LANL Presentations to WM2019

Fuel Cycle Research & Development

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Milestone M4SF-19LA01030304

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APPENDIX E

NTRD DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	M4SF-19LA010303042: LANL Presentations to WM2019
Work Package Title and Number	SF-19LA01030304 Salt International Collaborations - LANL
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Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-1 ☐ Nuclear Data	☐ QRL-2	☐ QRL-3	☒ QRL 4 Lab QA Program[3]

This deliverable was prepared in accordance with Philip H. Stauffer, Los Alamos National Laboratory
(Participant/National Laboratory Name)

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

This Deliverable was subjected to:

☐ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below
Name and Signature of Reviewers	**Name and Signature of Reviewers**
HARI VISWANATHAN [signature]	

NOTE 1: *Appendix E should be filled out and submitted with each deliverable. Or, if the PICS: NE system permits, completely enter all applicable information in the PICS: NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS: NE system or by using the NTRD Document Cover Sheet.*

- *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.*

NOTE 2: *If QRL 1, 2, or 3 is not assigned, then the QRL 4 box must be checked, and the work is understood to be performed using laboratory QA requirements. This includes any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

NOTE 3: *If the lab has an NQA-1 program and the work to be conducted requires an NQA-1 program, then the QRL-1 box must be checked in the work Package and on the Appendix E cover sheet and the work must be performed in accordance with the Lab's NQA-1 program. The QRL-4 box should not be checked.*

Table of Contents

ACRONYMS

DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
FY	fiscal year (October-September)
GDSA	geologic disposal safety assessment
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
NWTRB	Nuclear Waste Technical Review Board
PA	performance assessment
R&D	research and development
SFWST	Spent Fuel & Waste Science & Technology (DOE-NE program)
SNF	Spent nuclear fuel
SNL	Sandia National Laboratories
THMC	thermal-hydrological-mechanical-chemical (also THM & THC)
URL	underground research laboratory
US	United States
WIPP	Waste Isolation Pilot Plant (DOE-EM site)

1. Introduction

The Spent Fuel and Waste Science and Technology (SFWST) Campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) is tasked with conducting research and development (R&D) related to the geological disposal of spent nuclear fuel (SNF) and high level nuclear waste (HLW).

As part of the Spent Fuel and Waste Disposition (SFWD) program within the SFWST, LANL is supporting international collaboration. Our objective is to further knowledge sharing between the US and Europe on key technical issues related to salt. European experience may help LANL with some outstanding technical issues, including capillary behavior of run of mine salt, and acid gas generation. Discussions of measurements techniques existing in Europe may allow the US to generate new capillary data for mined salt that will improve model predictions for thermal waste behavior. US experience with mineral phase changes and the release of water through heating may help the Europeans to better understand the complexities of bedded salt formations.

LANL's primary international activities in the first half of FY2019 were centered on presentations at the international Waste Management Symposia 2019, held in March 2019 in Phoenix, AZ. LANL led three presentations at this event, including two oral presentations with associated technical papers (Bourret et al., 2019; Boukhalfa et al., 2019) and one poster (Stauffer et al., 2019). In the following sections we present each of the papers, presentations, and posters from this meeting. The oral presentations were presented in Session 015, Scientific, Strategic and Conceptual Contributions to Deep Geological Repository Siting Process. This session included presentations from projects in Germany, France, Australia, Israel, and the USA. Our team represented the only US HLW siting activity in this session, highlighting the benefit of our participation with this group of international researchers.

Feedback was positive and we made several international connections. Phil Stauffer is now a PAC supporter for the WM Symposium, and attended a breakfast session for planning the WM2020 program. Stauffer is actively working to coordinate a session on HLW with Thilo von Berlepsch (Germany).

This deliverable fulfills the Spent Fuel and Waste Disposition LANL Salt R&D Work Package Level 4 Milestone – LANL Presentations to WM2019 (M4SF-19LA01030304)

2. WM2019 Paper - 19431

This paper, "Development of an Experimental Approach for Thermal Testing in Bedded Salt.", describes the development of heated borehole experiments in WIPP and is related to several recent SFWD milestones (Stauffer et al., 2015; Kuhlman et al., 2017; Johnson 2017; Kuhlman 2019).

Below is a reproduction of the technical paper followed by the slides from the oral presentation that was given on Monday March 4, 2019.

2.1 Technical paper 19431

WM2019 Conference, March 3-7, 2019, Phoenix, Arizona, USA

Development of an Experimental Approach for Thermal Testing in Bedded Salt-19431

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ABSTRACT

Safe and permanent isolation of used nuclear fuel (UNF) and high-level nuclear waste (HLW) is an integral component of the cradle-to-grave philosophy of radioactive waste management. Out of the multitude of rock types considered for the permanent deep disposal of nuclear waste (tuff, shale, granite, clay, and salt), salt has received significant interest particularly because of the advantage offered by salt as an impermeable and dry medium with self-sealing properties. The concept of HLW disposal in salt has been investigated through several testing campaigns in the U.S. and in Germany. Serval knowledge gaps still exist in our understanding of how brine is generated and how it transports under heat generating conditions. These knowledge gaps limit our ability to build a robust safety case for the disposal of heat generating waste in salt. The current manuscript reports on efforts performed to develop a field-testing campaign to study brine and water vapor migration in heated salt. The paper summarizes initial work done in a phased thermal testing program in bedded salt at the Waste Isolation Pilot Plant (WIPP), Carlsbad, New Mexico. The testing to date has been focused on existing boreholes and is being used to 'shakedown' the process for implementation of a more refined testing program that will be implemented in freshly drilled boreholes planned for FY2019. We designed and deployed a heater assembly that consisted of a packer, borehole deformation gauge, heater block, a network of thermocouples, and a pressure transducer setup to measure in situ temperature and pressure. The assembly was deployed in an existing borehole and several heating and cooling experiments were performed to test the performance of the different instruments fielded. We report on the results obtained for brine generation as a function of time and heating and cooling cycles and temperature evolution in the rock salt.

INTRODUCTION

Safe and permanent isolation of used nuclear fuel (UNF) and high-level nuclear waste (HLW) is an integral component of the cradle-to-grave philosophy of radioactive waste management. Rock types considered for the permanent deep disposal of nuclear waste, include: tuff, shale, granite, clay, and salt. Recent work in the US has focused on studying generic salt repository concepts [1-4]. Historically, disposal in salt has received significant interest and was investigated through several testing campaigns in the U.S. and in Germany [5-11]. The disposal of nuclear waste in salt is particularly appealing because of the availability of salt formations that can accommodate the design and construction of repositories and the advantage offered by salt as an impermeable and dry medium with self-sealing properties [12]. Considerations of using salt formations for the disposal of heat generating nuclear waste (HGNW) have had support of the scientific community since early 1950s. Salt formations in the U.S. exist over large geographic areas [13]. Bedded salt formations with thicknesses often between 200 to 600 meters present favorable geologic settings for the construction of nuclear waste repositories. Extensive in situ field testing in salt was performed in the U.S. and abroad to evaluate the performance of salt as a medium for the disposal of nuclear waste.

Studies in bedded salt near Lyons, Kansas in 1965 were carried out to examine the effects of HLW in bedded SALT [13]. Studies were also performed from 1967-1978 [14] in the Asse salt mine to evaluate the behavior of salt in the presence of elevated-temperature HLW [6]. Testing was performed at the Avery Island salt mine in 1979 in Louisiana to examine brine migration and generation resulting from heating. Experimentation with heat generating elements was also carried out at the WIPP facility in New Mexico during the 1980s and early 1990s [10]. A report summarizing previous testing efforts was recently complied [15]. A field testing effort was designed by DOE-EM to address some of the knowledge gaps identified from the review of the historical data and explore a new disposal concept (SDI and SDDI). These drift-scale disposal demonstrations were not implemented because DOE-NE sought an effort that builds on experimentation and an intermediate scale is necessary before any large testing effort is performed. To this end, an intermediate scale testing effort was started to regain hands-on experience by performing in situ testing at WIPP and to address some of the knowledge gaps at a manageable scale. The intermediate testing campaign was developed in the previous years and the test design was published in a consensus document that outlined the goals and approach of performing the test [16].

Better understanding of the source, chemical composition, and fate of brine produced from heated bedded salt (i.e., brine availability) contributes to our ability to accurately predict the long-term performance of salt as a medium for the permanent isolation of nuclear waste [16,17]. Brine availability is relevant to three aspects of the waste isolation safety case: (1) water-driven corrosion of the metal waste packages and waste forms; (2) moisture-enhanced closure of excavations and brine backpressure effects on excavation closure; and (3) short-term drift-scale brine redistribution processes. Past examinations in the laboratory and in the field have shown that gas-free fluid inclusions migrate toward a heat source, brine moves under a pressure gradient near an excavation, and that evaporation and condensation of vapor changes the porosity of the salt near the heat source. However, modeling efforts would be improved by validation dataset regarding the quantity and composition of the brine that is likely to come in contact with the waste packages. Numerical models have been developed to couple the thermal properties of waste packages to the behavior of salt and brine availability in salt. There is a need to collect more experimental data on brine availability from the far field, and to collect datasets that can be used to validate and improve numerical models, which can be used to enhance long-term repository performance predictions. Run-of-Mine (ROM) salt reconsolidation is affected by the amount of available brine [17, 18], with small amounts of brine enhancing reconsolidation significantly. The intermediate scale testing effort described in this document was developed with the goal of answering some of the questions related to brine availability and migration. Additionally, the intermediate heater test is developed to test instrumentation and new analysis approaches for brine and gas sample collection, characterization of the enhanced permeability and porosity surrounding a borehole, and the effects temperature have on these processes in bedded salt.

EXPERIMENT AND MODEL DESCRIPTION

Experimental Design

The intermediate heater test described in this document was implemented in four existing 4.75" sub-horizontal boreholes drilled in 2013. A schematic representation of the boreholes and instrumentation fielded is shown in Figure 1. The heater borehole is about 18' long and received the heater assembly. The two adjacent boreholes temperature borehole which is 19.8' long and a small borehole which is 94 ' were instrumented with thermocouples.

