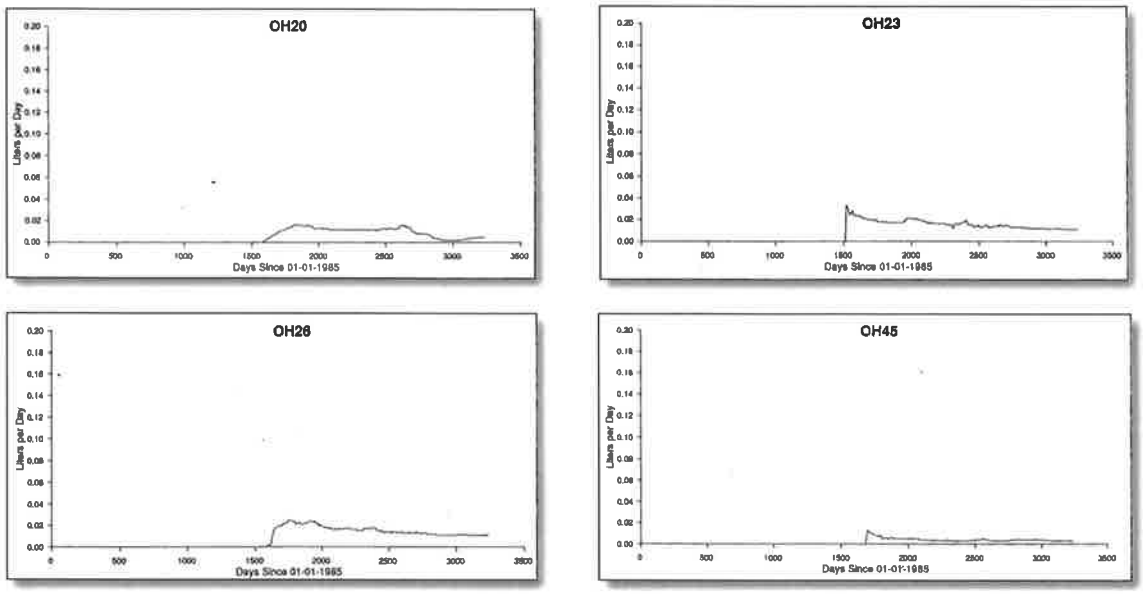

Figure 13. Isothermal brine inflow rates to horizontal boreholes completed predominantly in MU-0 (Appendix B of Deal et al. 1995).

Figure 14 shows normalized brine inflow data for both datasets (Finley et al. 1992 and Deal et al. 1995), assuming a brine density of 1.16 g/cm^3 to convert the volumetric rates reported in Deal et al. 1995 into mass rates. The fluxes are normalized by the area of salt open to the borehole, consisting of the surface of a cylinder (minus the end open to the access drift). The data from Deal et al. (1995) illustrate a long period (>2 years) of nearly constant brine inflow, while data from OH20 shows decline in brine production after 1,200 days. Multi-year heated brine inflow tests have been proposed to investigate the long-term stability of brine inflow to excavations (Section 2.8.3). The data from these boreholes do not adequately capture the early brine inflow peak after completion of the borehole. The data from L4B01 best capture the early time peak in inflow and the subsequent decline; this is why these data were used in the INTRAVAL project.

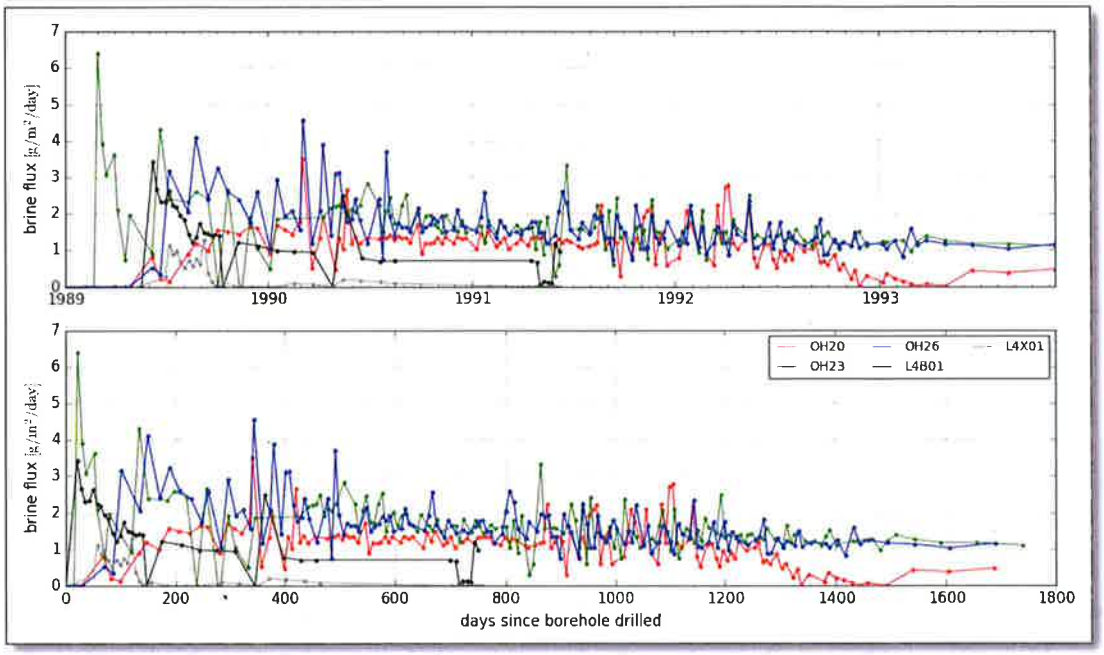

Figure 14. Normalized brine inflow data for boreholes completed in MU-0. Mass flowrate normalized by borehole wall area. Data from Finley et al. 1992 and Deal et al. 1995.

Using the normalized data plotted in Figure 14, we would expect between 1 and 2 g/m^2/day brine inflow to the test borehole under isothermal conditions (3 to 5 g/m^2/day immediately after borehole completion). A 6.1-m [20'] long, 15.2-cm [6"] diameter borehole has an inner area of 3 m^2, resulting in a scaled steady-state brine inflow of 3 to 6 g/day in the test borehole, with early peaks as high as 9 to 15 g/day. Appendix C relates the predicted brine inflow rates to minimum nitrogen consumption rates in the planned isothermal moisture extraction system.

A-1.2 MU-0 Insoluble Mineral Composition

Cores from L4B01 were analyzed in the laboratory for water content and insoluble residue content (Appendix D of Finley et al. 1992). Insoluble residue was less than 2 wt-% of the total sample and was mostly comprised of silicates (clay and quartz), with some sulfates (anhydrite, gypsum, and polyhalite), and trace feldspar (Figure 17). These or similar analyses would likely be run again on new cores collected (associated with the activities described in Appendix B-2).

Four samples (each with three sub-samples) from Borehole L4B01 were tested for total insoluble residue and weight change upon heating (Appendix D of Finley et al. 1992). The results (Figure 15) indicate MU-0 in Room L4 contains on average 0.51 wt-% water and 1.3 wt-% insoluble residue. These data are consistent with previously reported values of 0.22 wt-% and 0.75 wt-% water content in clean and argillaceous WIPP salt, respectively. The amount of weight change correlates well with total insoluble residue (Figure 16), indicating a significant part of the water content is associated with clays and hydrated sulfates. Figure 17 lists the relative major, minor, and trace content of insoluble minerals in these cores (hydrous minerals are highlighted).

In general agreement with geologic descriptions of MU-0 (Section 2.1.1), all samples 1, 2, and 3 have smectite as their primary hydrous insoluble mineral, while sample 4 includes sulfate minerals (polyhalite and gypsum) as the primary hydrous insoluble mineral. Although Finley et al. (1992) do not report the

locations of the samples in the boreholes, it might be inferred that samples 1-3 came from the upper, more clay-rich portions of MU-0, while sample 4 came from the lower, more polyhalite-rich portions of MU-0.

Sample number	Sample weight (g)	Weight change (g)	Weight change (wt.%)	Insol. Res. wt. (g)	Insol. Res. wt. %
1-1	84.052	0.574	0.68	1.424	1.69
1-2	76.239	0.418	0.55	0.930	1.22
1-3	84.099	0.534	0.64	1.241	1.48
2-1	84.817	0.250	0.30	0.510	0.60
2-2	93.658	0.233	0.25	0.388	0.41
2-3	89.234	0.186	0.21	0.309	0.35
3-1	76.300	0.502	0.66	1.317	1.73
3-2	86.290	0.627	0.73	1.655	1.92
3-3	90.536	0.645	0.71	1.688	1.86
4-1	67.768	0.280	0.41	1.237	1.82
4-2	66.763	0.318	0.48	0.902	1.35
4-3	49.102	0.263	0.54	0.677	1.38

Figure 15. Data from lab analyses on core from MU-0 in Room L4 (Appendix D of Finley et al. 1992).

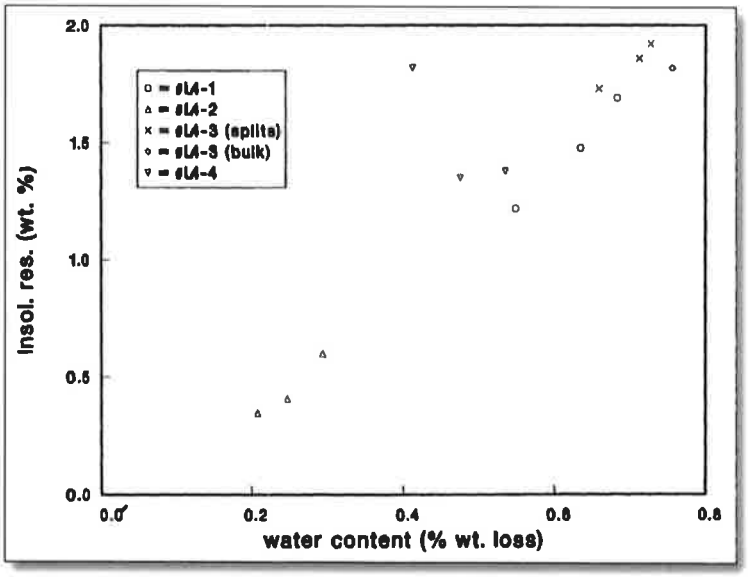

Figure 16. Water content vs. insoluble residue for MU-0 samples from Room L4 (Appendix D of Finley et al. 1992).

Sample	Major	Minor	Trace
1-1	quartz anhydrite	magnesite smectite	illite
1-2	quartz anhydrite	magnesite smectite	illite
1-3	quartz	magnesite smectite	illite anhydrite
2-1	quartz	magnesite smectite	illite anhydrite
2-2	quartz	magnesite smectite	illite anhydrite
2-3	quartz	magnesite smectite	illite anhydrite
3-1	quartz anhydrite smectite	magnesite illite	microcline
3-2	quartz anhydrite smectite	magnesite illite	microcline
3-3	quartz anhydrite smectite	magnesite illite	microcline
4-1	polyhalite gypsum	quartz anhydrite magnesite	illite
4-2	quartz	magnesite calcite gypsum anhydrite	microcline
4-3	quartz	magnesite anhydrite	illite smectite gypsum

Figure 17. Observed insoluble minerals in MU-0 samples from Room L4 (Appendix D of Finley et al. 1992). Hydrous minerals highlighted.

A-2. Observations of WIPP Salado Brine Chemistry

Observations have been made of brine chemistry at WIPP (IT Corporation 1995), both from boreholes collecting brine under isothermal conditions (in the targeted MU-0), and during heater tests (in vertical boreholes completed across Clay F). Understanding the expected brine chemistry and its evolution during concentration from evaporation and heating is important to designing the sampling and testing program.

It is important to note some brines reported in WIPP publications may not represent typical brine encountered in the underground. Some are believed to be strongly affected by WIPP construction efforts and contain components of groundwater from the overlying Culebra Member of the Rustler Formation (see stratigraphy in Figure 1) that flowed into the air intake shaft during and soon after construction. Shallow perched groundwater surrounding the WIPP surface facilities is still observed to drip down the exhaust shaft (Kuhlman & Malama 2014), and may impact brine composition samples collected in the vicinity of the shafts or in MB139. Other brines used commonly in WIPP performance assessment modeling include WIPP-12 and ERDA-6, which are not Salado Formation brines, but are Castile Formation brines (from wells that encountered pressurized brine pockets in the underlying Castile – see stratigraphy in Beauheim & Holt 1990 and Figure 1). This brine composition is important for WIPP performance assessment, but is not representative of Salado brine chemistry. Finally, the synthetic "Brine A" and "Brine B" were used in both laboratory and in situ experiments at WIPP (Molecke 1983), but are different from most brines observed at WIPP.

Brine chemistry of fluid inclusions and brines collected from boreholes and weeps show distinctive composition, indicating the source of available brine accumulating in boreholes is not purely from fluid inclusions. The marker beds at WIPP include MB139, which is a 1-m thick anhydrite and clay unit 1.5-m below the repository horizon, and MB140, a 4-m thick anhydrite and clay unit 15.5-m below the repository horizon. These marker beds have a distinct fluid composition compared to fluid inclusion brine and brines from boreholes completed only in halite units.

A-2.1 Brine Evolution During Isothermal Evaporation

Krumhansl et al. (1991a) described an experiment where they monitored the composition of WIPP brine (collected from a vertical borehole in floor near Room Q intersecting MB139) as it was left out to evaporate at room temperature for several months. The brine evolved into a magnesium-rich brine as the sample evaporated more than 50% (see red and green highlighting in last 4 samples of Figure 18). The evolution of these brines is discussed further in Appendix A-2.4.

Figure 19 illustrates the isothermal evaporation data and the salt mineral species in equilibrium at different relative quantities of SO_4, K_2, and Mg. The inset figure is from Wollmann (2010) and illustrates the potential complexities of these multicomponent (hexary: Na^+, K^+, Mg^{2+}, Cl^-, SO_4^{2-}, H_2O) brine systems (in Figure 19 inset: ph=polyhalite, anhy=anhydrite, goerg=görgeyite, and glaub=glauberite), beyond that portrayed in the Krumhansl et al. (1991a) figure. This indicates the brines used in the Krumhansl et al. (1991a) analysis were likely in equilibrium with polyhalite (which is consistent with the polyhalite content of MU-0 and PH-4 immediately above MB-139 where the samples were collected). Wollmann (2010) also presents these data at different temperatures, which would be useful for future heated evaporation experiments, that could be run to better understand field observations of brine composition.

Sample #	% Evap.	Na	Cl	Mg	K	Li	B	SO_4	Br	Ca	K/Mg	Na/Cl
1	0.0	67	163	17	14	23.5	1.45	13	1.2	0.30	0.86	0.41
2	1.1	66	163	17	14	23.2	1.44	13	1.5	0.30	0.86	0.40
3	2.0	67	164	17	14	25.9	1.45	13	1.4	0.30	0.84	0.41
4	2.9	67	164	17	15	23.7	1.46	13	1.4	0.31	0.84	0.41
5	4.3	67	164	18	15	25.2	1.52	14	1.4	0.32	0.84	0.41
6	9.6	65	164	19	16	24.7	1.56	14	1.5	0.34	0.84	0.40
7	9.7	62	164	19	16	25.2	1.58	15	1.5	0.33	0.84	0.38
8	14.1	61	164	21	17	28.3	1.68	16	1.6	0.36	0.82	0.37
9	16.7	59	165	22	18	30.1	1.79	16	1.6	0.37	0.83	0.36
10	20.0	57	166	23	19	23.7	1.89	18	1.7	0.30	0.82	0.34
11	24.9	52	166	25	20	30.1	2.08	19	1.8	0.27	0.82	0.32
12	40.7	33	172	39	28	45.5	3.02	27	2.7	0.16	0.72	0.19
13	57.0	7.4	193	69	18	98.3	5.61	47	5.2	0.04	0.26	0.038
14	61.6	1.5	245	107	0.6	127	4.51	29	7.8	0.03	0.006	0.006
15	65.8	1.2	248	89	0.5	172	5.62	211	79	0.02	0.006	0.005
16	66.0	1.3	245	91	0.5	199	6.35	285	100	0.02	0.006	0.005

Figure 18. Isothermal evaporation experiment brine compositions in g/L (Table 4 of Krumhansl et al. 1991a). Significant increases are green; significant decreases are red.