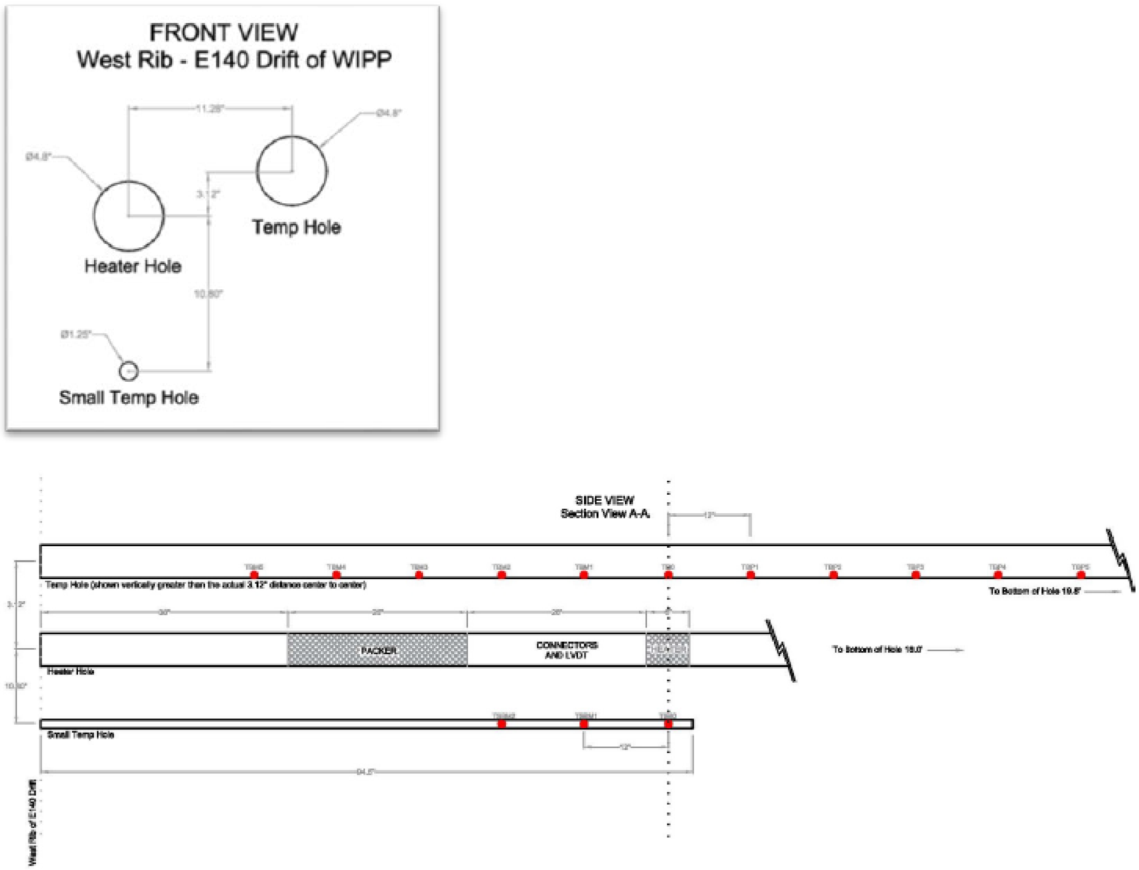

Figure 1. Schematic representation of the positions of the heater assembly and boreholes used positions in the heater test. The top schematic representation shows the front view of positions of the different boreholes looking from the drift area towards the drift wall. The bottom representation show a cross section of the boreholes with the exact locations of the heater packer assembly and instrumentation.

Design and Construction of the Heater Assembly.

The heater assembly used consisted of a stainless steel heater block heated by a Watlow heater cartridge. The temperature of the stainless steel block during heating was fixed to a set point by a temperature controller. The heater assembly was connected a 20 ' packer that was used to isolate the heater interval from the drift area. Thermocouples were deployed in adjacent boreholes were used to measure the temperature in parallel boreholes located a few inches below the heated borehole. The location of the thermocouples and RTDs and their description are summarized in Figure 1.

Design and Construction of the Borehole Closure Gauge.

The heater assembly deployed in the heated borehole was also equipped with a borehole closure gauge (LVDT) used to measure changes in the radial dimension of the heated borehole in multiple directions. The gauge was designed based on a survey of downhole equipment used in the oil and gas industry and past experience with similar measurements that were made at both WIPP and Yucca Mountain.

Of prime concern was the ability of the tool to withstand being moved within the borehole without getting hung up on the wall of the borehole or mineral deposits which have precipitated from brine inflow into the borehole. A picture of the device is shown in Figure 2. The gauge is built around a 1-inch Schedule 40 stainless steel pipe. Four bow springs are used to centralize the gauge in the borehole and deflect as closure of the borehole occurs. The bow springs are made of blue tempered AISI 1095 spring steel. The defection of the bow springs causes the sliding end collar, made of PEEK plastic, to slide along the stainless steel pipe component. The amount of sliding is measured by a linear variable differential transformer (LVDT). An LVDT from eddylab GmbH with a measurement range of 5 mm was used. The LVDT was chosen based on its ease of use, size, and ruggedness. The LVDT has an operating temperature range up to 120 °C (optional 200 °C) and IP68 rating of 10 bar (145 psi). The movement of the sliding end collar was linear throughout the range of different diameters used during the calibration of the borehole deformation gauge. Calibration was performed using a 0.010 inch (0.254 mm) thick × 3 inches (76.2 mm) wide × 18 inches (457 mm) long coiled strip of stainless steel shim material which was marked at various lengths corresponding to known diameters. The measurement of the movement of the sliding end collar is made using a linear variable differential transformer (LVDT) from eddylab® GmbH with a measurement range of 5 mm.

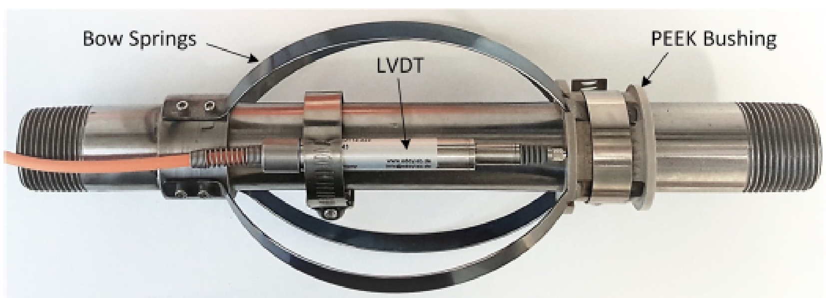

Figure 2. Picture of the Phase 1 LVDT device constructed to measure borehole closure

A schematic representation of the entire assembly deployed in the heated borehole along with a photograph of the actual assembly is shown in Figure 3.

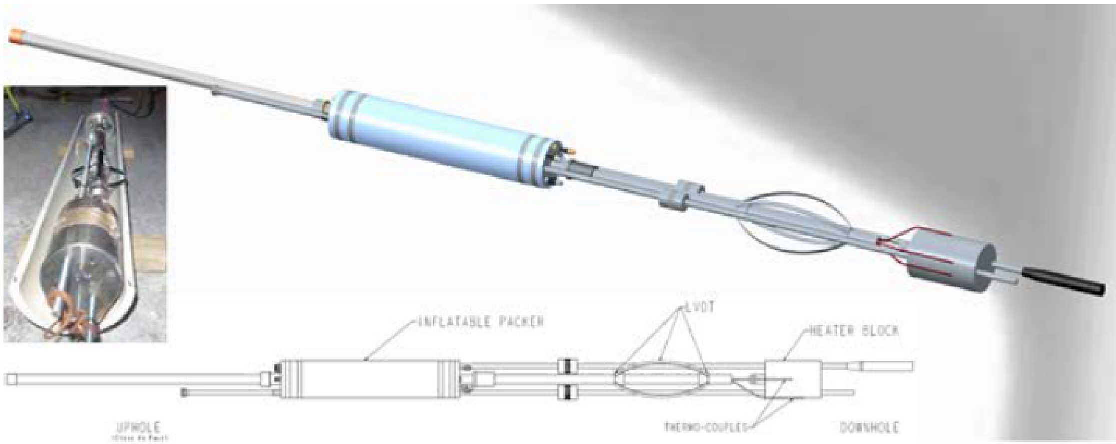

Figure 3. Schematic representation of the heater packer assembly. As-built rendering of Phase 1 heater/packer assembly.

Design and Construction of a Moisture Collection and Permeability Measurement System

The heated borehole was equipped with moisture measurement collection system used to measure changes in the relative humidity of the nitrogen circulated through the borehole. The setup was designed based on previous designs used for early testing performed heated salt experiments [5-11]. This setup was slightly modified to allow measurements of the permeability of the borehole. The system is schematically described in figure 4.

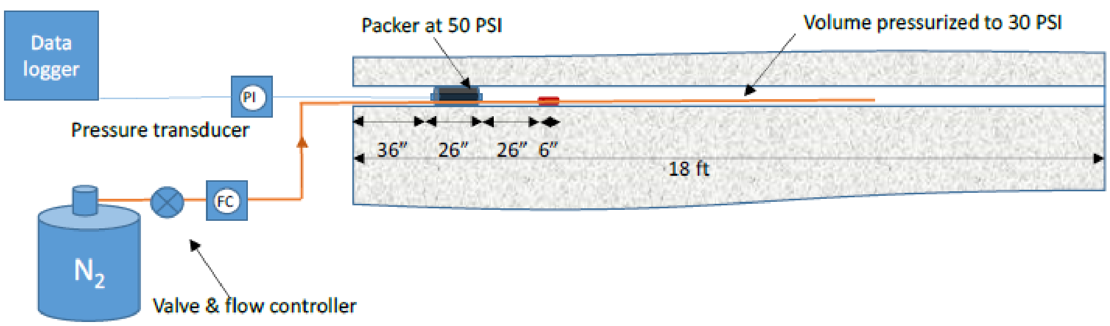

Figure 4. Simplified diagram showing the moisture collection and gas permeability measurement systems.