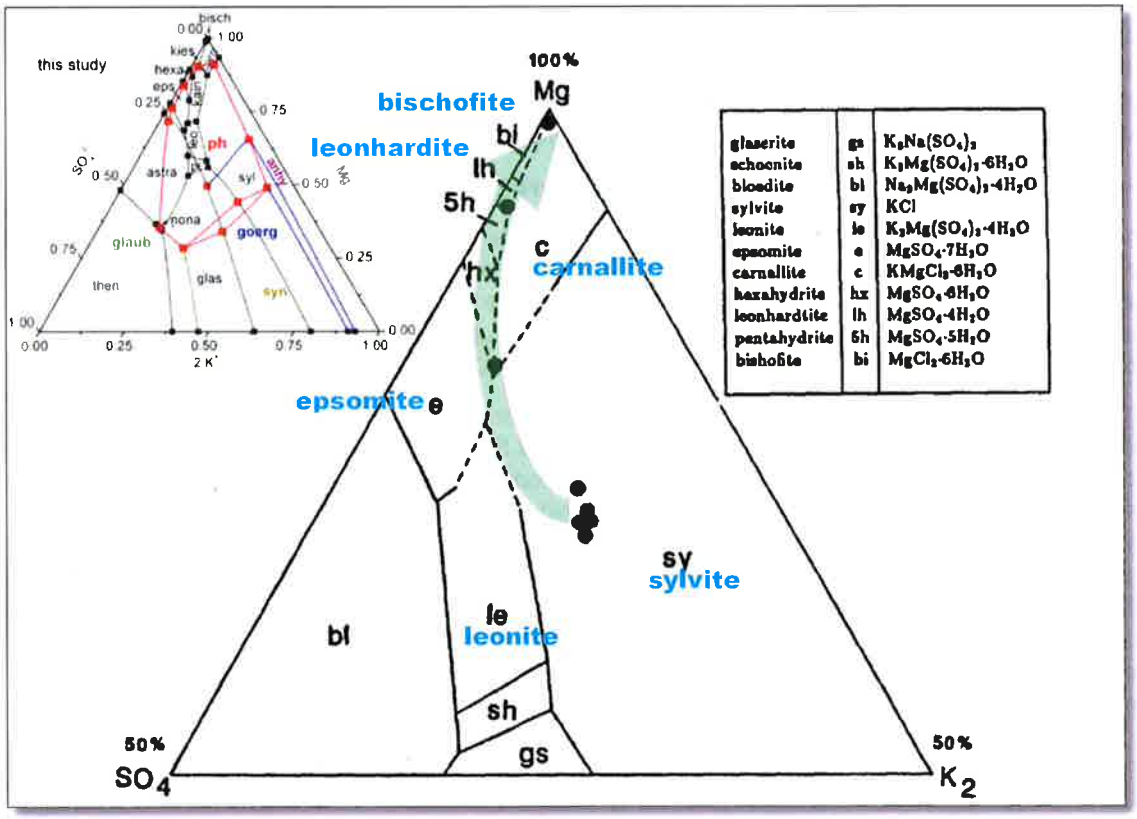

Figure 19. Jänecke diagram of isothermal brine evaporation data plotted as Mg-K_2-SO_4 (Figure 12 from Krumhansl et al. 1991a; inset Figure 100 from Wollmann 2010). Brine from MB139 (Room Q vertical borehole).

Roberts et al. (1999) presented results from geochemical modeling analyses that showed which minerals would precipitate from MU-0 waters: primarily halite, but with significant amounts of the hydrous chloride minerals carnallite [$KMgCl_3 \cdot 6(H_2O)$] and bischofite [$MgCl_2 \cdot 6(H_2O)$] (Figure 19 and Figure 20), which is largely consistent with the precipitation reaction path discussed in Appendix A-2.4.

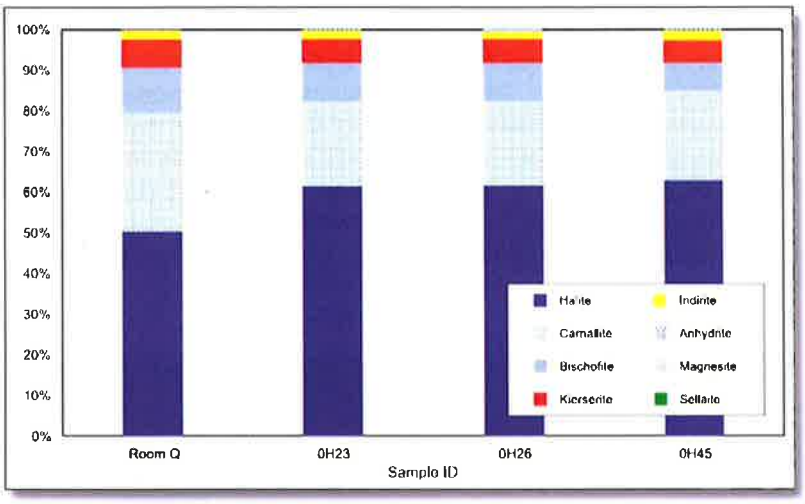

Figure 20. Normative salt assemblages for MU-0 brines (Figure 9-27 of Roberts et al. 1999).

Figure 21 illustrates the evolution of the equilibrium RH and specific gravity over a brine as it concentrates due to precipitation of salts. The path indicated on this figure is similar to that shown in Figure 19. Magnesium chloride salts tend to deliquesce much more readily than halite, since they equilibrate at a lower RH (<50%, compared to 75% RH). Greenspan (1976) summarizes laboratory data on equilibrium RH for several binary salts across a range of temperatures. Jové Colón et al. (2013) compared the TC model EQ3/6 to observations and showed the equilibrium RH for hydrous magnesium chloride salts decreases below 20% for temperatures above 100 °C.

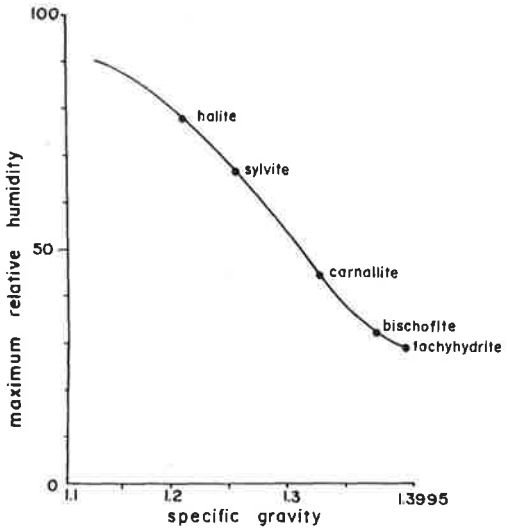

Figure 21. Equilibrium RH and specific gravity during brine concentration by evaporation (Figure 1 from Sonnenfeld & Perthuisot 1989)

A-2.2 Salt Precipitate During Heating

Krumhansl et al. (1991b) analyzed precipitated salts found on post-test exhumed heaters in Room B at WIPP (Figure 22 and Figure 23). Heater B042 was studied post-test via a 94 cm [37"] diameter overcore. Initially it was a 91.4 cm [36"] diameter vertical hole with a 61 cm [24"] heater placed in it without backfill. Maximum hole temperature was 130 °C. During the first 600 days of testing, B042 produced 35 liters of brine. The rind of salts observed between the heater and the creep-closed borehole only accounted for 20 to 23 liters of brine (e.g., see Figure 22 showing heater removal at WIPP – both heaters from Room B, but not necessarily heater B042). The rest of the salts were assumed to have been deposited in the formation, once the boiling isotherm moved out into the formation. The effect of hot steam migration through the intact salt (i.e., from the boiling point in the formation to the moisture collection system in the borehole) near the borehole was never examined. A combination of borehole closure and salt precipitation (Figure 21) filled the initial 15.24 cm [6"] annular space between the heater and the borehole wall.

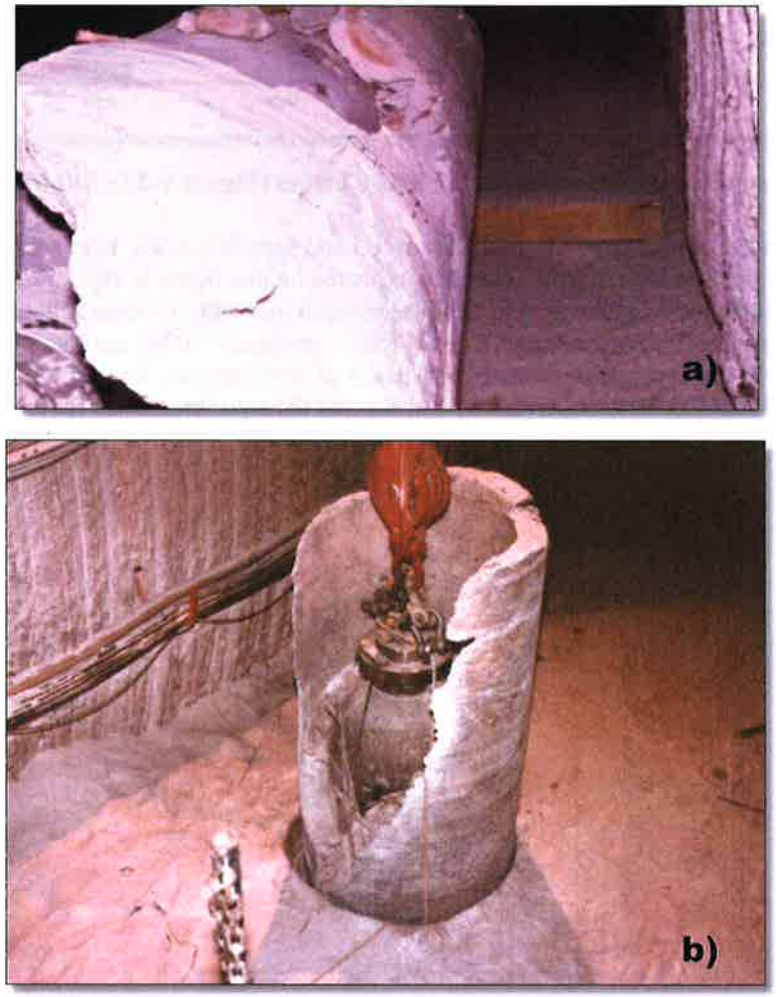

Figure 22. Post-test condition of heaters in WIPP Room B (a Figure 2.5 of Hansen et al. 2014; b Figure 2.2.1.2 of Brady et al. 2013).

Mineralogy of B042 Heater Scale
(Distance are downward from the top of the heater)

JS 57	From 0 to 1 foot down - halite.
JS 58	From 1 to 2 feet down - mostly halite and traces of bischofite and sylvite.
JS 59	From 2 to 3 down - mostly halite, a few good carnallite x-ray diffraction peaks (a few important ones missing between 24 and 26.5°). Possibly traces of kieserite, bischofite and sylvite.
JS 60	From 3 to 4 feet down - mostly halite but the carnallite x-ray diffraction peaks are well represented in this sample; possibly a trace of bischofite also.
JS 61	From 4 to 5 feet down - halite, carnallite and sylvite.
JS 62	From 5 to 6 feet down - some small clear gemmy non-cubic crystals which proved to be pure carnallite. The bulk of the sample was halite with a lesser, but significant, amount of carnallite. May contain traces of bischofite as well.
JS 63	From 6 to 7 feet down - halite and probably a little carnallite.
JS 64	From 7 to 8 feet 4 inches down - halite and a definite, though minor, amount of carnallite. (This sample originated from the junction between the bottom of the weep salt accumulations and the top of the crushed salt filling the hole bottom)
JS 65	From 8 feet 4 inches to the heater bottom. Essentially pure halite.
JS 66	Hardpan heater scale taken from the dense salt - halite and possibly a little bischofite.

Figure 23. Mineralogy of observed B042 heater scale (Table 3 of Krumhansl et al. 1991b). Hydrous minerals highlighted.

A-2.3 Acid Gas Generation at Elevated Temperatures

Acidic vapors have been observed several times in heater tests in both bedded and domal salt, including:

- WIPP Room B vapor collection system (pH 0.93 – Molecke 1986) and during overcoring of Room B heaters (10 ppm HCl vapor – Brady et al. 2013);
- WIPP Room J Materials Interface Interactions Test (MIIT). This test used artificial brine, likely experienced a significant heater over-temperature event, and was not carried out in N_2 gas (Krumhansl 1986);
- Lab experiments involving salt, brine, and candidate waste package materials (Molecke 1983); and
- Asse during the large-scale brine migration experiment (Coyle et al. 1987; see Appendix A-5.2).

Krumhansl et al. (1991b) and Molecke (1986) proposed HCl was generated by decomposition of solid magnesium chloride bearing salts to produce periclase (MgO). The proposed reactions are:

$$MgCl_2 + H_2O \longrightarrow MgO + 2HCl$$

$$MgCl_2.H_2O \longrightarrow MgO + 2HCl$$

$$MgCl_2.2H_2O \longrightarrow MgO + 2HCl + H_2O$$

$$MgCl_2.4H_2O \longrightarrow MgO + 2HCl + 4H_2O$$

These reactions from Krumhansl (1986) are correct, but thermodynamic data indicate they might not be likely under expected borehole conditions (40 to 75% RH and ≤150 °C). MgO does not form except at elevated temperatures of several hundred degrees Celsius (Sugimoto et al. 2007; de Bakker et al. 2012). Trace MgO was observed on the MIIT heaters (Krumhansl 1986), but not on the Room B heaters (Figure 23). The MIIT heaters also showed evidence of molten halite (sample 4), which indicate the heaters likely shorted or experienced significant over-temperature (several hundred degrees Celsius) before failing. The MIIT heaters were in vertical boreholes filled with synthetic brine (i.e., Brine A – see Figure 25), and were not being flushed with dry N_2; ample oxygen was present to form oxides.

Under the expected conditions, the first thing to precipitate is likely a magnesium hydroxychloride phase, $Mg_x(OH,Cl)_{2x}{:}YH_2O$. Anhydrous phases include Mg(OH)Cl and $Mg_2(OH)_3Cl$, but multiple hydrous phases with different (OH):Cl ratios or degrees of hydration have been reported (de Bakker et al. 2012), that precipitate from concentrated magnesium chloride solutions as base is added, or if the solution is heated. Reaction to form these would also produce acid. For instance, for the simplest anhydrous phase:

$$H_2O+Mg^{2+}+2Cl^- \rightarrow Mg(OH)Cl+HCl_{(g)}$$

but it is not clear under what temperature and pH conditions these phases will form, or which ones will be stable. Magnesium-hydroxychlorides precipitate readily from Salado brines, under high pH conditions they will form Sorel cement.

Another possible mechanism for acid gas generation produces HCl vapor directly from the liquid phase. It relies on presence of a concentrated Na-Cl or Mg-Cl brine and a downstream relatively pure H_2O condensate. This mechanism is consistent with the conditions where acid brines in heated salt have been observed to form. Molecke (1986) indicated the most acidic brine observed in the Room B moisture release experiments was "previously assumed to be essentially condensed, distilled water."

For a chloride-rich brine at any pH a non-trivial amount of HCl will exist in the atmosphere above the brine. As the atmosphere moves to a downstream cold trap or outlet and cools, the partial pressure of HCl gas does not change. Thus, at the location where condensate forms, the P_{HCl} will be the same as was present in the atmosphere over the brine, and will be in equilibrium with the condensate as it forms.

A Na-Cl brine begins to precipitate halite at ionic strength of about 5 molar, while a Mg-Na-Cl brine can reach higher molarities (e.g., see increasing brine specific gravities associated with Mg-Cl salts in Figure 21), and therefore drive the acidity even lower. The ionic strength of the brine will increase due to evaporation, precipitation of halite, and due to temperature effects.

A secondary goal of the intermediate scale borehole heater test is to gather field data to better understand the mechanisms for acid gas generation (i.e., decomposition of hydrous magnesium chloride minerals and acidification of condensate in the presence of a strong Na-Cl or Mg-Cl brine). The mechanism occurring in the field may be a combination of the two processes given above, and to further understand them would likely require carefully designed laboratory experiments and numerical modeling (Jové Colón et al. 2013).

A-2.4 WIPP Salado Brine Composition Survey

Figure 24a shows the variability in composition of brines from the repository horizon at WIPP. Two groups of halite fluid inclusions are presented. Group II (open squares) is closer to being a direct result of seawater evaporation (heavy arrow and upper stippled area marked "Brantley et al, 1984"). Group I (partially filled squares) are likely the result of polyhalite conversion from anhydrite or gypsum, which lowers K levels relative to Mg levels (Figure 24b). This suggests that disseminated polyhalite in the repository horizon, and in stratigraphically lower portions of MU-0, may be an alteration product of gypsum rather than a primary deposit. The halite containing the fluid inclusions likely re-crystallized about the same time the polyhalite was formed. Age dates for polyhalite in WIPP are approximately 200 million years (Stein & Krumhansl 1986), indicating these transformations likely happened soon after

deposition. Stein & Krumhansl (1988) presented these similar plots with additional data, which further supported these same proposed relationships (data from Stein & Krumhansl, 1988, Roberts et al. 1999, and Deal et al. 1995 are summarized in Figure 25).

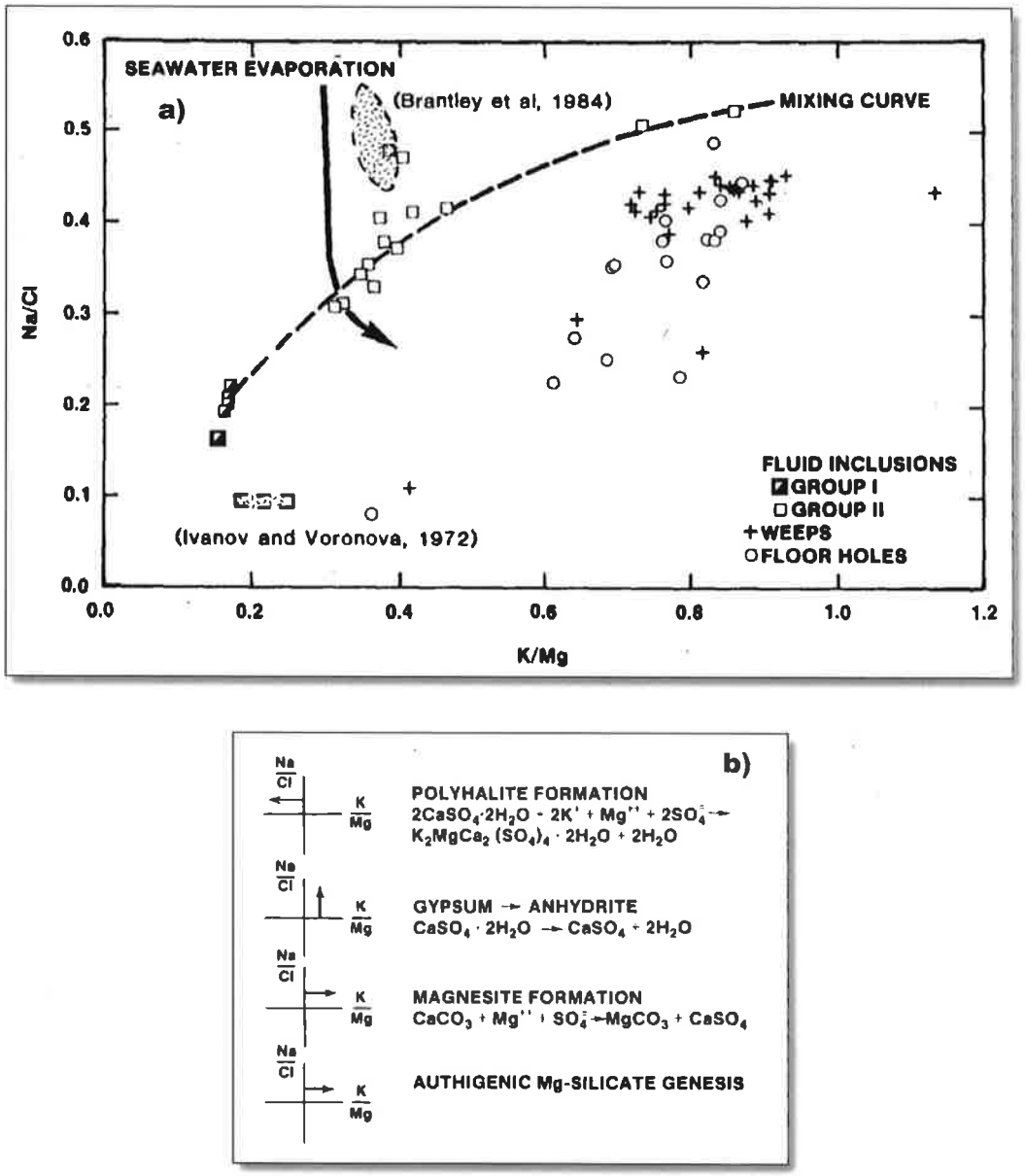

Figure 24. WIPP Salado brines a: K/Mg vs. Na/Cl (by weight) in WIPP brines (Figure 2 of Stein & Krumhansl 1986). b: qualitative effect of different mineral transformations on relative position (Figure 3.10 of Lappin 1988).

Table 2 shows that the gypsum dehydration temperature range (75-175 °C) is much lower than the "uncontaminated" polyhalite dehydration range (340-360 °C), so this proposed *in situ* transformation is significant from a brine availability point of view. Dehydration of polyhalite typically only occurs at

temperatures significantly above the brine inclusion decrepitation temperature, and would therefore make this water unavailable for migration into excavations.

Weeps and floor holes in Figure 24 have an apparently different composition from fluid inclusions, likely because most floor holes at WIPP cross MB139, which is a significant anhydrite and clay layer (about 1 m thick and 1.5 m below the repository horizon). Brines from MB139 (orange circles) and MB140 (blue circles) are in some ways quite different from fluid inclusion brines and different from each other.

Brines collected from MU-0 (pink triangles) are shown in Figure 25 to be markedly different in composition compared to Group I and all but possibly 2 samples from Group II fluid inclusions (open black triangles). MU-0 brines are much closer to MB139 and Room Q brines. MU-0 is located stratigraphically between Room Q (which followed the orange marker band [MU-1] and intersected MU-0 along the bottom of the room) and MB139 (approximately 1 m below the bottom of MU-0 – unit PH-4 lies between them – see Figure 5). GSEEP brine in Figure 25 is likely derived from MB140 brine (Roberts et al. 1999). Data for many of the "weeps" and "floor holes" in Figure 25 may have experienced significant evaporation, starting from a composition closer to MB139 and MU-0. The isothermal evaporation line is data from the Krumhansl et al. (1991a) evaporation experiment, which started with brine collected from a vertical borehole near Room Q (i.e., in MB139). Brine A (Molecke 1983) and typical seawater composition are plotted for comparison.

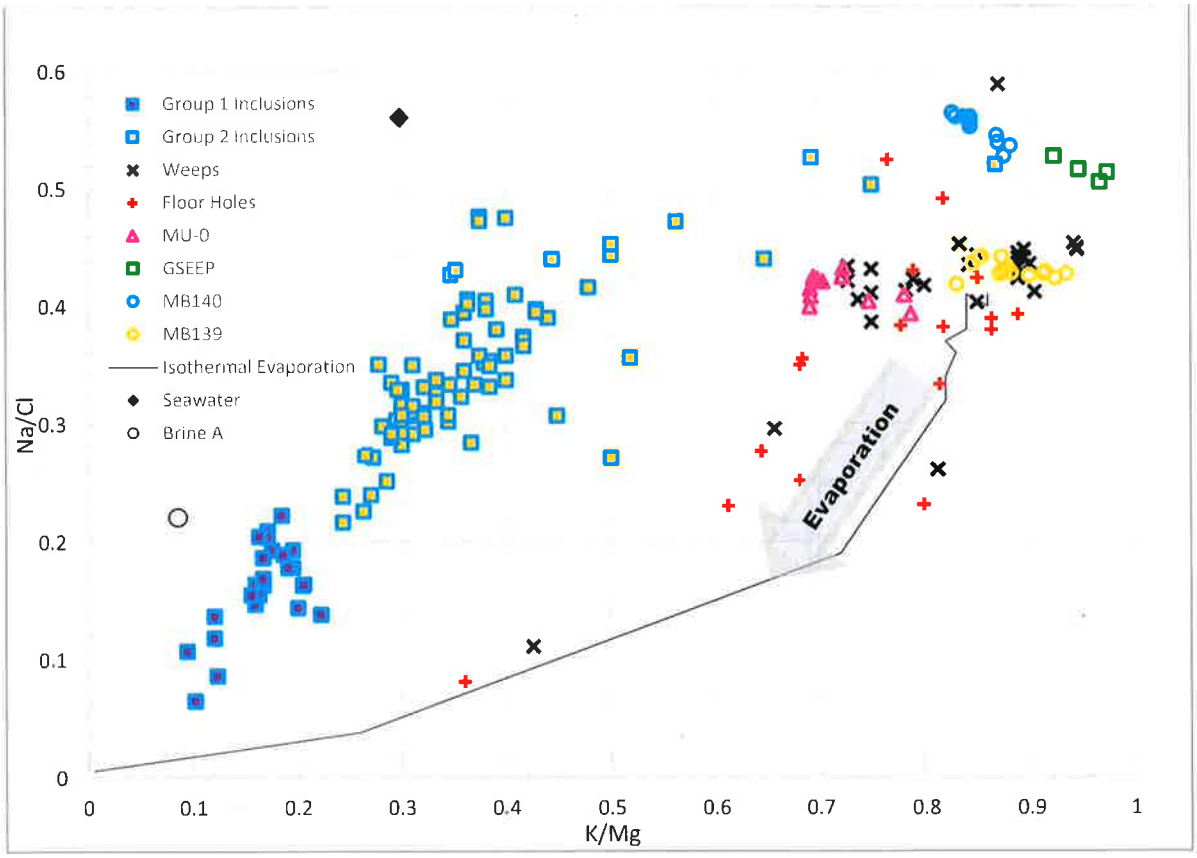

Figure 25. Salado brine chemistry summary plot (data from Molecke 1983, Stein & Krumhansl 1988, Krumhansl et al. 1991a, Deal et al. 1995, and Roberts et al. 1999).

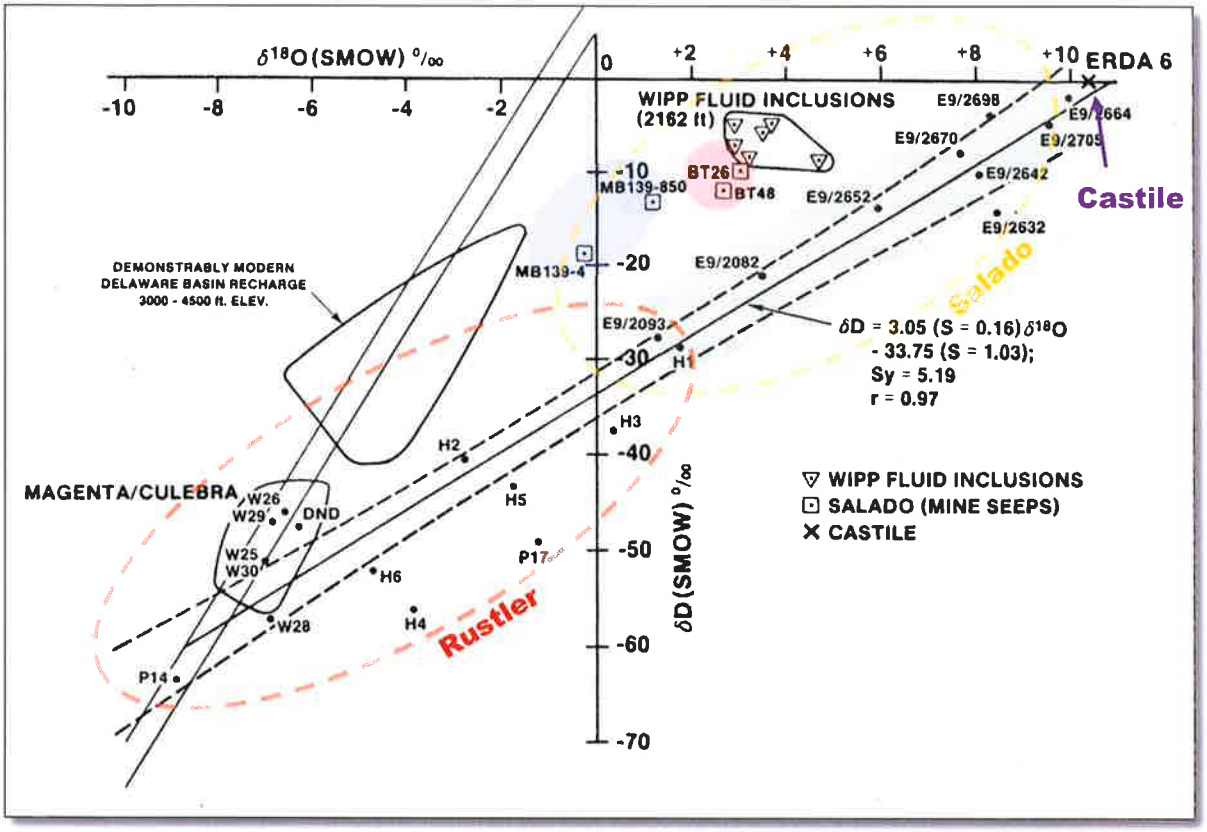

Figure 26. Stable-isotope composition of fluids from WIPP-relevant horizons (Figure 3.11 of Lappin 1988). Samples BT26 & BT48 from Duval potash mine (McNutt Potash Zone; Figure 1); blue shaded samples are from MB139.

A-2.5 WIPP Salado Stable Isotope Data

Figure 26 shows the relative levels of oxygen and hydrogen isotopes in WIPP waters, including Salado brines. The small isotopic difference between Salado halite fluid inclusions and MB139 brine (inverted triangles and squares) is not completely understood (Lappin 1988; p. 60), but this is relatively small compared to the compositional differences among these waters (Figure 24). The ERDA-6 sample in Figure 26 is from the Castile Formation (below the Salado Formation, the source of high-pressure brine pockets – Figure 1). The ERDA-9 samples are from a range of depths across the Salado (green shaded box), and seem to span from the deeper ERDA-6 sample to the shallower Rustler Formation (Figure 1) samples (i.e., H-, P-, and W-series samples circled with red dashed line).

Samples collected from boreholes generally follow an indicated trendline on Figure 26, while samples from mined excavations do not. This distinction is not completely understood, and may be an artifact of sample collection methods or contamination from drilling fluid in boreholes. Lambert (1992) presented stable isotope data similar to those in Figure 25.

A-3. Avery Island Brine Migration Tests

A series of isothermal and heated vertical borehole brine inflow tests were conducted at Avery Island (domal salt) in the late 1970s and early 1980s (Stickney & Van Sambeek 1984). The relevant test details include:

- Utilizing deuterated water as an introduced tracer
- Salt gas permeability observations were made:
  - At different temperatures, and
  - During cool-down period after brine migration heater test

A-3.1 Deuterium Tracer in a Salt Heater Test

Three identical groups of boreholes (see Figure 27 for layout of a typical group) were monitored for bine inflow (one unheated, two heated). Test design is documented in Krause (1979) and test results are summarized in Krause (1983) and Stickney & Van Sambeek (1984). One of the heated boreholes utilized a traced synthetic brine (SB), where the heater and tracer boreholes were later overcored and analyzed post-test. The synthetic brine composition introduced into boreholes B2, B4 and B8 was 25 g/l D_2O, approximately 2 wt-% D_2O (Clynne et al. 1981).