Dry nitrogen is circulated behind the heater block to drive moisture toward a relative humidity (RH) analyzer and desiccant system downstream. The nitrogen flow rate is controlled by a flow controller placed on the inlet tube. The technical details of the components of the moisture collection system are described in more details in the supporting materials section. The packer, nitrogen bottle, and plumbing are also used to characterize the gas permeability of the borehole/packer system. To perform permeability measurements, the ports connecting the packer to the moisture collection system are sealed and the pressure of the packer set to 50 psi while the pressure of the gas behind the packer is set to 30 psi. After the pressure is stabilized to 30 psi the nitrogen valve is shut to restrict flow and the pressure decay is recorded by a pressure transducer that is connected to the isolated interval behind the packer by a pass-through valve. The permeability of the formation is calculated by fitting the pressure decay curve using a 3D model that assumes a fixed permeability value.

Model Description

To compare results from the borehole heater testing with output from numerical simulations, a numerical model for the borehole configuration was built and was used to perform flow and transport modeling with FEHM. A complete description of the equations in FEHM, including specific modifications for salt can be found in Johnson et al. (2018) [7] and references therein. A more detailed description of the modeling effort related to this test is reported in paper 19192.

RESULTS AND DISCUSSION

Salt Heating Experimental Results and Modeling. Testing was initiated by collecting baseline temperature and moisture release data for up to three weeks prior to the initiation of heating. The first phase of heating consisted of a staged heating in steps to test the system at higher temperatures and also test gas collection for analytical chemistry (Figure 5).

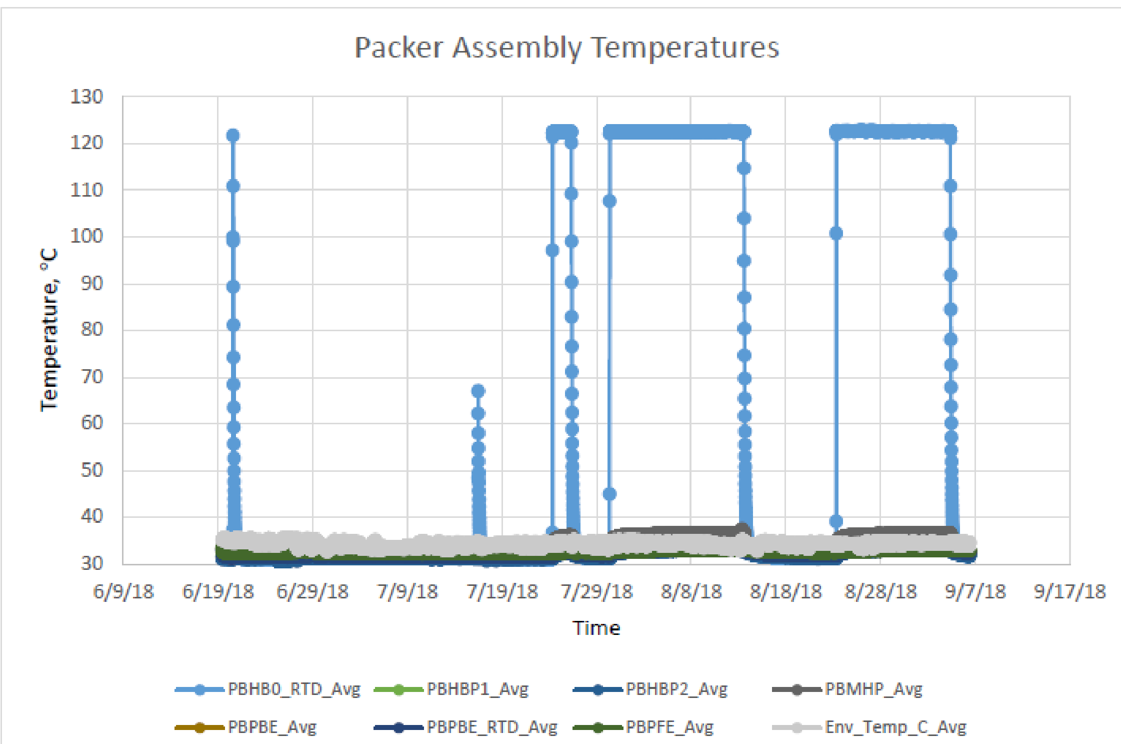

Figure 5. Temperature profiles recorded by thermocouples and RTDs during the heater test in the heated packer borehole. The different colored lines represent individual thermocouples and RTDs positioned at different distances from the heater.

The initial testing was followed by several heating tests during which the temperature of the heater was set to a maximum temperature of 120 °C. Moisture release and temperature evolution in the rock salt were monitored continually. The plots in figure 5 shows the temperature profiles during several heating events recorded by thermocouples and RTDs positioned at different distances from the heater in the heated packer borehole. The data show a very rapid response of the heating assembly (PBHB0). Equilibrium is reached in less than an hour. However, the temperatures drop off significantly a short distance away from the heater block in all directions. The temperature in the isolated interval past the heater (PBHBP1 and PBHBP2), which are positioned at 1 ft and 2 ft from the center of the heater block never exceed 36.5 °C (less than 4 degrees C above ambient). It is also the same for the temperatures before the heater (PBPM, PBPB, PBPF). These temperatures are the same as the drift temperatures and indicate the heater setup lacks effectiveness to heat the air temperature in the isolated interval of the borehole.

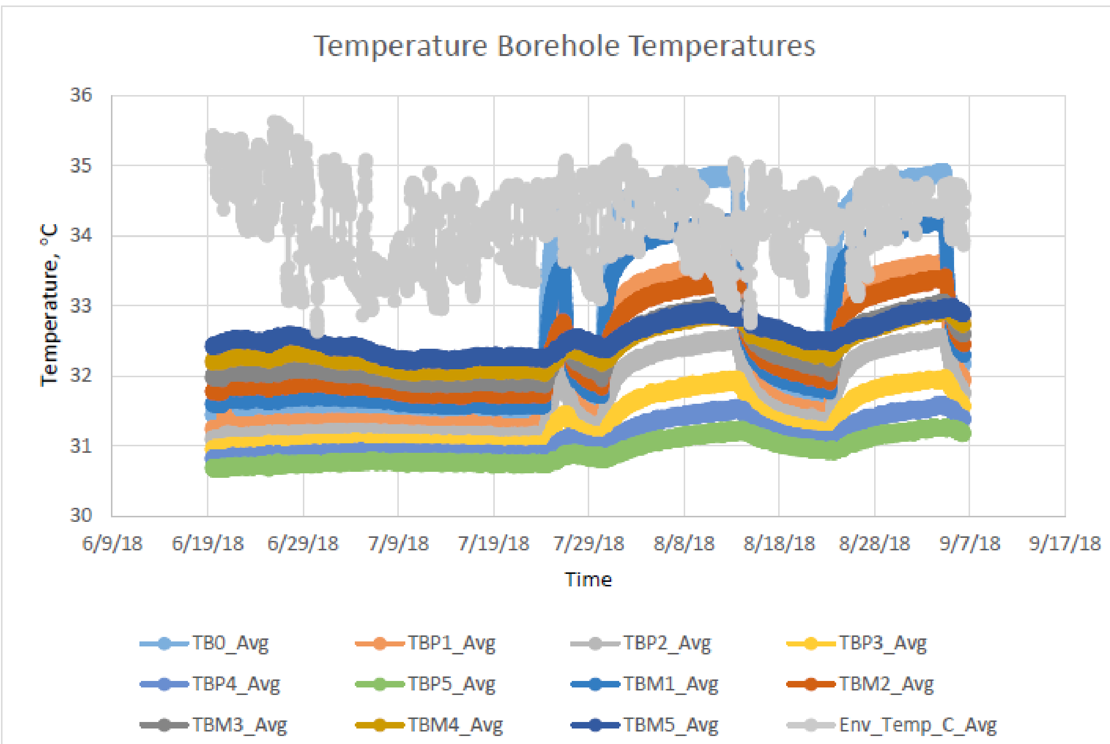

Figure 6. Temperature profiles recorded by thermocouples and RTDs during the heater test in the temperature borehole. The different colored lines represent individual thermocouples and RTDs positioned at different distances from the heater. Exact positions of the individual heaters are shown in Figure 1.

The plot in Figure 6 shows the evolution of the temperatures in two monitoring boreholes situated at 11.3 inches horizontally to the right (TB) and 10.8 inches below the heater borehole (TSB) (Figure 1). The data show a large delay between the response of the heater block and the temperatures at the wall of the observation borehole. The temperature does not reach steady state even after more than ten days of continuous heating. The amplitude of the temperature increase is also significantly smaller than expected. The temperature at TB0, which is immediately below the heater, increased by less than 4 degrees in 10 days of continuous heating. Thermocouples positioned at 1 ft past the heater indicate less than one degree of temperature increase. All thermocouples are reading temperatures below the ambient drift temperature which is anomalously high because of the low flow of air in the drift area. Temperatures in the small observation borehole (TSB) situated at about 7 inches immediately below the heater (See Figure 1) are shown in Figure 7. The temperatures are consistent with the temperatures recorded in the temperature observation borehole shown in Figure 6. The thermocouple in contact with the wall directly below the heater recoded the greatest temperature increase, however the increase is less than 4 degrees. All the remaining thermocouples recorded minor temperature increases. The temperature in the rock salt did not increase significantly and is well below model predictions made before the test was implemented.

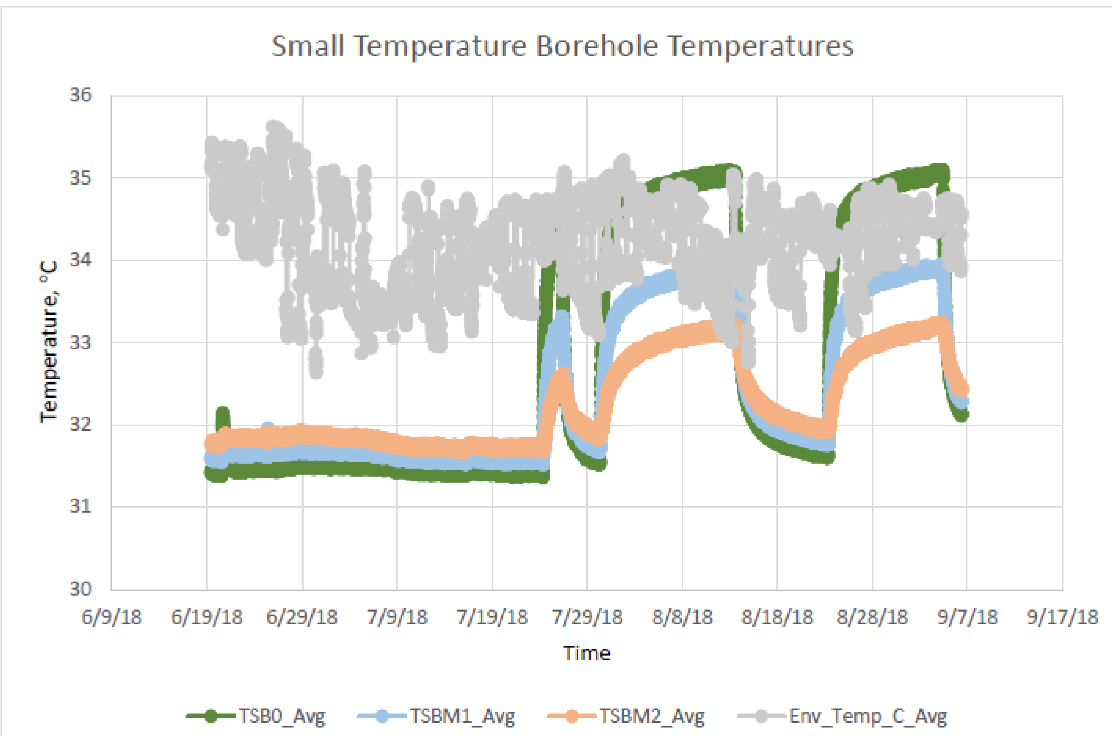

Figure 7. Temperature profiles recorded by thermocouples and RTDs during the heater test in the small temperature borehole. The location of the temperature probe is shown in Figure 1.

We compared results from the borehole heater testing with output from numerical simulations performed using FEHM. The numerical mesh used for all simulations is three dimensional and centered on Borehole SNLCH112 at x = 0 z = 0 (Figure 21). In the directions of the drift face, the mesh extends 1.52 m away from the center in each direction, with up and right being positive values of z and x respectively.

The mesh extends from the face of the drift wall 7 m into the rock salt as shown in Figure 22. The mesh has 238107 volume elements with volumes ranging from 7.05 x 10-4 m3 in the far-field to 1.86 x 10-6 m3 in the center of the borehole. The initial material properties are given in Table 1. The variable thermal conductivity of the rock salt follows the function described in [17] and references therein.

Table 1. Material properties of the simulations

	Porosity	Density (kg/m^3)	Thermal conductivity (W/(m K))	Heat capacity (J/(kg K)	Permeability (m^2)
Rock Salt	0.001	2170	Variable	931	1×10^{-20}
Air	-----	1	0.06	1000	1×10^{-12}
Packer	0.9	300	1	500	1×10^{-26}
Heater	0.001	8000	15	1000	1×10^{-12}

The simulations of the time dependent temperature response on nearby boreholes (TB and TBS, as shown on Figure 1) are shown in figure 8.

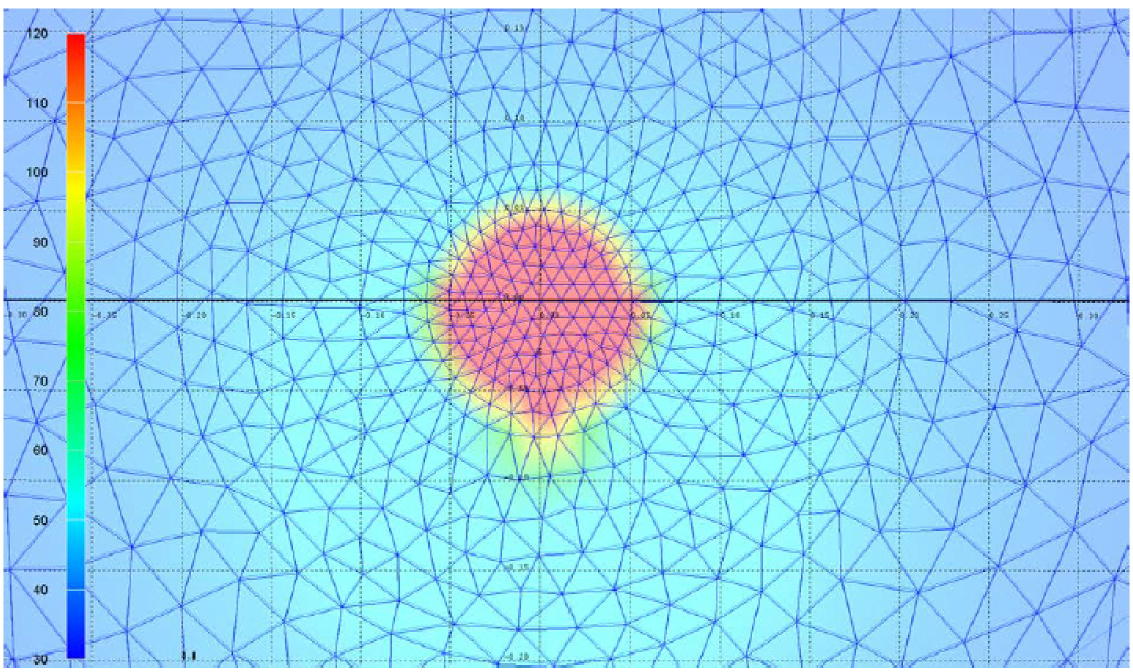

Figure 8. Figure showing simulated temperatures in the rock salt with minimal heater coupling to the rock salt.

The initial simulations that assumed full coupling between the heater and the borehole showed temperatures that were significantly higher than the temperatures measured during the experiment.

Simulations assuming full coupling clearly over predict the actual measured temperatures at monitoring locations TB0 and TSB0. This is attributed to the air gap between the heater bock and the borehole wall which significantly reduced the heat transfer to the rock salt. Air has a low thermal conductivity, and radiative transport from the heater block is likely low at the 120 °C temperature, as stainless steel is not optimized to generate radiative energy. As the coupled area is reduced, simulated temperatures in the surrounding boreholes begin to approach the data (Figure 8).

Moisture Collection and Brine Inflow Measurements

Brine is available in the salt formation in the form of brine inclusions, as intergranular brine, and as water associated with hydrous minerals in the salt. Thermal gradients, dilation, and fracturing of the salt formation are known to facilitate brine migration. The chemical composition of the brine is also affected by brine transport. One of the main objectives of the heated borehole test is to quantify brine inflow into the isolated borehole interval as a function of the temperature, pressure gradient, and heat gradient developed in the rock salt. It is also of great interest to develop an understanding of how the chemical composition of the brine in the borehole is affected by contributions from the three water sources in salt. The experiments were setup to examine brine inflow under isothermal conditions at ambient temperature flowed by examinations of brine inflow under constant heating at a set point of 120 °C. Quantification of brine inflow under isothermal conditions were setup by eliminating all available brine that ponded at the back of the borehole using a vacuum cleaner with a long hose and the isolation of the borehole from the drift area. We used dry nitrogen (99.999% N_2) as a carrier gas to sweep the isolated interval of the borehole and drive any available moisture toward a small polycarbonate chamber equipped with a relative humidity probe that monitors the RH continually. The nitrogen gas existing the RH analysis chamber is redirected towards two cartridges filled with a desiccant that scavenges moisture carried by the carrier gas. The weight of the cartridges was measured daily or as often as access to the underground experiential area at WIPP permitted. Total moisture released from the isolated interval of the borehole was determined by integrating the flow rate and RH readings over the duration of the experiment. The moisture accumulated in the desiccant cartridges is compared to the RH data for validation.

The data in Figure 9 show plots of the RH (green line) over a period of active monitoring. The flow rate was maintained at 200 ml per minute for most of the monitoring duration and completely stopped after 8/17/18. The temperature of the heater in the isolated borehole interval is shown in (blue line) for the same monitoring period. The total extracted moisture captured by the desiccant cartridges is represented by the orange line. The RH plot shows that the reading of the RH of the nitrogen gas exiting the isolated borehole interval decreases from about 50% to about 28%. The initial elevated RH is due to the brine saturating the porosity of the salt in the borehole wall that was present before the start of the borehole isolation. After the initial period of high RH (~50%), the moisture content in the nitrogen stabilized and fluctuated between 20 to 30% RH. There is no obvious correlation between the heater temperature and the RH of the nitrogen gas sweeping the isolated interval of the borehole. The rate of moisture accumulation in the desiccant cartridges was almost constant throughout the entire testing period (Figure 10) and averaged 4.2 g/day.