The results of the isotopic analysis of water samples and desiccant cartridges by the USGS were not easily interpretable, but Clynne et al. (1981) had the following observations about the fractionation processes in the heater test at Avery Island:

> "(1) Evaporation of the brine arriving at the heater hole fractionates deuterium. In the Avery Island situation, where vapor is continually removed from the system and the brines are very saline, evaporation initially enriches the residual solution in deuterium. As evaporation proceeds a reversal takes place and the residual solution is depleted in deuterium. The point of reversal is dependent upon evaporation rate, temperature and brine chemistry (Sofer and Gat, 1975).
>
> (2) A second fractionation in the brine arriving at the heater hole involves the crystallization of hydrated minerals. The volumetrically important hydrated minerals crystallizing from NaCl-saturated WIPP-A at 55°C are carnallite ($KMgCl_3 \cdot 6H_20$) and bischoffite [*sic*] ($MgCl_2 \cdot 6H_20$) (D'Ans, 1933). There is a deuterium fractionation between water of hydration in minerals and the solution from which they crystallized, and the process is temperature and composition dependent. Although the crystallization of hydrated minerals normally enriches the residual brine in deuterium, minerals that deplete brine deuterium are known. No data exist for the effect of carnallite and bischoffite [*sic*] crystallization on isotopic composition."

These discussed fractionation effects would be going on in the planned heater test, and should be considered in the test design and interpretation. On the order of 35,000 ppm D_2O was observed in the desiccant canisters associated with the SB heated borehole at the conclusion of the test, showing the tracer did flow into the heated borehole. Additional fractionation mechanisms were observed related to the desiccant canisters and their treatment in the laboratory, which precluded their use in a quantitative analysis.

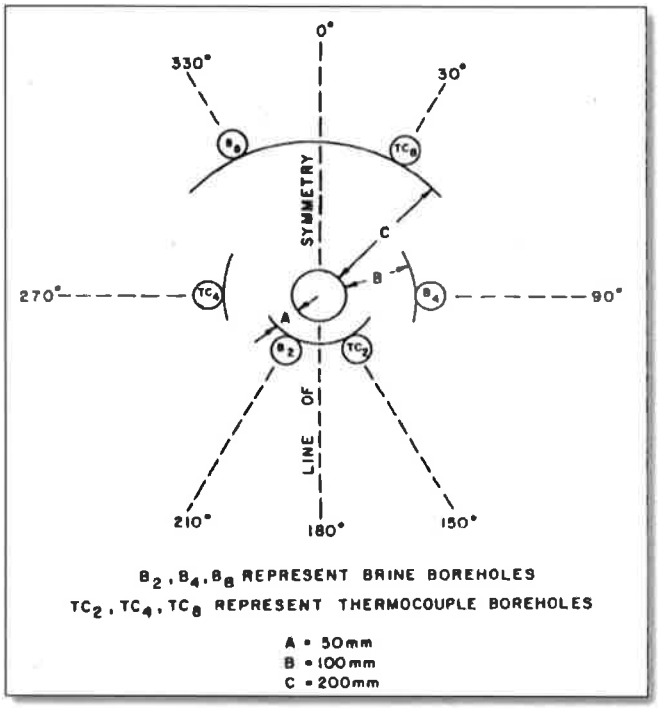

Figure 27. Layout of typical Avery Island brine inflow experiment (Figure 2 of Krause 1983).

Brine inflow at all three sites was monitored for several months, showing stable brine inflow rates after approximately one month of monitoring (Figure 29). Brine inflow rates were approximately 100 times lower in domal salt at Avery Island than in bedded salt at WIPP; comparing unheated site AB from Figure 28 with Figure 10.

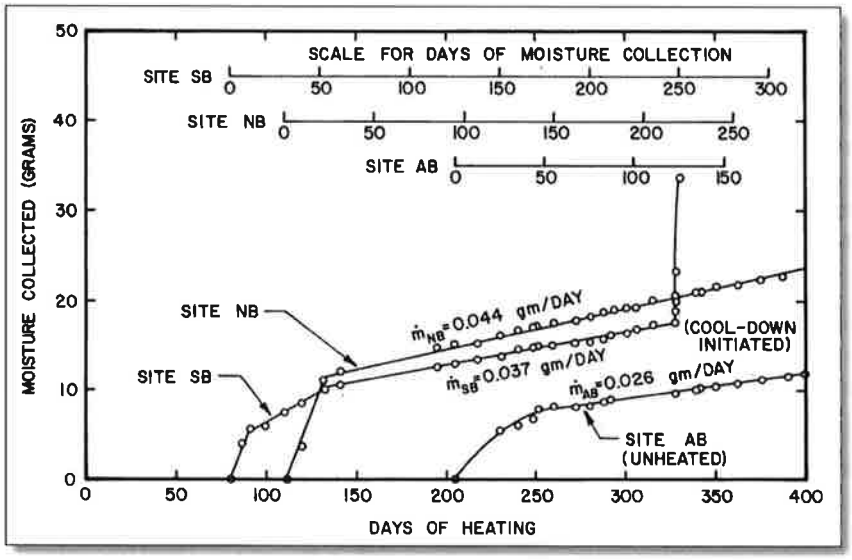

Figure 28. Brine inflow through time in Avery Island vertical boreholes (Figure 20 of Krause 1983).

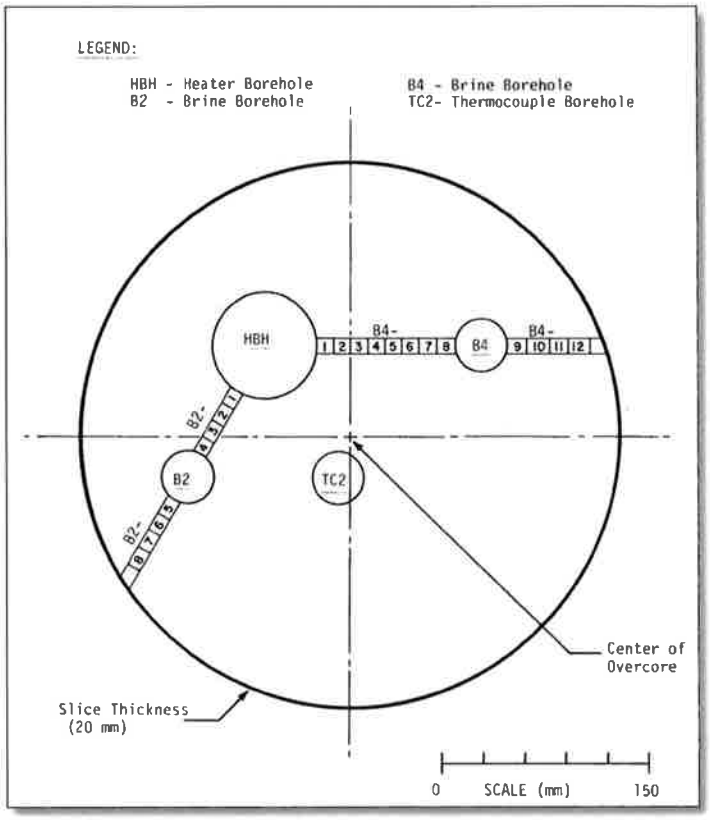

Figure 29. Illustration of over-coring and profiles of lab D_2O samples between boreholes (Figure 34 of Krause 1983).

The distribution of D_2O through space in the salt (after the end of heating) was estimated by overcoring around the smaller-diameter borehole B2 (50 mm [2"] to edge of heater borehole) and the heater borehole, and testing small samples along profiles between the boreholes (Figure 29).

The distribution of D_2O in the intact salt after heating is shown in Figure 30. The observed values were low, within a factor of 5 of the background level. The background level was estimated to be 3 ppm/gram salt D_2O by quadrupole mass spectrometer at SD School of Mines (see sample preparation description on p. 46 of Krause 1983), which would correspond to 300 ppm for 1% porosity. All the planned analyses were not carried out "because of the low concentration of D_2O in the synthetic brine" (p. 49 Krause 1983). A Mg tracer was also added to the traced brine, but interpretation of Mg data was harder, because of low spatially heterogeneous background levels of Mg in the salt.

Based on this information, a high enough level of D_2O should be spiked in the satellite borehole to ensure the signal in the water flowing to the main/heated borehole is detectable, but the fractionation of deuterium during evaporation and precipitation of hydrous minerals will complicate interpretation.

Given how much deuterium was added to borehole B2 (25,000 ppm or 2% by weight – Clynne et al. 1981), and how much was collected in the desiccant canisters (on the order of 35,000 ppm – Krause 1983, p. 52), the low levels of D_2O in the salt are a function of the low advective porosity of the salt.

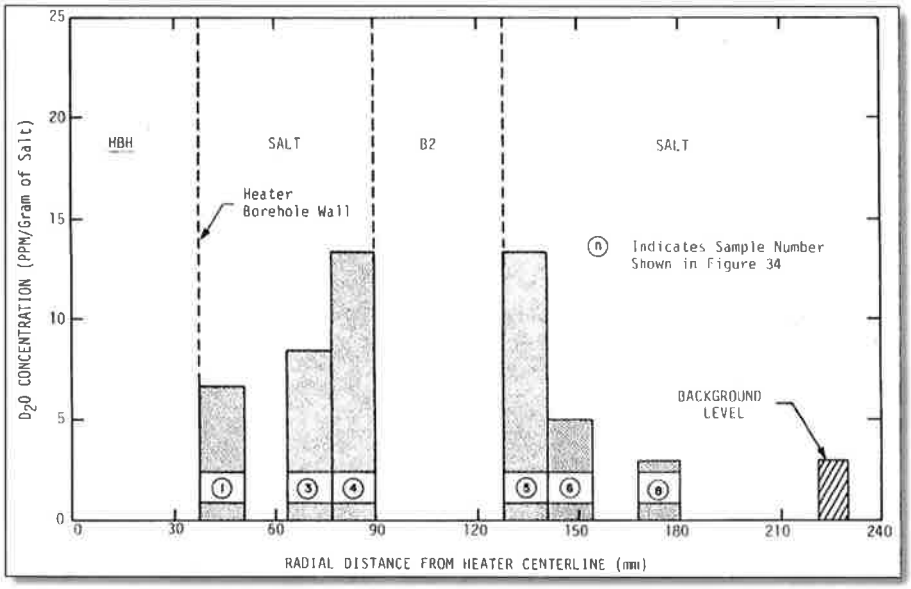

Figure 30. Results showing distribution of D_2O in lab samples from overcored salt at Avery Island (Figure 35 of Krause 1983).

A-3.2 Salt Gas Permeability During Cooling

Gas permeability measurements were made in small-diameter vertical boreholes at Avery Island, using a pipe-based neoprene compression plug as the isolation tool Figure 31b). Additional borehole sealing was achieved by placing grout above the plug in the borehole (Stickney & Van Sambeek 1984; p. 32). Both constant-head and falling-head permeability tests were conducted using the same setup, and produced results which agreed with one another. The tests were conducted at different radial distances away from a long-term heater tests (i.e., distance from the heater was proportional to salt temperature). Figure 32b shows permeability was observed to decrease with an increase in temperature. Since these tests were run in shallow boreholes in the floor of the mine, the heat from the long-term heater test at Site C was causing the salt to expand and close up micro- and macro-fractures in the DRZ.

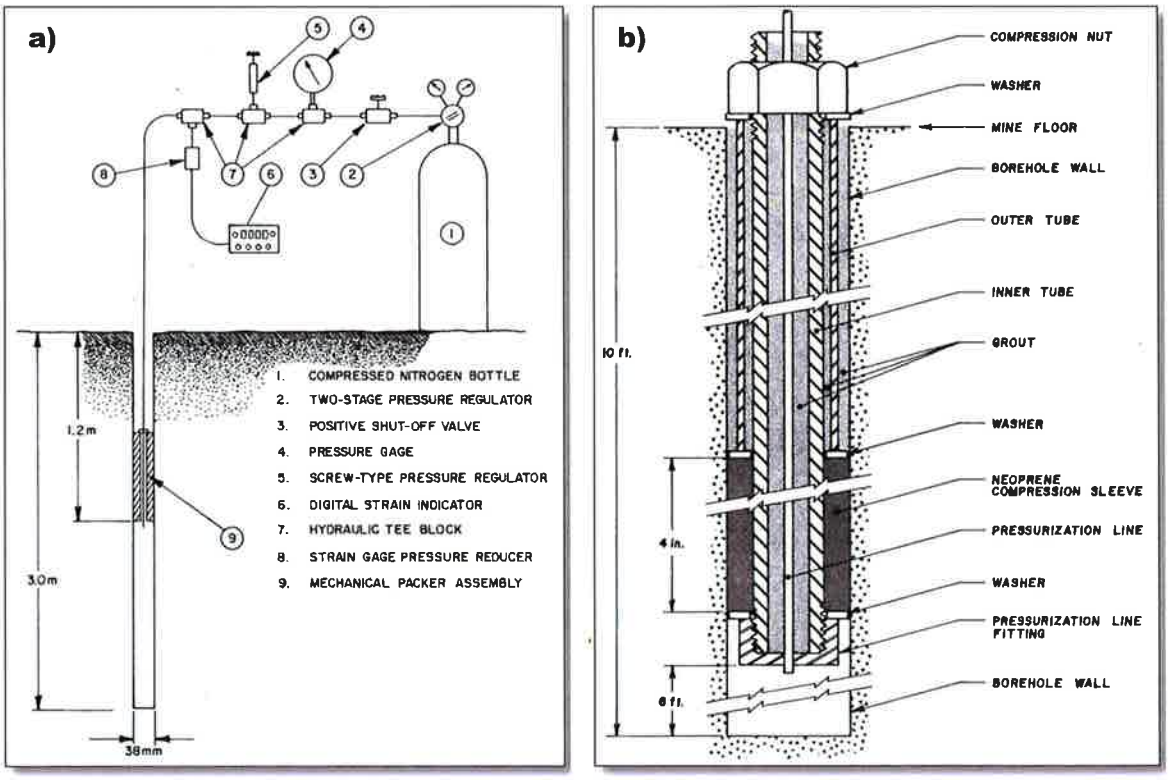

Figure 31. Salt gas permeability testing apparatus used at Avery Island (a: Figure 4-1 of Stickney & Van Sambeek 1984; b: Figure 1 of Blankenship & Stickney 1983).

Approximately half the total brine inflow at site SB occurred during the cool-down period (Figure 28). In conjunction with brine collection, further nitrogen gas permeability tests were conducted. Salt permeability was observed to increase by as much as five orders of magnitude (to 1.2×10^{-16} m^2 from 2.0×10^{-21} m^2) while heater power was stepped down over a period of five days (Figure 31a).

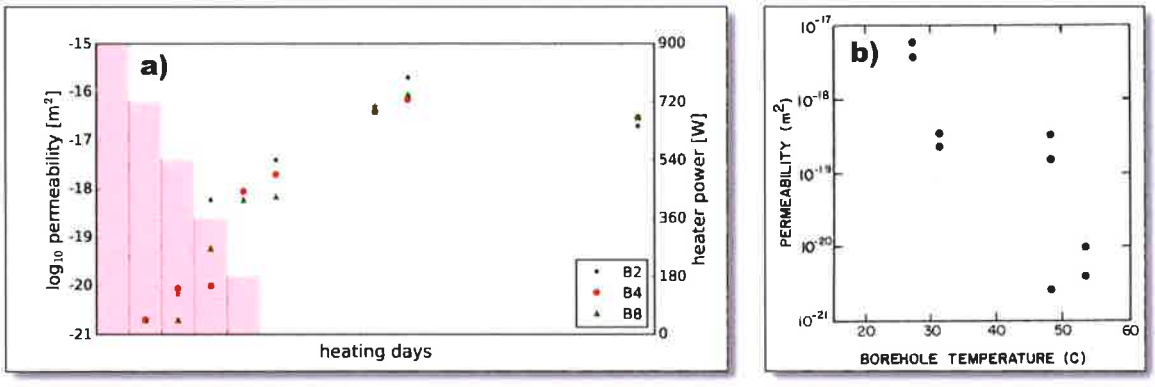

Figure 32. Avery Island borehole gas permeability. a: during cool down at site SB (Figure 4.4 of Kuhlman & Malama 2013); b: near heater Site C (Figure 4-2 of Stickney & Van Sambeek 1984).

A-4. Salt Block II: High-Frequency Brine Inflow

The Salt Block II experiment (Figure 33) included a large (1-m diameter) block of bedded salt from the MCC potash mine in the McNutt Potash Zone (Figure 1), located stratigraphically above WIPP in the Salado Formation (Hohlfelder 1979; Lambert 1979). The block was heated axially, and brine inflow to the heater was monitored via N_2 circulation through chilled mirror hygrometers (CMHs) and desiccant canisters. This large-scale lab experiment was unique with respect to the high-frequency brine inflow measurements made via CMH.