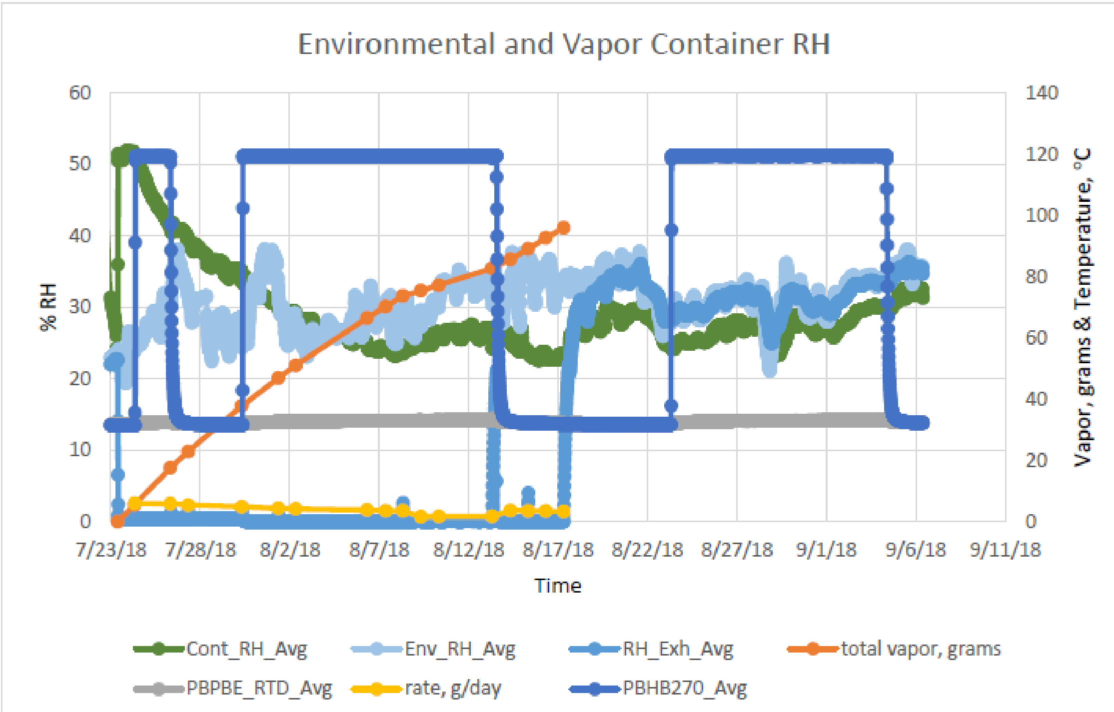

Figure 9. Plot showing water extraction by nitrogen circulation through the isolated interval of the borehole.

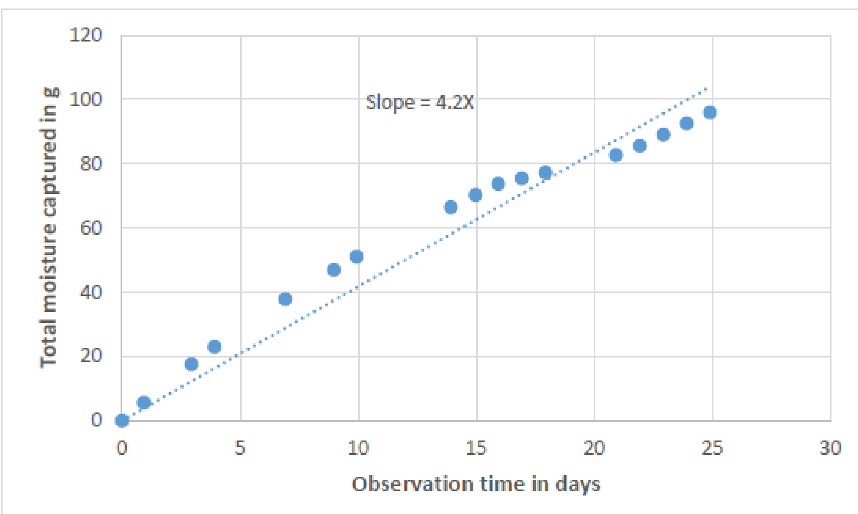

Figure 15. Plot of the total moisture captured by the desiccant cartridges as a function of observation days (Phase 1).

If we assume an average RH of 30 % for the entire observation time and a temperature of 100°F which is close to the measurements shown in Figure 14, then the total moisture carried by the dry nitrogen is estimated to 103 g over the entire observation period. This estimation was calculated by assuming an air density of 1.2 kg/m3, a flow of 200 mL/min (7.7 m3) over the observation time, and a water content of 0.012 g/L. The daily average moisture capture is estimated to be 4.14 g/day. This average is almost identical to the number determined from the weight of the desiccant cartridges shown in Figure 15. The moisture capture using the desiccant cartridges and the RH measurement probe are consistent. However, the lack of an enhanced brine inflow into the borehole during periods of heating is not consistent with our initial assumption. This is due to the lack of coupling between the heater and salt formation which resulted in an inefficient heating of the salt (i.e., only a small temperature rise). The data presented in the next section, which documents the evolution of the rock salt temperature as a function of the heater temperature, supports this interpretation.

Borehole Closure Gauge Calibration and Measurements

Calibration of the LVDT was performed using a 0.010 inch (0.254 mm) thick × 3 inches (76.2 mm) wide × 18 inches (457 mm) long coiled strip of stainless steel shim material which was marked at various lengths corresponding to known diameters. The measurement of the movement of the sliding end collar is made using a linear variable differential transformer (LVDT) from eddylab GmbH with a measurement range of 5 mm. The instrument translates the displacement of the collar into an electric signal. The amplitude of the voltage is generated is directly proportional to the collar displacement which in turn is related to the stainless steel shim displacement caused by the borehole deformation. Measurements performed during the heating cycles caused measurable borehole deformation. However, the voltage calibration setup exceeded the 5 V data logger measurement range and no exploitable data were obtained. The calibration range will be adjusted in the next iteration of the heating and cooling cycles.

CONCLUSIONS

The development and deployment and instrumentation of a heater assembly in existing boreholes underground at WIPP has been extremely valuable. Thermocouples and RTDs performed as planned. We determine that coupling between a stainless steel heater block and salt rock was poor. The temperature in the rock salt was significantly lower than the simulated temperatures calculated assuming full coupling. The next stage of testing will used a different heater design that will improve the coupling between the heating element and rock salt. Moisture collection using desiccants and direct analysis using relative humidity probes yielded comparable results and the results were consistent with prediction obtained using numerical simulations. Heating cooling cycles did not influence brine transport and moisture generation significantly. This is likely due to the low coupling between the heat source and the rock salt which reduced the thermal effect on salt. The borehole closure gage (LVDT) responded to the heating and cooling cycles showing that this setup can be used to gage borehole deformation. However, calibration needed to be readjusted to within the range of the deployed data logging systems. Collection of liquid brine was not possible during this initial testing. This is mainly due to the low yield of brine production during the different heating and cooling systems initiated. Lessons learned from the initial shakedown test are being implemented in the design of the next phase of testing.

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ACKNOWLEDGEMENTS

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2.2 Presentation - 19431

Development of an Experimental Approach for Thermal Testing in Bedded Salt

WM Symposium 2019 - Abstract 19431

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Los Alamos NATIONAL LABORATORY EST.1943

March 4, 2019
Phoenix, AZ

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA
LA-UR-19-21501

Outline

- Motivation
- Research objectives
- Test Location
- Test Bed Outline
- Experimental Results
- Future Work

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Motivation: Salt as Disposal Medium

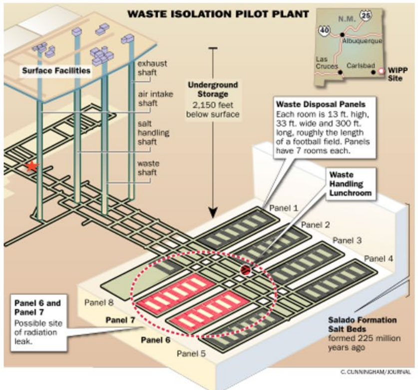
- **Salt long-term benefits as disposal medium**
  - Low connected porosity (0.1 vol-%) and permeability ($\leq 10^{-22}$ m^2)
  - High thermal conductivity (~ 5 W/(m · K))
  - No flowing groundwater (≤ 5 wt-% water)
  - Hypersaline brine is biologically simple, has less-stable colloids
  - Cl (~ 190 g/L) and B (~ 1 g/L) in brine reduce criticality concerns
  - Excavations, DRZ, and fractures will creep closed
  - Mined salt reconsolidates and heals to intact salt properties
- **Technical Objectives**
  - Constrain brine availability and brine chemistry in bedded salt;
  - Collect datasets that can be used to validate numerical models and improve understanding of the constitutive and conceptual models applied to generic salt repository science;
  - Collect field data to improve understanding of acid gas generation mechanisms; and
  - Maintain the legacy of underground tests at WIPP and ensure continuity of knowledge and experience.

Motivation: Brine in Salt

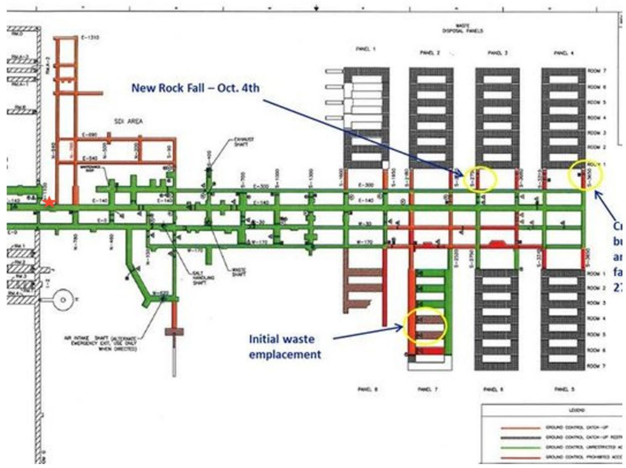
- No flowing groundwater, but not dry (≤ 5 wt-% water)
- Water sources in salt
  1. Hydrous minerals (clay, gypsum, bassanite)
  2. Intragranular brine (fluid inclusions)
  3. Intergranular brine (interconnected pores)
- Brine content correlates with clay content
- Only *intergranular* brine moves under pressure gradient
- Water types respond differently to heat
  - Hydrous minerals evolve water vapor, which can become brine
  - Intragranular brine migrates under thermal gradient
- Brine types have different chemical / isotopic composition