This high-frequency data allowed observation of additional shorter timescale trends and details of behavior not observed with daily weighing of desiccant canisters seen in most field salt heater tests.

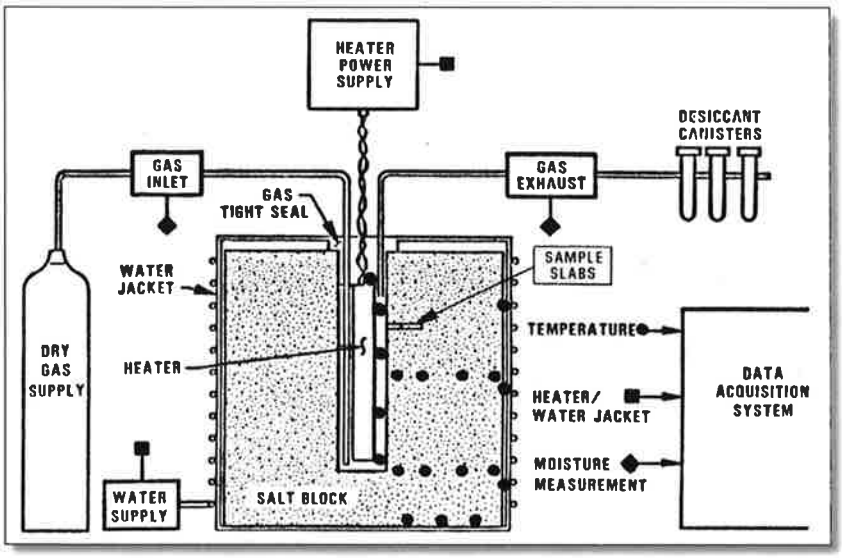

Figure 33. Salt Block II laboratory experiment setup (Figure 1 of Hohlfelder, 1979).

For the first portion of the experiment (Figure 34), both the CMH and the downstream desiccant canisters were used to measure brine inflow. The two methods agreed within 10%. The CMH approach was abandoned after approximately 83 days after the data became unreliable due to fouling of the mirrors.

This experiment showed that measuring brine inflow by two methods would be useful to assure data quality. This was one of the few datasets with high-frequency water inflow data during heating at different temperatures and during cooling. This also illustrates the large amount of brine released after the heaters were shut down (>40% of total brine collected). Steady state brine inflow is plotted in Figure 2 as a function of borehole temperature.

There was a temperature drift in the experiment due to uncontrolled conditions in the laboratory where the experiment was conducted, which also shows that large scale experiments require careful environmental control.

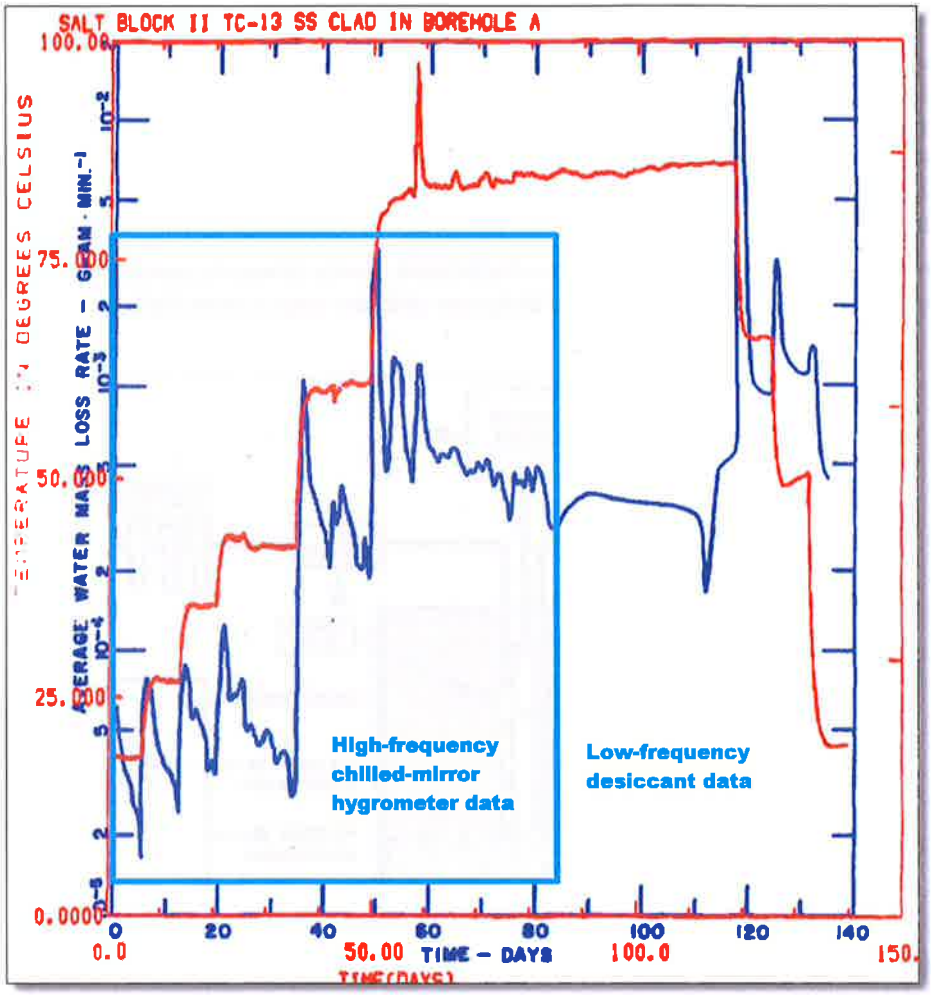

Figure 34. Water mass loss rate (blue line) and temperature (red line) observed in Salt Block II test. Blue box highlights high-frequency CMH data, other data are from daily weighing of desiccant canisters (Figures 17 & 27 of Hohlfelder, 1979).

A-5. Asse Brine Migration Experiments

The Asse Brine Migration test was jointly conducted by Westinghouse (US) and then West Germany (Federal Republic of Germany) in the Asse salt mine (Westinghouse 1987; Rothfuchs et al. 1988). The test included four identical sets of heated boreholes and observation holes. Two of the boreholes included radioactive ^{60}Co (other two had no radioactive material), and two were sealed during heating (while the other two had gas continuously extracted from them). Relevant observations or techniques used during testing included:

- Sampling and analysis of gases during testing,
- Use of a cold-trap type of brine collection system,
- AE monitoring.

This test was a very complex test with significant engineering design (Westinghouse 1987) and budget, but the tests produced some unique data. Four sites were established (Figure 36), with one sealed radioactive, one unsealed radioactive, and two more non-radioactive sites (sealed and unsealed).

A-5.1 Cold Trap Moisture Collection

The moisture collection system was similar to that proposed in this report, with dry nitrogen pumped through the two unsealed sites to flush any inflow of moisture, but instead of using desiccant or a CMH, they used a cold trap to condense all the liquid out of the gas stream (Figure 36). This is an alternative approach to using desiccant canisters (cheapest and most robust, but labor intensive and low-frequency) or inline hygrometers (higher frequency data, but more expensive and less robust). Maintaining a cryogenic cold trap in the underground would be relatively expensive and complex.

A-5.2 Gas Sampling While Heating Salt

Gas samples were collected from two of the four sites (the unsealed ones). The following statement from Coyle et al. (1987, p. 71) discusses the gases collected (example data shown in Figure 37).

> "These gases also contribute to the total pressure increase. It is of interest that hydrogen is observed in the nonradioactive sites as well as in the radioactive sites. The hydrogen in the nonradioactive sites is probably produced by corrosion reactions of the released brine. It will be of great interest to retrieve those different metal samples, which were attached to the thermocouple cage for corrosion investigations. The production of small amounts of hydrocarbons, carbon dioxide, and carbon monoxide is not surprising since it is known from former investigations that these components usually occur in rock salt. *The production of hydrogen chloride (HCl), observed in four measurements at sites 1 and 2, is possibly due to hydrolysis of bischofite ($MgCl_2 \cdot 6H_2O$).* This mineral could occur in small traces in the salt. In order to prove this assumption, special chemical analyses will need to be performed on salt samples of the test formation after the tests are completed."
>
> "Since *hydrogen production at the nonradioactive test sites is considered to be due to corrosion reactions*, it should be expected that the hydrogen production would decrease when either the brine release rates decrease or the metal surfaces are protected by oxide coatings. And in fact, it can be observed at test site 2 … that the hydrogen production decreased approximately 400 days after start-up of operation when the brine release rates became very small. Since the same effect can be observed at test site 1 where the water vapor is kept in the borehole, it can be concluded that the hydrogen production is also reduced because of the oxidized metal surfaces."

We would expect less production of hydrocarbons, the presence of any injected tracers, and possibly additional different gases due to differences between bedded and domal salt. This dataset of gases produced during the Asse Brine Migration test has not been generated for bedded salt.

Gas sampling was conducted downstream of the cold trap (Figure 36), so other condensable components in the gas phase (e.g., HCl) would likely have condensed out of the gas stream with the H_2O.

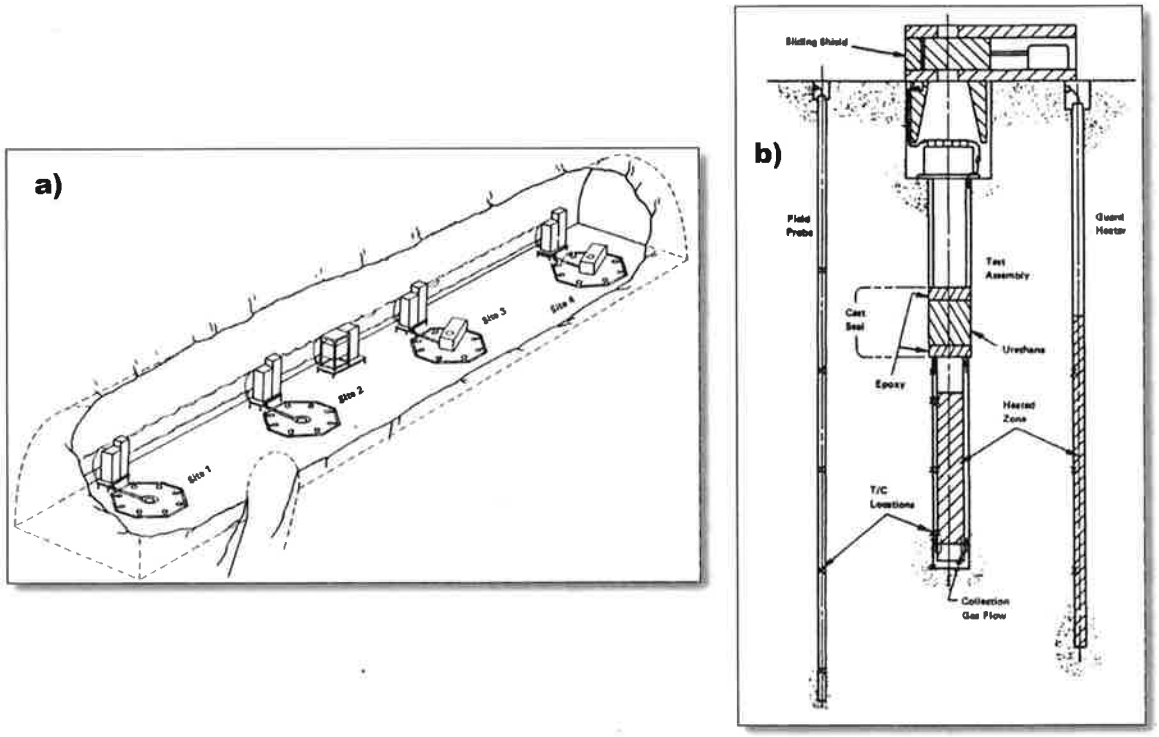

Figure 35. Layout of brine migration test at Asse (Figures 4-1 (a) and 4-2 (b) of Coyle et al. 1987).

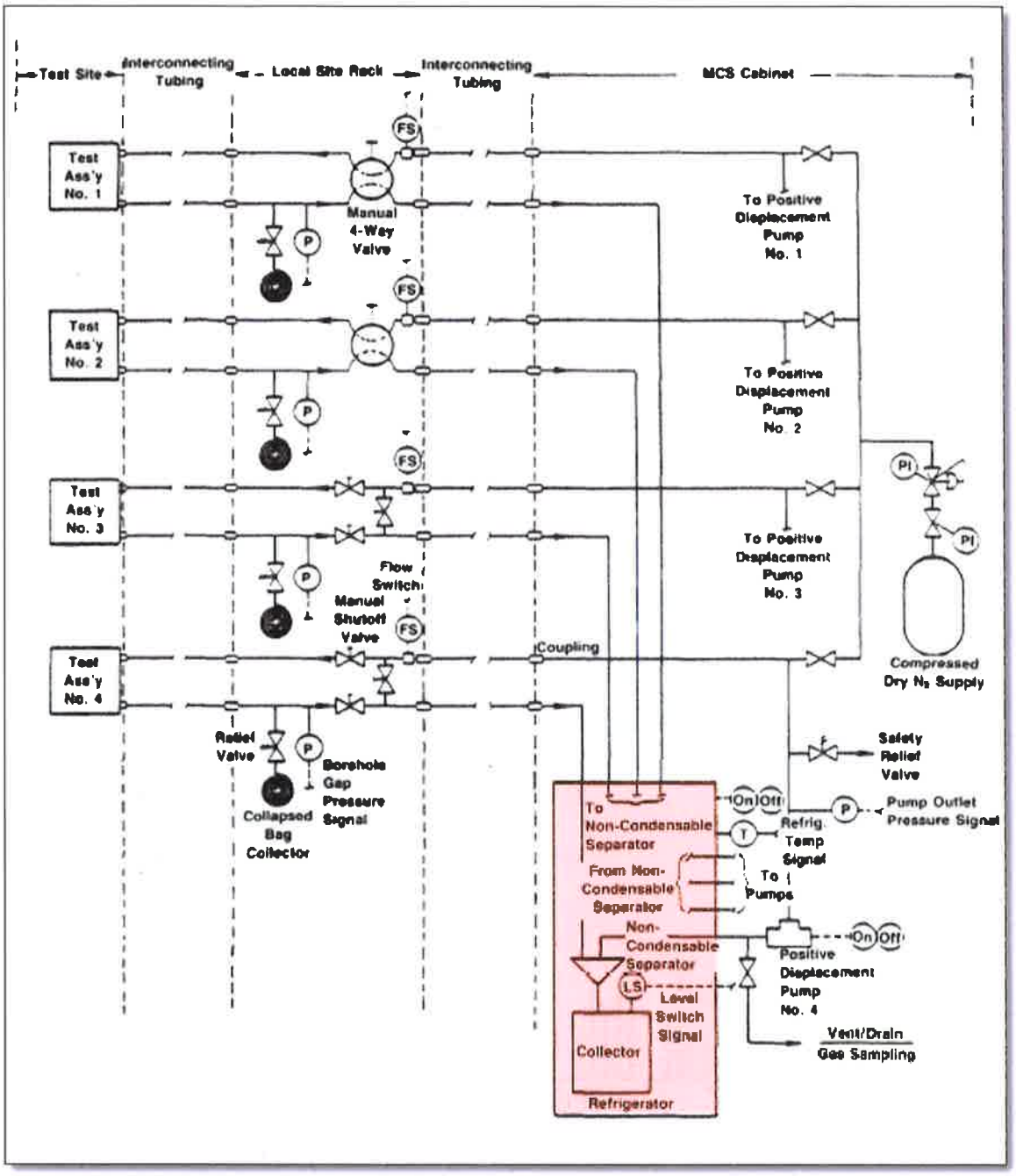

Figure 36. Moisture collection system at Asse (Figure 4-9 of Coyle et al. 1987). Cold trap and sample port highlighted.

Date of Sampling	Test Day	Sample No.	Component (Vol. %) H_2	O_2	N_2	CO_2	CO	CH_4	C_2H_6	C_3H_8
May 25, 83	0	1/1	-	0.9	98.9	0.034	-	0.0005	-	-
June 15, 83	21	1/3	-	0.4	99.3	0.69	-	0.02	0.005	0.0063
July 20, 83	56	1/4	0.01	1.04	-	1.5	0.096	0.033	0.0027	-
Aug. 23, 83	90	1/5	0.45	2.8	94	3.1	0.052	0.06	0.0287	0.164
Sept. 23, 83	121	1/6	0.6	0.74	93.6	4.04	0.32	0.0678	0.04	0.195
Oct. 25, 83	153	1/7	1.43	0.56	91.4	7.1	0.51	0.1140	0.00495	0.216
Nov. 23, 83	182	1/8	1.34	1.1	89.9	7.0	0.27	0.123	0.073	0.163
Dec. 19, 83	208	1/9	1.94	1.1	89.8	6.8	0.31	0.167	0.0715	0.159
Jan. 17, 84	237	1/10	1.47	0.84	93.1	4.1	0.30	0.152	0.058	0.125
Feb. 15, 84	266	1/11	1.40	0.51	93.8	4.7	0.26	0.167	0.027	0.13
March 14, 84	294	1/12	1.72	0.59	90.6	6.0	0.40	0.18	0.015	0.072
April 17, 84	328	1/13	2.21	0.24	91.4	5.46	0.39	0.22	0.03	0.10
May 15, 84	357	1/14	1.84	0.72	92.7	4.30	0.24	0.185	0.024	0.075
June 16, 84	386	1/15	2.31	0.28	91.8	4.95	0.29	0.18	0.024	0.075
July 13, 84	415	1/16	1.54	0.26	92.5	4.70	0.30	0.20	0.025	0.061
Aug. 16, 84	449	1/17	1.05	0.38	92.7	4.70	0.31	0.214	0.022	0.068
Sept. 17, 84	481	1/18	0.74	0.39	92.0	5.19	0.30	0.25	0.02	0.07
Oct. 15, 84	509	1/19	0.58	0.28	93.5	5.3	0.31	0.24	0.02	0.06
Nov. 8, 84	537	1/20	0.23	2.3	93.1	4.1	0.14	0.2	0.02	0.05
Dec. 14, 84	569	1/21	0.27	0.72	93.2	4.2	0.16	0.18	0.02	0.02
Jan. 15, 85	601	1/22	0.26	0.28	93.6	4.6	0.22	0.21	0.022	0.035

Figure 37. Example of non-condensable gases collected in samples from Asse brine migration test (Table 6-16 of Coyle et al. 1987).

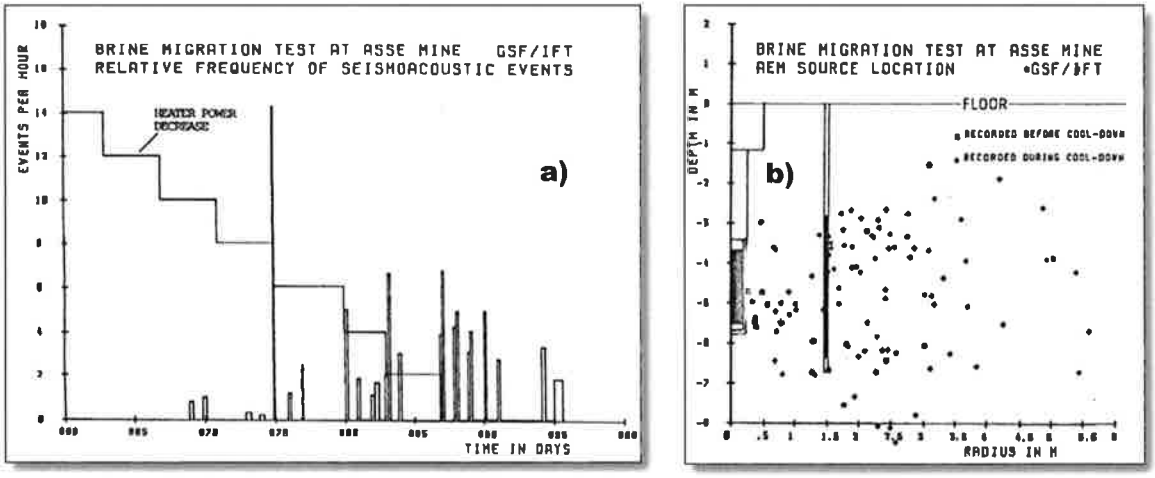

Figure 38. Acoustic emissions a: through time (during cool-down) and b: projected onto cross-section (Figures 6-54 and 6-56 of Rothfuchs et al. 1988).

A-5.3 Acoustic Emissions During *in situ* Heating

AE were monitored at multiple locations during heating and cooling. Figure 38 shows the distribution of AE events in time (during cool-off and heater step-down in power) and in space (near guard heaters). AE had been successful in SNL laboratory tests (Hohlfelder et al. 1981), but this is one of the only large-scale observations of AE during a field-scale salt heater test.

A-6. Project Salt Vault: Brine Collection

The first major *in situ* effort to characterize salt for disposal of radioactive waste was performed by ORNL in bedded salt deposits in Kansas as part of Project Salt Vault (Bradshaw & McClain 1971). This testing is relevant because:

- Several approaches were investigated to collect and quantify the moisture release of the salt, and
- Both vertical and horizontal borehole heater tests were conducted.

A-6.1 Brine Collection System Design

The following statement from Section 10.5.2 of Bradshaw & McClain (1971, p. 128) summarizes the issues encountered in the bedded salt of Lyons, KS:

> "Several special experiments were carried out in an effort to accurately measure the rate at which moisture was entering the array holes due to the migration of brine inclusions in the salt … The difficulty with these measurements was due to the moisture already in the mine air (40 to 60% relative humidity) and the low rate of moisture production from the salt in the array holes. These special experiments included the use of Drierite columns in the off-gas lines; cold traps using ice and brine, dry ice, and liquid nitrogen; *and one series of experiments (the most successful) where dry nitrogen gas was swept through the hole and off-gas system.*"

More from Project Salt Vault on brine collection can be found in Section 11.2.2 (Bradshaw & McClain 1971, p. 168), indicating the importance of using *very* dry nitrogen:

> "By about the middle of June 1967 (shortly before shutdown) the total condensate collection in room 1 was about 1.7 liters, and in room 4 it was about 0.8 liter. … Several attempts were made to determine if water was migrating into the holes during the periods between the sporadic collections. These included the use of Drierite columns and the determination of the dew point by means of the refrigeration units on the condenser systems. However due to the fact that the mine air normally ran about 40 to 60% relative humidity (a rough average moisture content of about 11 g/m^3) these methods were unsuccessful. *Several tests using dry nitrogen gave the most reliable estimates*, although even these were good only for upper limit values. The best test was performed in room 1 on January 19-20, 1967 (about 70 days since there had been any condensate collection). In this test there was a 1-hr sweep of dry nitrogen through hole IV at 7 liters/min. This should produce more than three volume changes of the gas in the hole (greater than 95% removal of the original gas, if complete mixing is assumed), so that a negligible amount of water vapor (less than 0.1 ml) should remain in the hole. After this the hole was closed off for 24 hr to permit the diffusion of water from the salt into the hole. Then nitrogen at a flow rate of 2.1 liters/min for about 3½ hr was passed through the hole and into a system of traps at a temperature ranging from about 0 to 5° F. About ½ ml of liquid was collected in the traps. This meant that, if the nitrogen was absolutely dry when it entered the hole, it picked up enough moisture in the hole to become saturated at around 12°F. If that was the case, then the total emission of water from the salt into the hole during the 24-hr period was no more than 1 ml. *On the other hand, a test on the nitrogen alone (without its passing through the array hole) produced some traces of condensate at similar temperatures. (This was in spite of the fact that the nitrogen supplier said that the dew point should be below -20°F.)* Thus it must be concluded that the water collected from the array hole after the 24-hr period of no off-gas flow may not have come from the salt at all, so that the maximum inflow rate from the salt at that time must have been between 0 and 1 ml/day."

A-6.2 Brine Collection in Horizontal vs. Vertical Boreholes

Morgan (1963, p. 29-30) discussed some early efforts at heated boreholes in bedded salt:

> "Cylindrical heaters, 6 in. in diameter by 4 ft long, were used in 10-in. diameter holes in the floor and in a column of the mine to investigate the physical properties of salt in situ at temperatures above 300°C. Instrumentation was provided to measure floor rise around the heater in the floor and column expansion about the wall installation and to collect water vapor from the holes. Both the floor- and wall-cylinder tests began on July 18, 1962, with a power input of 3500 w each. Salt-temperature rises in the plane perpendicular to the center of the heater are shown … [Figure 39 of this report], along with theoretical curves based on the 100°C salt thermal properties. After 45 and 49 hr operation of the wall test and the floor test, respectively, the power was turned off for 3 hr, during which time the heater was removed from the hole and the hole diameter was calipered at 1-ft intervals. Both heaters were restarted at 5000 w; and the power remained constant, with the exception of a 5- to 10-min daily period (to record heater temperatures) and one period of about 45 min (to inspect the wall heater hole)."

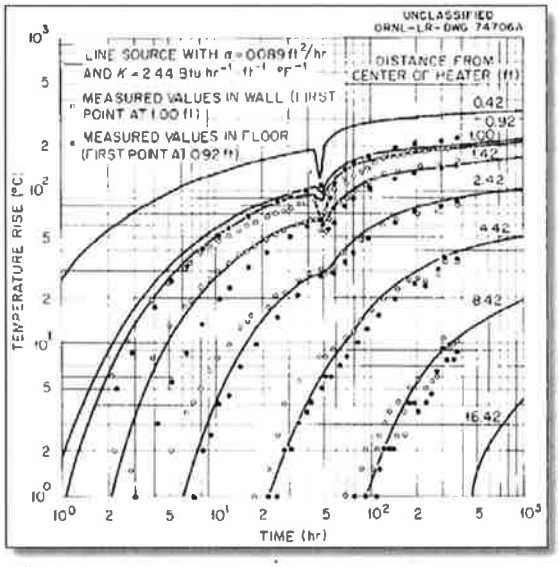

Figure 39. Comparison of temperature rise in horizontal and vertical boreholes to analytical solution (Figure 3.9 of Morgan et al. 1963).

> "Although the salt shattered at an estimated 280°C, it did not seem to have significantly affected heat transfer … Water evaporated from shale partings or released by salt shattering was condensed at mine temperature in air-cooled condensers. *About 15.5 liters from the floor heater hole and 250 ml from the wall heater hole were recovered.* One-gallon samples of the water from the floor hole, together with a reference sample of known recent water, were submitted to the laboratory of the U. S. Geological Survey for tritium dating."

A-7. Carlsbad Potash Mine Heater Tests

Preparing for the first shafts to be constructed at WIPP, *in situ* tests were conducted at the nearby MCC potash mine (Shefelbine 1982). This relatively shallow mine (350 m level) allowed access to the Salado Formation, but in the McNutt Potash zone (stratigraphically above the WIPP horizon; Figure 1). These tests were in some ways a "dry run" for the *in situ* tests being planned at WIPP. At least two borehole heater tests were conducted in the MCC mine. These tests demonstrated:

- Use of radiative "quartz lamp" heaters,
- One of a small number of horizontal borehole heater tests in bedded salt,
- Photography of salt crust growth during heater test,
- Heated boreholes to several different temperatures and monitored brine inflow, and
- Brine collected in unheated "observation" boreholes.

A-7.1 Quartz Lamp Radiative Heaters

Quartz lamp radiative heaters were first tested in a vertical borehole at Avery Island (Ewing 1981a), and the same lamps were then re-used in two different tests at MCC (Figure 40). One was a horizontal heated borehole configuration with nine lamps (Ewing 1981b), and the other was a vertical three-borehole configuration with one lamp in each (Shefelbine 1982).

Applying radiative heat directly to the borehole wall is efficient through air, and may lead to some convection, but does not rely on convection to heat the salt.

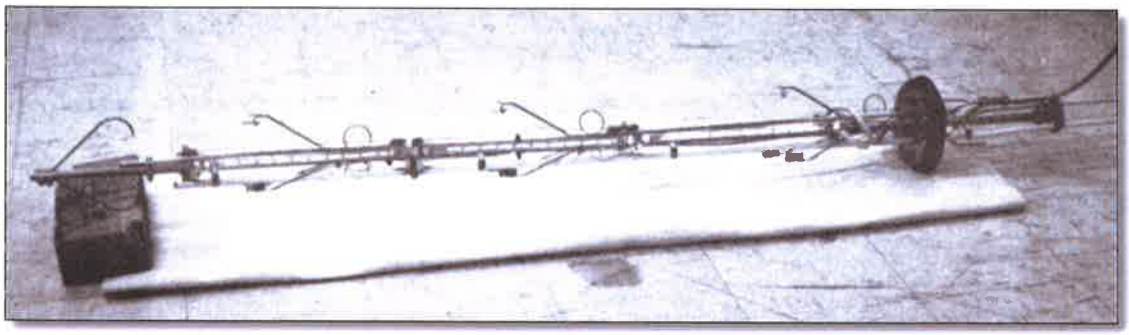

Figure 40. Nine-element quartz lamp radiative heater (Figure 2 of Ewing 1981a).

A-7.2 Horizontal Heater Test in Bedded Salt

The horizontal heater test at MCC was documented by Ewing (1981). This test was mostly a dry-run for testing to be done at WIPP (but this arrangement of quartz lamp heaters was not used at WIPP). There were electrical problems (power outage across the entire mine and a power overage to the test that brought borehole temperatures to 270 °C and led to decrepitation). But the general test design was successful. During nominal operation, the borehole wall temperature was 200 °C and brine was collected at approximately 2 grams per day.

The horizontal borehole was only 1.88 m [74"] long (Ewing 1981b; p. 18), with the heater placed near the end of the borehole (Figure 41). This means the access drift DRZ likely intersected the test interval.

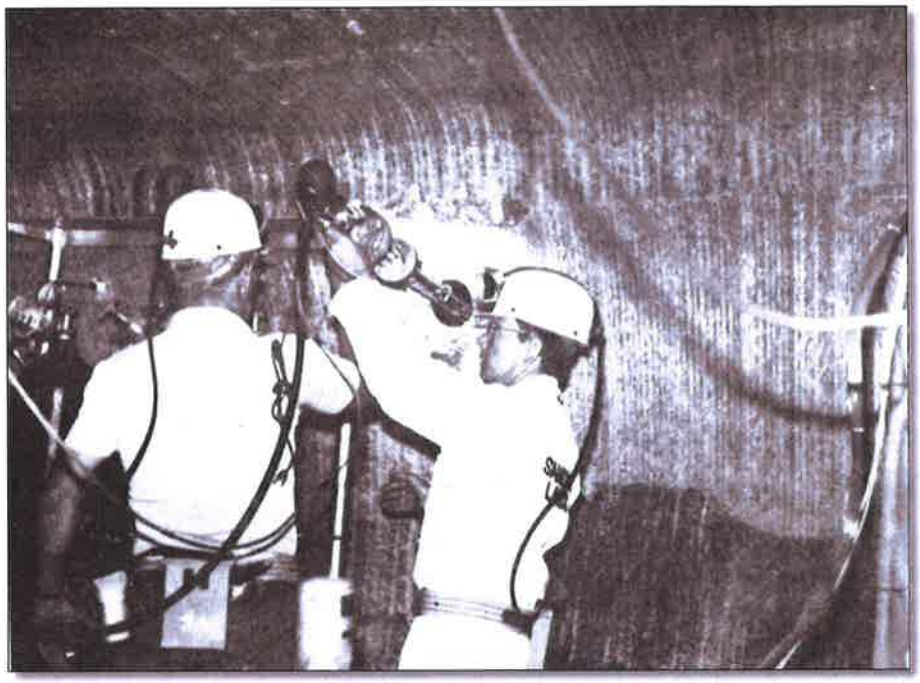

Figure 41. Installation of heater in horizontal borehole at MCC (Figure 5 of Ewing 1981b).

A-7.3 Photography of Salt Crust Growth

The quartz lamp heater allowed photography of salt encrustation growth during the experiment (Figure 42). The photos were captured with a low-resolution VHS system, and the photos are not of high quality. This approach might allow additional diagnostic information during testing, if conducted with modern equipment.