- **Q**: How do 3 brines contribute to *Brine Availability?*

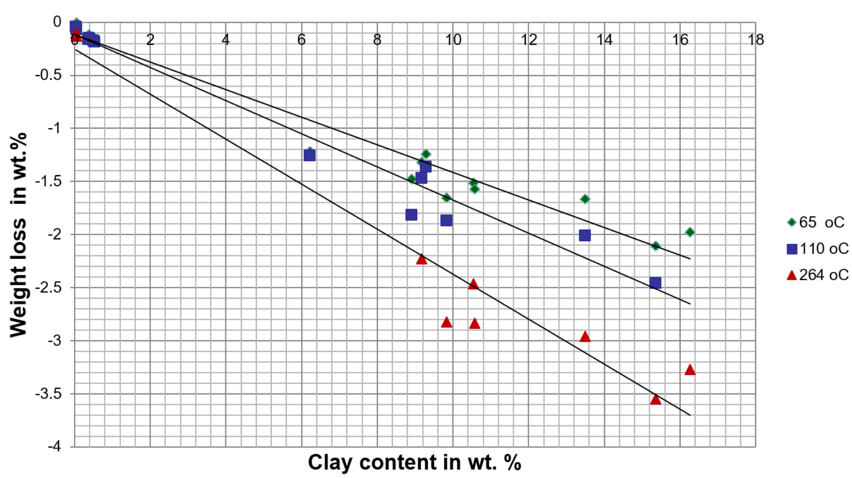
WIPP



Location of phase I borehole testing



WIPP Salt dehydration as a Function of Temperature and Clay Content



- Clay content in salt controls its moisture content
- Moisture release from salt is directly controlled by the salt’s temperature

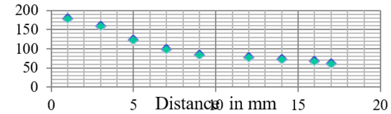
Liquid Inclusions Migration Under Temperature Gradient

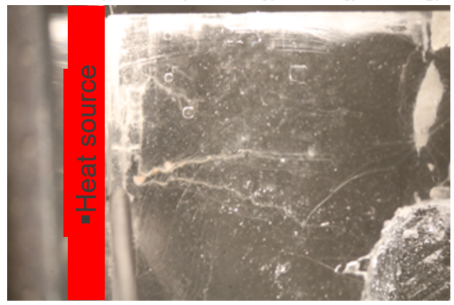
Conditions:

Temperature at the hot surface = 200 ºC
Temperature at the cold side: ambient
Applied temperature gradient 30 hours
Temperature gradient: non linear

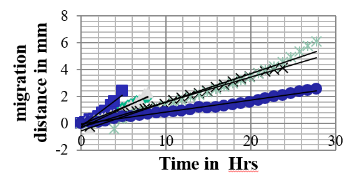
Two step migration mechanism

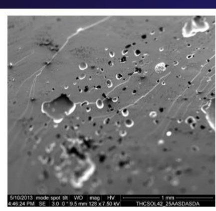
- *Transition state*: Inclusions change shape starting from the cold side
- *Steady State*: inclusions migrate at a constant rate

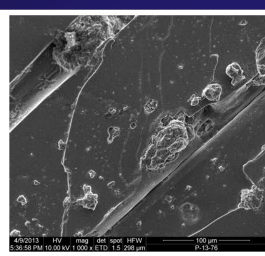


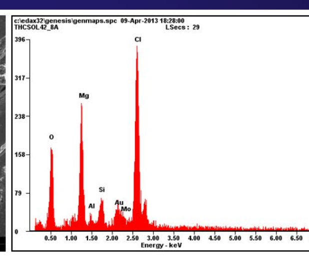


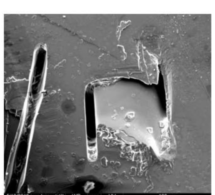
- **Liquid inclusions migrate toward the heat source**
- **The migration rate is mostly affected by the temperature of the salt and the size of the inclusion**

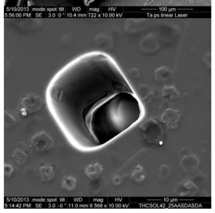


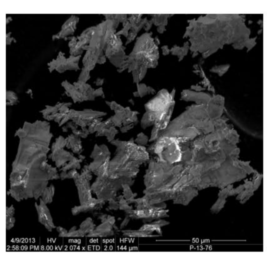


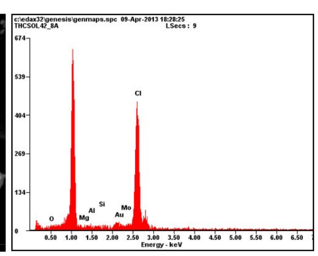








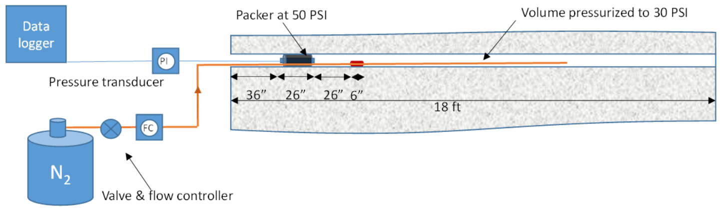


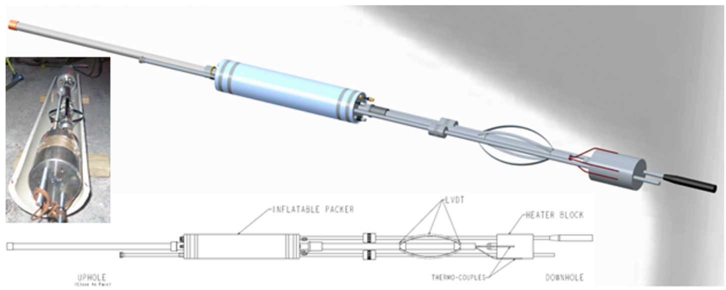


- Dissolved salt is deposited along the migration of channels at crystal edges
- The salt deposited along the migration of channels becomes NCl enriched

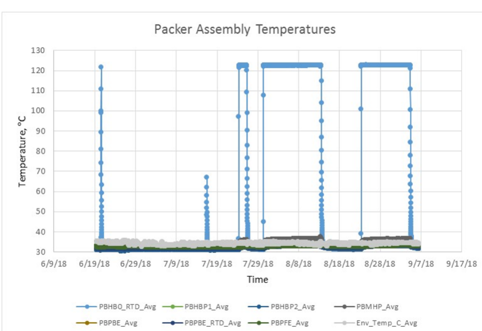
Test Design

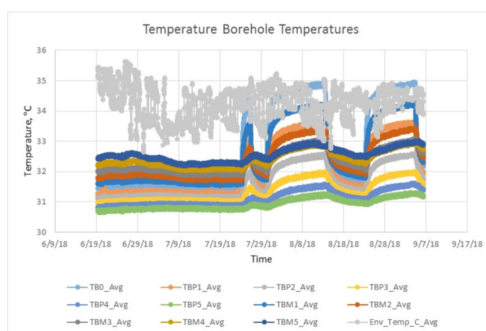
- Behind packer
  - Circulating dry N_2
  - Heater block (1000 W)
  - Borehole closure gage
  - Gas permeability before / after
- Samples/data collected
  - ➢ multiple thermocouple strings
  - ➢ access tube to sample brine at the back of the borehole
  - ➢ nitrogen flow system designed to circulate
  - ➢ moisture accumulation and measurement system
  - ➢ linear variable differential transformer (LVDT) - borehole deformation





Temperature profiles recorded by thermocouples and RTDs during the heater test in the heated packer borehole.

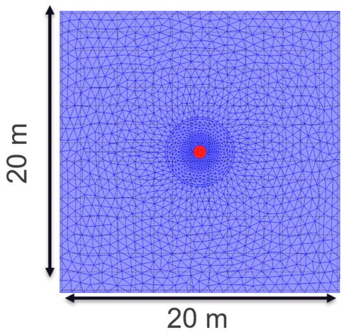




The temperature in the rock salt did not increase significantly and is well below model predictions made before the test was implemented.

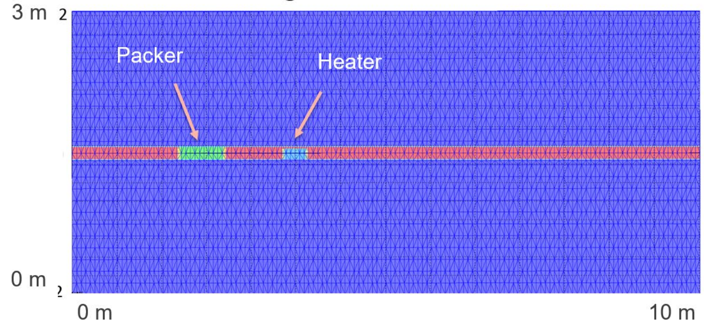
WIPP Heater Test: THC Model of Field Test

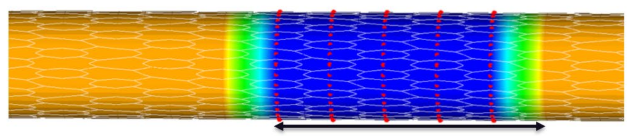
Shakedown Test
3D Borehole heater
simulation domain