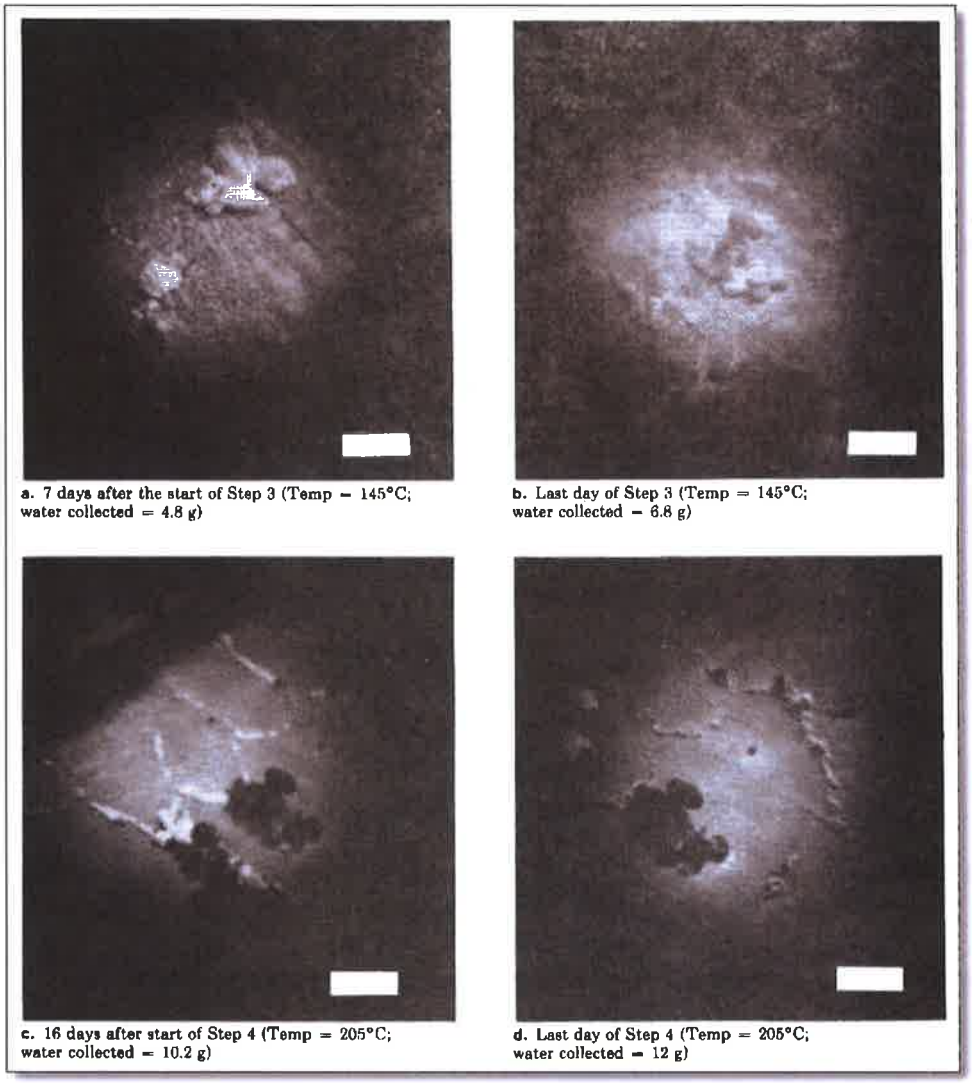

Figure 42. In situ growth of efflorescence in MCC three-heater experiment. Scale bar is ~0.5 cm (Figure 29 of Shefelbine 1982).

A-7.4 Brine Migration Test at Multiple Temperatures

The three-heater test at MCC included running the heaters in the boreholes at four different temperatures. Of the three boreholes (located 1 m apart), two were heated the whole time (boreholes A & C), while borehole B wasn't heated until the final step. Brine was collected in borehole B through the entire test (Figure 44). This shows the amount of brine inflow increases with temperature, but the steps chosen (90 °C, 110 °C, 145 °C, and 205 °C) do not correspond directly to the minerals discussed in Table 1.

The Salt Block II large-scale laboratory experiment (Hohlfelder 1979) also produced brine at multiple borehole heater temperatures (Appendix A-4). Data from these tests and the Salt Block II experiment are plotted in Figure 3 and listed in Appendix A-10.

A-7.5 Brine Collection in Unheated Boreholes

Figure 43 shows that the brine collected in borehole B did increase slightly when the temperature was increased to 145 °C in boreholes A & C. These boreholes might have been too far apart for a brine migration study, but too close to be unaffected by heating going on in adjoining boreholes.

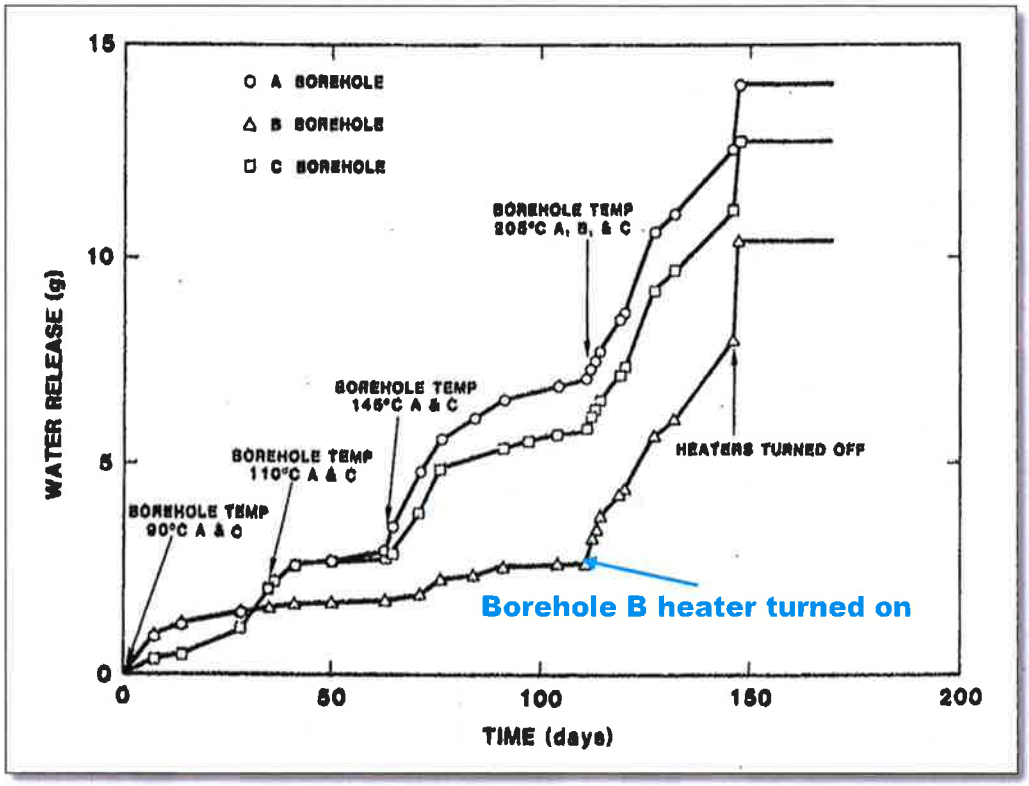

Figure 43. Water release for MCC three-heater experiment (Figure 28 of Shefelbine 1982).

A-8. Resistivity Measurements in Salt

Resistivity surveys or electrical resistivity tomography (ERT) can be used to estimate the brine content of the salt if a relationship between brine content and resistivity is available. Figure 44 shows some early data from WIPP (Skokan et al. 1989; Borns & Stormont 1988), while Figure 45 includes more recent references from an application in Germany at Asse (Jockwer & Wieczorek 2008).

If salt is dry (salt will still adsorb humidity from the air) resistivity of the salt will be high. WIPP salt tends to have low natural resistivity due to its brine content. Damaged salt also has higher resistivity than intact salt (Stormont 1997b, Figure 4). Resistivity of the brine itself is also a function of ionic strength and temperature (Figure 46); it is assumed any water in the salt will be a saturated brine.

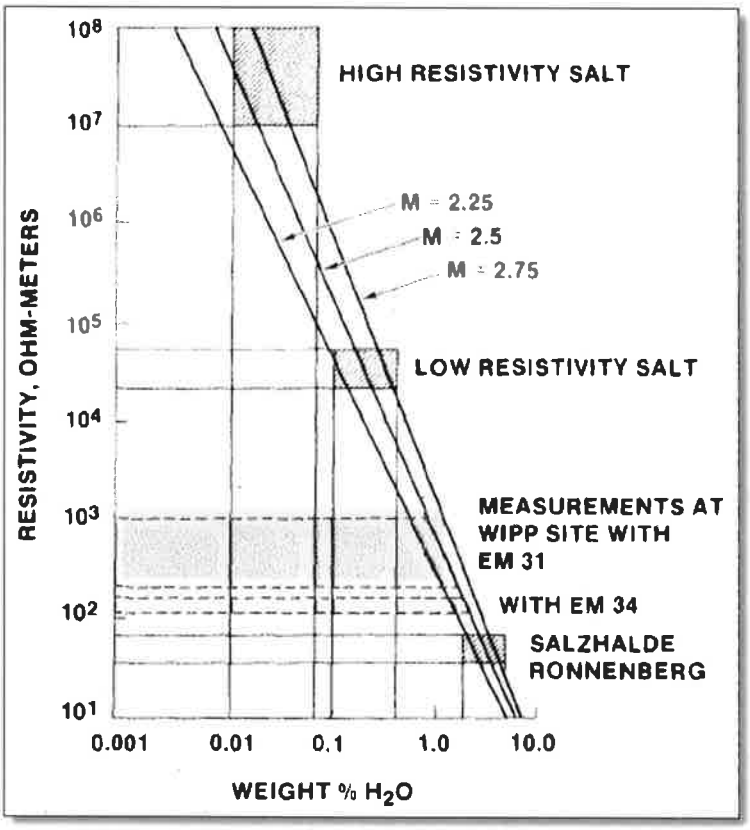

Figure 44. Resistivity of salt as a function of water content, showing range of resistivity observed at WIPP (Figure 7 of Skokan et al. 1989).

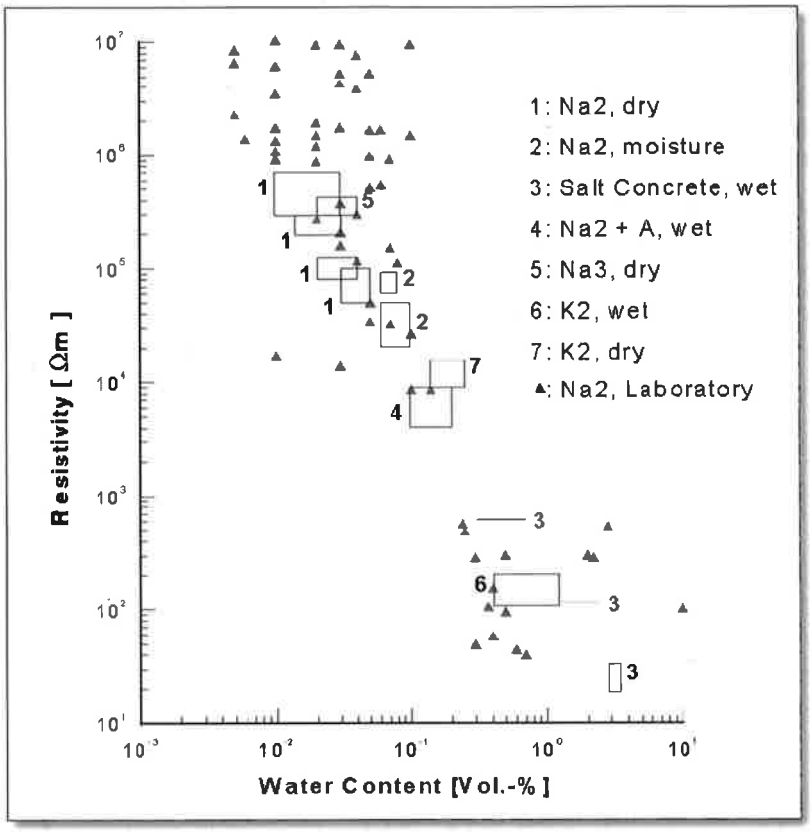

Figure 45. Relationship between water content and electrical resistivity for rock salt (Fig. 4-3 of Jockwer & Wieczorek 2008).

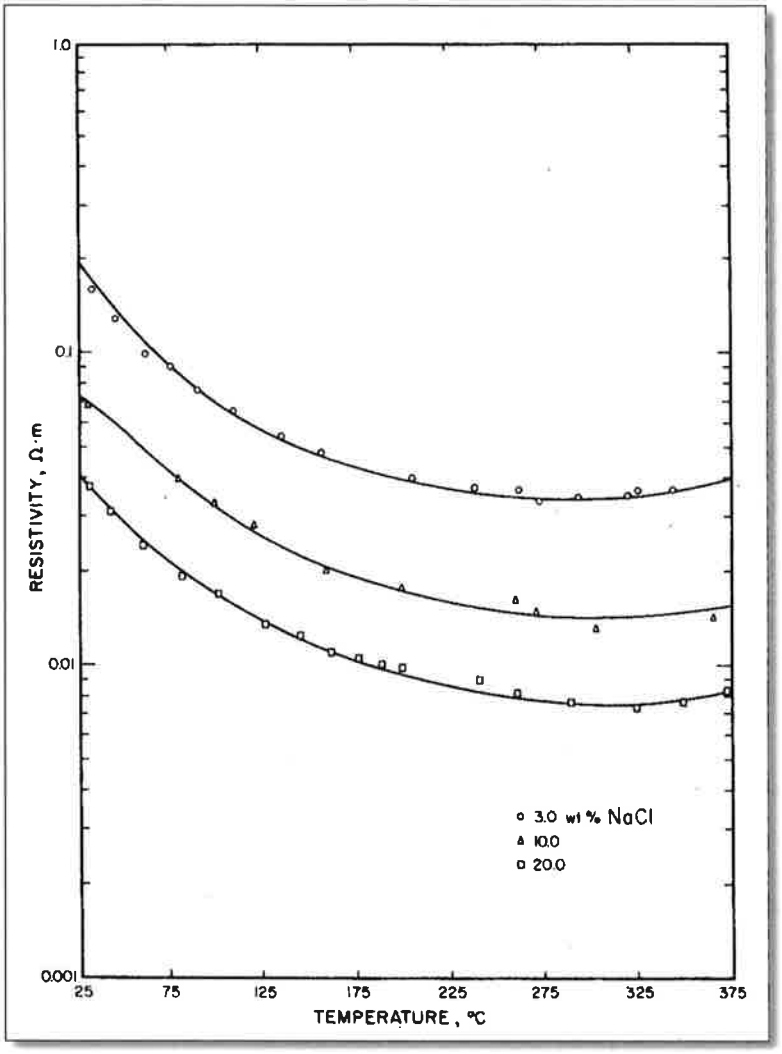

Figure 46. Brine resistivity as a function of ionic strength and temperature (Ucok et al. 1980).

A-9. Mapping the WIPP DRZ Extent with Gas Flow Tests

Gas permeability testing and gas tracer testing were conducted at WIPP to assess permeability and map the extent of the DRZ, and to assess transport pathways through the DRZ (Stormont 1997a). This series of tests is relevant because they conducted low-pressure constant-pressure and falling-pressure gas permeability tests of the types proposed in this report.

Figure 47 shows the results of a constant-head gas permeability borehole testing campaign at WIPP in the N1100 and N1420 drifts (North Experimental Area). This testing showed where high permeability exists, and is associated with the extent of the DRZ. Stormont (1988) published the test plan for these experiments, including a system drawing. Borns & Stormont (1988) discussed the testing results illustrated in Figure 47:

> "Beyond 1 m the flow rates are consistently small (< 1 SCCM [1 standard cubic centimeter per minute]) and within 1 m of the excavation, flow rates vary by many orders of magnitude (1 to 10^3 SCCM)."
>
> "In the 3.5 × 6 m N1100 drift an array of holes was drilled radially to a depth of about 10 m. Gas flow tests were conducted in numerous intervals along each hole. [Figure 48] presents the results as contours of the normalized flowrate magnitude surrounding the drift. These results clearly demonstrate increased flow rates in the immediate vicinity of WIPP facility excavations. The contours in the halite suggest a circular or elliptical pattern centered on the drift with flow rates decreasing radially outward from the excavation. Anomalous zones of high flow were measured in MB139."