Drift view looking
into horizontal hole

Side view along the horizontal hole





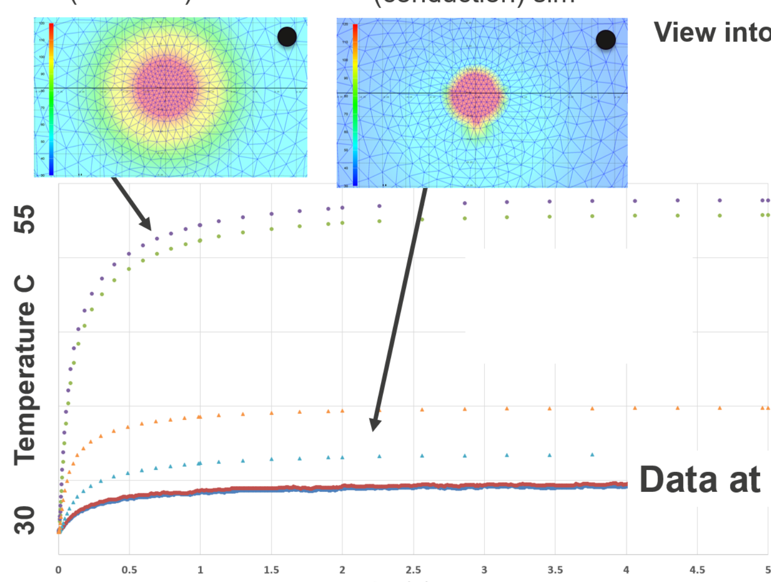
Zoom into the heater mesh

THC Model of Field Test that Accounts for Coupling Between the Heater and Salt

Full contact
(radiation) sim

Small contact
(conduction) sim

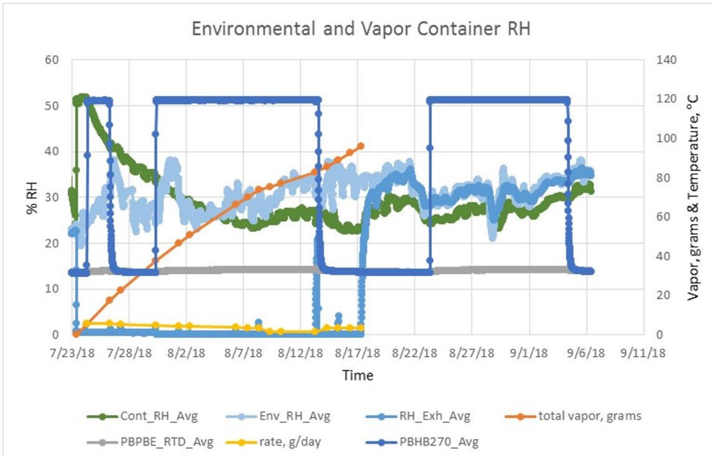
View into heated borehole



Data at 0.3 m

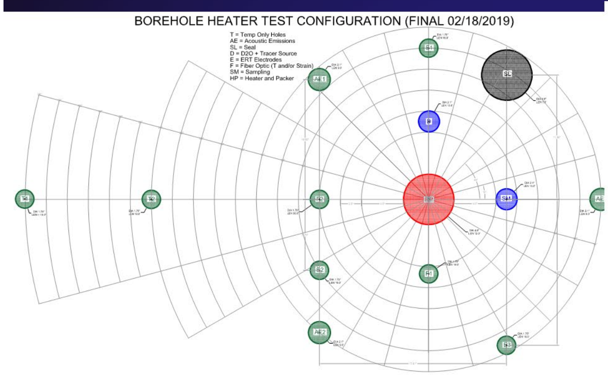
Simulations compared to shakedown data show that infrared heating would better transfer heat to the rock salt.

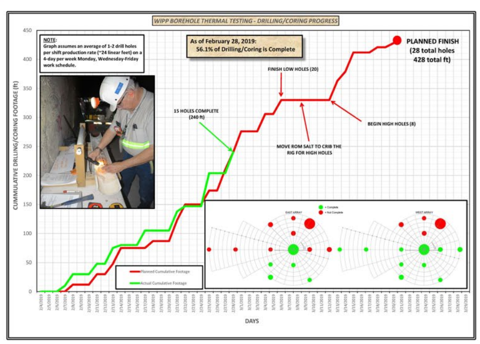
Water Vapor Extraction

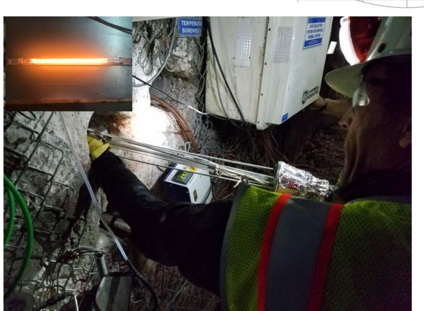


- The daily average moisture capture is estimated to be 4.14 g/day.
- Moisture collection was independent from the temperature of the heater

Future Work







- New radiative heater placed into borehole Feb. 20
- Modeling matches temperature conditions with 750 W heater
- Variable heat conductivity capability appears to representing physical conditions well.

Summary of FY18 and FY19 progress

- Successfully implemented a heater test design and tested instrumentation to monitor temperature, brine flow, and formation porosity.
- Very low coupling between block heaters and salt rock
- Radiative heater was tested and is much more effective at transferring energy to the rock salt
- Monitoring brine sources, inflow, and composition in heated salt through geophysical methods and direct liquid & gas sampling – provides criteria for model calibration and evaluation.
- Characterize brine source and their response to temperature through modeling and parameterization
- THMC process-model developments to better design & interpret field tests
- A new borehole layout and experiment design was developed and is being implemented
- Work on-going to improve results and assess assumptions

3. WM2019 Paper - 19192

This paper, "Experiments and Simulation of a Borehole in Salt to Understand Heat, Brine, and Vapor Migration", describes the simulation of shakedown test results related to our WIPP heated borehole experiments.

Below is a reproduction of the technical paper followed by the slides from the oral presentation that was given on Monday March 4, 2019.

3.1 Technical paper - 19192

WM2019 Conference, March 3 - 7, 2019, Phoenix, Arizona, USA

Experiments and Simulation of a Borehole in Salt to Understand Heat, Brine, and Vapor Migration – 19192

Suzanne Bourret*, Peter J. Johnson**, Shawn Otto***, Douglas Weaver***, Brian Dozier***, Hakim Boukalfa****, Terry Miller*, Philip Stauffer*,

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LA-UR-18-30194

ABSTRACT

Disposition of heat-generating nuclear waste (HGNW) remains a continuing technical and sociopolitical challenge. Numerous concepts for HGNW management have been proposed and examined internationally, including an extensive focus on geologic disposal. One proposed geologic material is salt because of its low permeability and viscoplastic deformation that causes self-repair of damage done to the salt by waste emplacement activities. Evaluating the safety and technical challenges of storing HGNW in a salt repository is an ongoing process involving experiments and supporting numerical simulation. Currently an experiment is underway at the Waste Isolation Pilot Plant (WIPP) to explore how the presence of a heat generating source affects phenomena such as brine migration, vapor transport, and mechanical changes to the bedded salt.

A sub-horizontal heated borehole test is in progress in the underground at the WIPP that includes a centrally located 10.2 cm diameter borehole with an adjustable heater surrounded with smaller diameter boreholes instrumented with thermocouples. The central borehole contains an inflatable packer, heating block, brine sampler, and constantly flowing nitrogen gas circulation system. Air-injection tests performed in the central borehole provide pressure measurements that are used to constrain permeability of the system. The steady-state temperatures, as well as the rise and fall of temperature when the heater is cycled on and off, have been measured for up to 60 days. In the borehole, dry nitrogen gas circulation evaporates water and outflows to a desiccant container where water mass is measured daily during the experiment to quantify vapor removal.

Although this test is a 'shake-down' for a planned second round of fresh borehole testing, we have gathered a rich dataset. These data allow us to build simulations using the Finite Element Heat and Mass transfer code (FEHM) to evaluate the experimental results, determine field-scale parameters, and identify code improvements to reproduce important physical processes that may not be accounted for at present. A 3-D numerical mesh, built using LaGrit software (lagrit.lanl.gov; Miller et al., 2007), includes increasing resolution around the central borehole. Modeling of the experiment allows for determining the local thermal conductivity and permeability of any damaged bedded salt around the borehole, where damage from drilling may change the permeability, porosity and saturation conditions, by parameter testing and inverse methods. Additionally, assumptions about brine and vapor flow and transport are being tested by comparing measured and simulated results. The combination of experimental data and model results provide additional data to help support the safety case for safe and effective HGNW disposition in bedded salt formations.

Initial results from this experiment show that water flow into the borehole is within previous experimental results. Further, we have found that the design of the heater block is restricting energy to flow into the rock salt. Thus, this test has proven useful in design of the next generation experiment where infrared heating may be used to bypass issues caused by air gaps located around the current stainless steel block heater.

INTRODUCTION

The Spent Fuel and Waste Disposition (SFWD) campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) is supporting research programs into nuclear waste repositories in salt formations [1]. Through a collaboration with the DOE Office of Environmental Management (EM), experiments in the underground at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM are being implemented with the help of the WIPP Test Coordination Office (TCO). With a specific objective to improve disposal system performance and safety, Los Alamos National Laboratory (LANL), as part of a multi-lab SFWD team, has been performing experiments and simulations to improve our understanding of the complex and coupled processes that occur when hot waste interacts with salt formations. Research at LANL has focused on using theory, experiments, and modeling in combination with existing data, collected from previous experiments at WIPP and other salt formations, to assess disposal system performance, and reduction of uncertainty associated with heat-generating nuclear waste (HGNW) is a paramount objective of this work. Thermal, hydrological, mechanical, and chemical (THMC) coupling and related modeling are part of this objective. HGNW is defined herein as the combination of both heat-generating defense high-level waste and civilian-spent nuclear fuel.

Salt is an attractive material for the disposition of HGNW because of it is self-sealing, viscoplastic, and reconsolidation properties [2], as well as being a relatively impermeable and low water-content geological material. The rate at which salt consolidates and self-seals depends on the composition of the salt, including its weight percent of accessory minerals, brine content, and temperature. Physicochemical processes, such as mineral hydration/dehydration, salt dissolution, and precipitation significantly influence the rate of salt structure changes. Brine and mixed-phase migration of fluids in salt is important for understanding the self-sealing behavior of a salt repository [3]. In some cases, porosity may migrate towards a thermal source for small-scale fluid inclusions within salt crystals [4], however, when pore space in salt is sufficiently connected for fluid migration to occur, porosity may be expected to migrate away from a heat source [5,2,6]. As porosity changes, the capillarity of pores spaces increase or decrease, changing the brine retention characteristics of salt [7]. Additionally, vapor pressure lowering in brine water controls phase that can also affect porosity migration, and this physical change that is specific to the dissolved salt and accessory minerals for WIPP salt [8]. Field observation from WIPP run-of-mine salt suggests that condensation occurs when the relative humidity of the air is above 25 %. This response is important for retention characteristics of water within pores and the consequent dissolution and precipitation of salt in the presence of a thermal gradient. For HGNW storage at the WIPP, the dynamic conditions of water, brine, and gas content in the salt will change with the air temperature and relative humidity, temperature variation around HGNW over time, and mechanical changes to a borehole or drift. Properly representing brine and vapor migration, porosity and capillary changes, and vapor pressure lowering in simulated representations of HGNW repositories at WIPP is critical for predicting the THMC coupling, which results in deformation and self-sealing behavior of the salt.