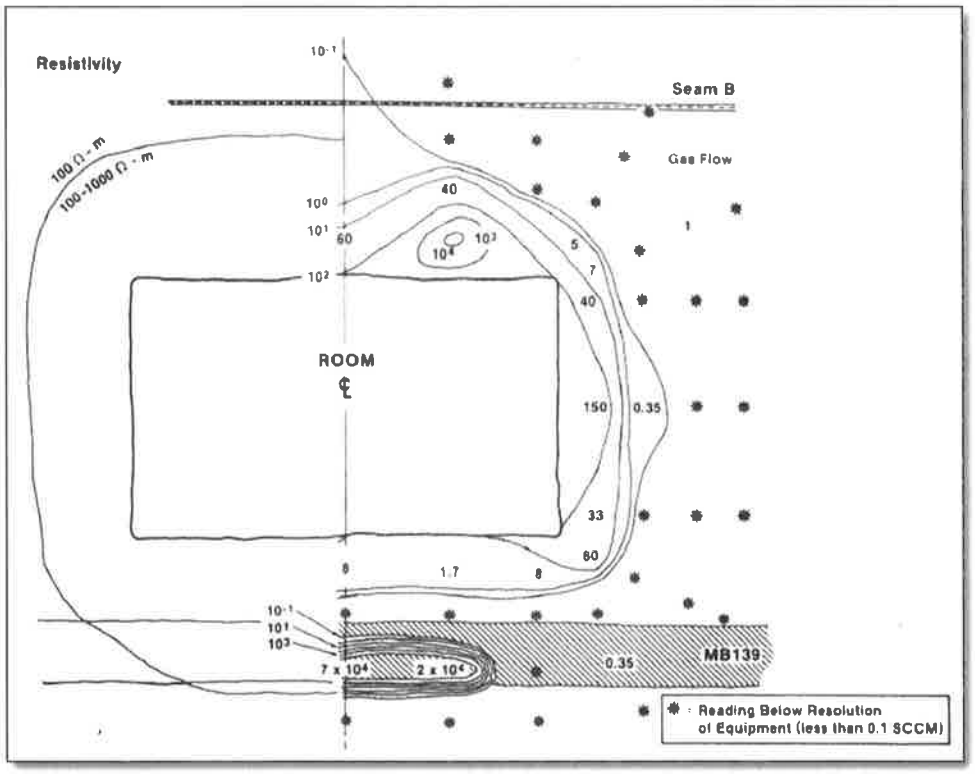

Figure 47. Results of gas flow tests and electrical geophysical surveys (Figure 5 of Stormont 1997a).

Beauheim & Roberts (2002) summarized extensive work to characterize the brine permeability of evaporites at WIPP. Brine permeability is more relevant to long-term flow and performance assessment, but gas permeability is much easier to measure. Gas has a much lower viscosity than brine, and it is largely unreactive with the salt. Gas flow through low-permeability rocks at low working pressures does have to take the Klinkenberg gas-slip mechanism into account, or absolute permeabilities will be overestimated.

A-10. Summary of Brine Production in Boreholes

Shefelbine (1982) summarized early heater tests in salt. Table 12 from his report is expanded here (Table 5) and modified to include additional tests, to separate Project Salt Vault test data, and to change the normalization of brine production (not dividing by wt-% H_2O in salt). Data from Table 5 are illustrated in Figure 3.

Table 5. Water released in bedded salt (expanded from Table 12 of Shefelbine 1982)

Experiment	wt-% H_2O	Heated Surface Area [m^2]	(V)ert. or (H)oriz.; Clay?	Max Temp [°C]	Test Duration [days]	H_2O Collected [g]	Steady Rate [g/day]	Norm. Rate [$g/d/m^2$]
Salt Vault Room 1£	0.25	12.3	V, No	200	572	≥1,710	≥3.0 <14	≥0.24 <1.1
Salt Vault Room 4£		12.3	V, No	175	572		≥1.5 <12	≥0.12 <0.98
Salt Vault Room 5£		12.3	V, Yes	142	580		>70 <650	>5.7 53
SB II – 1§	0.3	0.24	V, No	38	7	0.7	0.03	0.13
SB II – 2§				59	7	0.5	0.04	0.17
SB II – 3§				81	15	1.2	0.03	0.13
SB II – 4§				130	14	11	0.3	1.3
SB II – 5§				200	69	39	0.5	2.1
Thin Disk§	0.3	0.035	H, No	200	42	2.2	0.035	1.0
MCC single§	0.3	0.41	H, No	200	113	190	0.4	0.98
MCC3 – 1§	0.3	0.15	V, No	90	35	1.9	0.014	0.093
MCC3 – 2§				110	28	0.8	0.012	0.08
MCC3 – 3§				145	48	3.6	0.015	0.1
MCC3 – 4§				205	35	5.4	0.12	0.8
WIPP B041¥	0.22 to 0.75*	8.61	V, Yes	130	600	37,000	50	5.8
WIPP B042¥		7.17	V, Yes	130	600	35,000	50	7.0
WIPP A1041¥		7.17	V, Yes	50	425	4,200	8.5	1.2
WIPP A1042¥		7.17	V, Yes	52	425	4,300	9.5	1.3

* 0.22 wt-% water content reported for clean WIPP halite, while 0.75 wt-% water content reported for argillaceous WIPP halite (Finley et al. 1992; Appendix D)

§ data from Shefelbine (1982)

£ data from Bradshaw & McClain (1971)

¥ data from Nowak & McTigue (1987)

Appendix B EXPERIMENTAL SEQUENCE

This appendix presents a high-level chronological summary of the testing

B-1. Borehole *in situ* Testing

1. Prior to drilling boreholes, map visible/accessible geology and stratigraphy in the access drift at the test location.
2. Core test borehole (samples to be preserved immediately to prevent dry-out, for use in laboratory measurements) and drill surrounding smaller-diameter observation boreholes.
3. Before heating:
    a. Visually characterize borehole surface (i.e. azimuthal borehole image log), observing presence and locations of unmapped clay stringers, spalling, open cracks, efflorescence, and liquid brine.
    b. Measure and record borehole dimensions (collar location and borehole diameter, length, orientation, and straightness).
    c. Perform gas flowrate packer tests at 30 cm [1'] intervals along the borehole to characterize damaged salt as a function of depth. In the test borehole, use dry N_2 for gas flow tests. In observation boreholes use mixtures of N_2 carrier gas with <10% Ar and Xe tracers.
    d. Mix and emplace cement sample to end of test borehole.
    e. Install electrical resistivity testing equipment in adjacent observation boreholes. Conduct an initial ERT survey before installing further metal components in observation and test boreholes.
    f. Install heater, packer, and sensor package into test borehole. This package should be initially assembled and tested in the laboratory to confirm correct wiring and plumbing.
    g. Add D_2O to interval in observation borehole, isolated with multiple plugs or packers.
    h. Begin continuously monitoring RH, barometric pressure, and air temperature in access drift.
    i. Install temperature sensors into observation boreholes.
    j. Install AE sensors by setting them at the end of observation boreholes via epoxy or grout. Install any active ultrasonic sources (other than piezoelectric AE sensors) in different intervals of the same boreholes.
4. During test (heating):
    a. Baseline monitoring will be conducted under isothermal conditions for two weeks before turning on the heater, to gather background data and to allow direct comparison of some results from the first two boreholes (i.e., assess heterogeneity and repeatability).
    b. External (access drift):
        1. Continuously monitor drift air conditions including temperature, barometric pressure, and RH.
    c. In test borehole:
        1. Monitor salt movement due to creep and borehole closure by collecting data from extensometers or BPCs in observation boreholes.
        2. Monitor borehole closure around heater block in test borehole via LVDT gauges.
        3. Monitor temperature in both radial and azimuthal profiles via RTDs.
        4. Collect 2-3 gas samples per week during test (starting with samples before heating).
        5. Collect 2-3 brine inflow samples per week during test (starting with samples before heating).
        6. Monitor flowrate, temperature, and pressure of circulating N_2 inflow.

7. Monitor flowrate, temperature, pressure, and RH of circulating N_2 outflow stream at CMH.
8. Passively monitor AE generated during heating and cooling.
9. Periodically conduct tomographic ultrasonic wave surveys using AE network.

d. In observation boreholes during test:
   1. Monitor radial profile of temperature via RTDs in two boreholes at different distances from the test borehole.
   2. Perform gas flowrate tests to characterize permeability of borehole as a function of depth during the test. Use gas with minor tracers.
   3. Perform electrical resistivity tomographic surveys between two observation boreholes (on either side of test borehole) to characterize changes in brine content with time.

5. Post-heating (for at least two weeks after the end of heating):
   a. In test borehole:
      1. Continue to monitor temperature in both radial and azimuthal profiles via RTDs.
      2. Continue to collect gas samples during cool-down part of test (possibly higher frequency).
      3. Continue to collect brine inflow samples during cool-down part of test.
      4. Continue to monitor flowrate, temperature, and pressure of circulating N_2 inflow.
      5. Continue to monitor flowrate, temperature, pressure, and RH of circulating N_2 outflow stream with CMH. There will likely be a pulse of increased brine inflow after turning off the heater, so the N_2 rate may need to be adjusted, or higher-frequency CMH readings may needed.
   b. In observation boreholes:
      1. Continue to monitor radial profile of temperature via RTDs in two boreholes at different distances from the test borehole.
      2. Continue to perform gas flowrate tests to characterize permeability as a function of depth during cooling.
      3. Perform electrical resistivity tomographic surveys between two observation boreholes (on either side of test borehole) to characterize changes in brine content with time.
6. Post-test (after heating and cool-down testing periods):
   a. Remove packers, plugs, and heater/sampling equipment from test borehole. Remove non-destructively if possible.
   b. Visually characterize borehole surface (i.e. azimuthal borehole image log), observing heating-induced damage, spalling, and open cracks, efflorescence, and liquid brine.
   c. Measure and record post-test borehole dimensions (diameter, length, and orientation).
   d. Perform gas flow tests at 30 cm [1'] intervals along the borehole to characterize damaged salt as a function of depth.
   e. Perform post-test ERT survey, once metal components have been removed from test borehole (for comparison with pre-test survey before metal components were installed).
   f. Collect efflorescence and precipitated salts deposited in borehole, preserving them for quantitative analysis of D_2O content and mineral composition (preserve to prevent dry-out).
   g. Sample cement plug by coring.
   h. Collect salt cores from around borehole and perform laboratory analysis.
      1. Some samples should be near the heater borehole, to observe high-temperature effects of fluid inclusions, dihedral angle, and any dissolution due to migration of steam through the salt (preserve samples to prevent dry-out).

2. Samples should be collected between the heater and observation boreholes to observe the distribution of D_2O in the intact salt porosity (preserve to prevent dry-out, including additional fractionation of water in samples).
3. Collect one core that intersects test borehole at an angle to test interval borehole, to observe how any changes to salt from heating vary moving away from the heater.

B-2. Laboratory Core Sample Testing

Laboratory testing on solid salt is summarized. Tests do not necessarily follow a strict sequence. Some laboratory tests could be conducted much later, if samples are properly preserved. Most of the core or solid salt analyses will be performed on sets of samples collected both during drilling the test hole (pre-test) and from the test interval after heating (post-test). Analyses will include the following tasks:

- Determine mineral distribution in core from both before and after testing by thin-section and X-ray diffraction.
- Determine elemental composition of solid samples from X-ray fluorescence and SEM/EDS.
- Determine fluid inclusion features such as size, frequency, brine chemistry.
- Characterize flow properties in core including porosity and pore size distribution (Hg-injection porosimetry).
- Characterize three-dimensional pore morphology, pore connectivity, micro-mechanical defects, and pore-grain dihedral angles using serial imaging methods, including: micro-CT, FIB-SEM, multi-beam SEM, STEM, the Robo-Met.3D optical imaging/polishing tool, and SANS.
- TGA will be used to analyze volatile content of salt samples, and may be used in conjunction with a gas chromatograph to quantify the composition of gases evolved during heating.
- Precipitated salt (i.e., efflorescence) samples scraped or cored from the borehole wall will be analyzed using similar methods used on intact salt.
- Gas chromatography will be used to analyze head space that develops after dissolving salt in de-aerated water inside a vacuum container.

B-3. Laboratory Liquid/Gas Sample Testing

Laboratory tests on fluid (i.e., liquid and gas) samples are summarized. Tests do not necessarily follow a strict sequence. Some laboratory tests could be conducted much later, if samples are properly preserved.

From the liquid brine samples collected during testing, perform the following tasks:

- Analysis of major and minor ions by ion chromatography and inductively coupled plasma mass spectrometry.
- Analysis of stable water isotopes using CRDS.
- Brine electrical conductivity, pH, alkalinity, total dissolved solids, fluid density, and equilibrium RH will be estimated using appropriate laboratory methods.

From the gas samples collected during testing, including both the borehole gas collection system and any samples of the drift air collected, perform the following tasks:

- Analysis of major gas components using gas chromatography (will be mostly N_2 and H_2O).
- Analysis of stable water isotopes using CRDS.
- Quantification of naturally present noble gases (e.g., He and Ar) that may have started off dissolved in brine or contained in salt grains, and were released from the salt during heating. These gases should be identifiable via gas chromatography.
- Consideration should be made for condensable components in the gas stream that might have entered the sample container, but may not remain in gas form in the laboratory during testing (e.g., H_2O and HCl).

Appendix C NITROGEN TANK LIFETIME ESTIMATE

This appendix presents a preliminary estimate of the required flowrate of dry N_2 gas in the moisture collection system.

The contents of a large N_2 gas tank at STP has a volume of 300 [ft^3] = 8,495 [L]. The gas is dry at first, but for isothermal conditions (30 °C) and atmospheric pressure

$$P_{sat} = 0.0419\ [\text{atm}] \times 0.75\ [\text{salt RH}] = 0.0314\ [\text{atm}] = X_{H_2O}$$

which is equivalent to the mole fraction of water vapor in equilibrium with salt. After circulating through the borehole, we assume the dry gas will be 75% RH and the same volume. At STP, water vapor has the density 0.804 g/L.

$$8{,}495\ \left[\frac{\text{L } N_2}{\text{cylinder}}\right] \times 0.023475\ \left[\frac{\text{L } H_2O \text{ vapor}}{\text{L } N_2}\right] \times 0.804\ \left[\frac{\text{g } H_2O}{\text{L } H_2O \text{ vapor}}\right] = 215\ \text{g } H_2O$$

Appendix A-1.1 indicates between 3 and 5 g/day brine flowed into boreholes in room L4 under isothermal conditions. Assuming a density of 1.16 g/cm^3, this results in 2.6 to 4.3 g/day of H_2O flowing into a borehole of similar size in MU-0.

At a rate of 4 g/day brine production, and the lower limit of N_2 usage (assuming the gas becomes completely saturated as it passes through the borehole), it would be expected at 300 ft^3 tank of N_2 would last at most 53 days.

Leslie McMinn (CONTR)

From:	Leslie McMinn (CONTR)
Sent:	Tuesday, April 30, 2019 2:19 PM
To:	'veal.lee@epa.gov'
Cc:	'Peake.tom@Epa.gov'; 'walsh.jonathan@epa.gov'; 'rosencrantz.ingrid@epa.gov'; 'Stone.nick@Epa.gov'; 'Mocknick, John'; 'betsy.forinash@em.doe.gov'; 'alton.harris@em.doe.gov'; Kirk Lachman; George Basabilvazo; Mike Brown; Russ Patterson; 'Shoemaker, Paul - SNL'; 'klkuhlm@sandia.gov'; 'Elkins, Ned - LANL'; 'dozier@lanl.gov'
Subject:	Response to the EPA Letter dated March 26, 2019 and Status on the Salt Disposal Investigation and Salt Defense Disposal Investigation at the Waste Isolation Pilot Plant
Attachments:	Enclosure 2.pdf; Enclosure 3.pdf; 19-0016 Ltr.pdf; Enclosure 1.pdf

Please see the attached correspondence. If you have any questions, please contact Mike Brown at (575) 234-7476, or George Basabilvazo at (575) 234-7488.

Thank you,

Leslie McMinn

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