In order to include these complex and coupled processes into our models of salt behavior around a heat source, experimentation and comparison to model results is the primary basis for model validation.

New capabilities have been recently added to the Finite Element Heat and Mass Transfer Code (FEHM; https://fehm.lanl.gov), a hydrologic multiphase flow and transport model developed at LANL [9,10,11] to simulate the coupled non-linear physics involved with the THMC changes in granular salt. FEHM uses a finite volume method for solving the conservation of mass and momentum equations, and a finite element approach for solving the stress/strain equations. Recent FEHM capability additions include improved capillary functions, time-variable relative humidity boundary conditions, and non-condensable gas boundary functions to better simulate THMC processes in the underground and match experimental results at WIPP [7,8].

To evaluate knowledge gaps and model capability, a field-scale experiment has been designed and a 'shakedown' experiment (Phase 1) has been performed in the underground at WIPP to explore thermal processes in a borehole and collect multiple datasets to be incorporated into numerical models [12]. This experiment builds on previous experiments and modeling efforts performed to improve our capabilities in predicting long-term behavior of salt and its performance as a safe geologic material for permanent storage of HGNW [13,14,15,16,17,18], and will provide insight and data to aid in planning a similar future experiment in freshly-drilled horizontal boreholes (Phase 2). The test described in this paper (Phase 1) focuses on brine availability to a 10.2 cm diameter sub-horizontal borehole. Quantifying brine availability is a primary goal of Phase 1 and 2 experiments [19]. When natural brine flows into an excavated area, such as a borehole or drift, it is able to enhance waste package corrosion, limit the closure of brine-filled cavities, or enable transport of radionuclides [20]. A secondary goal is to understand brine composition and how it may change due to migration of different water sources toward the boreholes. Data collected during the Phase 1 experiment in response to the imposed constant-humidity and low-pressure conditions at the central borehole will provide a basis for validation of numerical models under controlled conditions that will build confidence when performing similar modeling for THMC process in salt for less controlled experiments in the future.

The Phase 1 experiment and simulation discussed in this paper involves an inflatable packer with a heating block which was placed in a sub-horizontal borehole in a wall of a drift at WIPP, drilled in 2012. The wall is instrumented to determine local permeability, temperature, and brine removal rate around the heater and borehole. This shakedown test designed to be a low-cost method to plan for a future, detailed and controlled upcoming Phase 2 experiment that will use newly drilled boreholes. The results of the Phase 1 experiment are compared to model results to identify shortcomings in our understanding of the physical processes around the heater in salt and also in our simulation approach and capabilities prior to the formal experiment.

EXPERIMENT AND MODEL DESCRIPTION

Experimental Design

Phase 1 testing has a goal of being a low-cost, small spatial-scale experiment performed in order to design instrumentation and methods for further experimentation in the WIPP underground. For Phase 1, a single heater is placed in a borehole to observe brine migration and chemistry, as well as vapor migration in salt in the presence of temperatures up to 120 °C (Fig. 1). Although Phase 2 plans includes drilling fresh boreholes for instrumentation for capturing early-time behavior of brine migration and brine chemistry in newly disturbed salt, Phase 1 testing was performed in existing bore holes drilled in 2012 to allow the collection of preliminary results and data to help in the design of Phase 2. Fig. 2 shows a schematic design of the Phase 1 experiment including instruments in the drift and into the salt formation.

WM2019 Conference, March 3 - 7, 2019, Phoenix, Arizona, USA

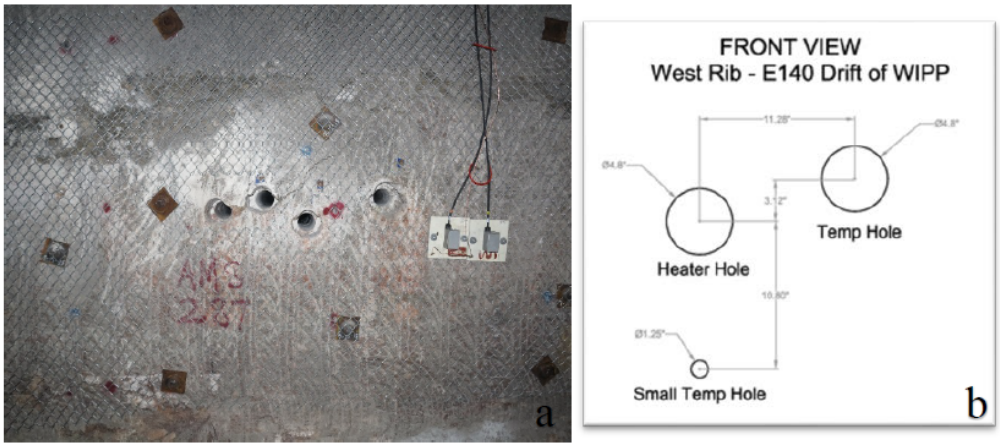

Fig. 1. (a) The face of the wall on which the horizontal boreholes are located for Phase 1 experimentation. Also seen in this picture are the rock bolts and chain link fence used to secure the drift face and reduce the likelihood of rock falls. The image predates the majority of instrument installation, however the power supply junction boxes can be seen to the right of the existing boreholes. The boreholes used in Phase 1 testing shown in schematic view in (b) that includes the heater borehole (HB), a temperature borehole (TB), and a small temperature borehole (TSB).

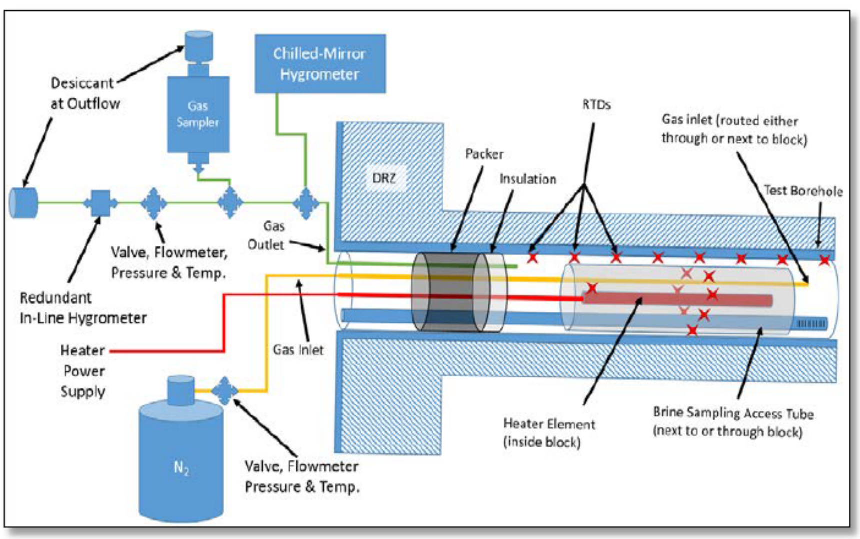

Fig. 2. Detailed view of the borehole and instrumentation to perform a heater test.

The Phase 1 experiment has the following components:

- inflatable packer system to isolate the borehole from the drift area
- heater block
- multiple thermocouple strings
- resistive temperature devices (RTD)
- access tube to collect and sample brine at the back of the borehole
- nitrogen flow system designed to circulate nitrogen behind the packer system within the borehole
- moisture accumulation and measurement system designed to quantify brine leaving the borehole outlet in the vapor phase
- linear variable differential transformer (LVDT) to measure borehole deformation

The instruments are placed into the existing boreholes to measure temperature at multiple distances from the heater block. The heater/packer system and accompanying instrumentation were built into a single train assembly. The components of the assembly in the HB were mounted around a 2.54 cm steel pipe which provide passage for wires from the heater, thermocouples, RTDs, and LVDT. The void space of the pipe is filled with an epoxy resin to provide an air-seal. More details on the experimental and instrument description can be found in Boufkhalfa et al. (2018) [12]. The LVDT measurement parameters do not relate to simulations described in this paper and thus are not discussed further.

Model Description

To compare results from the borehole heater shakedown testing with output from numerical simulations, a numerical model for the Phase 1 borehole configuration was built and used to perform flow and transport modeling with FEHM. A complete description of the equations in FEHM, including specific modifications for salt can be found in Johnson et al. (2018) [7] and references therein.

The numerical mesh used for all simulations is three dimensional and centered on the borehole instrumented with the heating block at $x = 0$ and $z = 0$ (Fig. 3). In the directions of the drift face, the mesh extends 1.52 m away from the center in each direction, with the z-axis oriented with gravity and positive x direction associated with the right-hand side from the drift view. The mesh extends from the face of the drift wall 7 m into the rock salt (Fig. 4). The mesh includes increased resolution radially around the borehole, resulting in 238,107 elements with volumes ranging from 1.86×10^{-6} m^3 in the center of the borehole to 7.05×10^{-4} m^3 in the far-field.

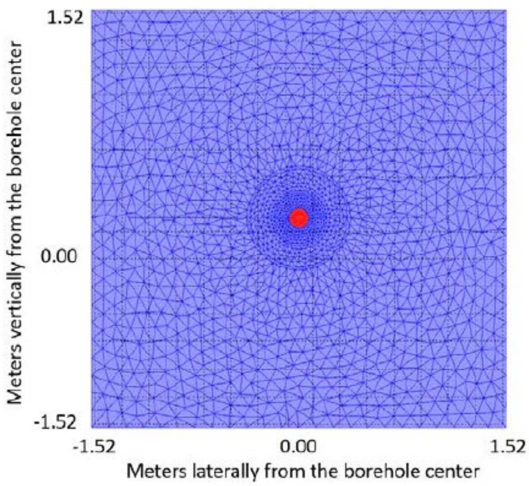

Fig. 3. Drift face view of the numerical mesh showing the borehole as red with the rock salt as dark blue.

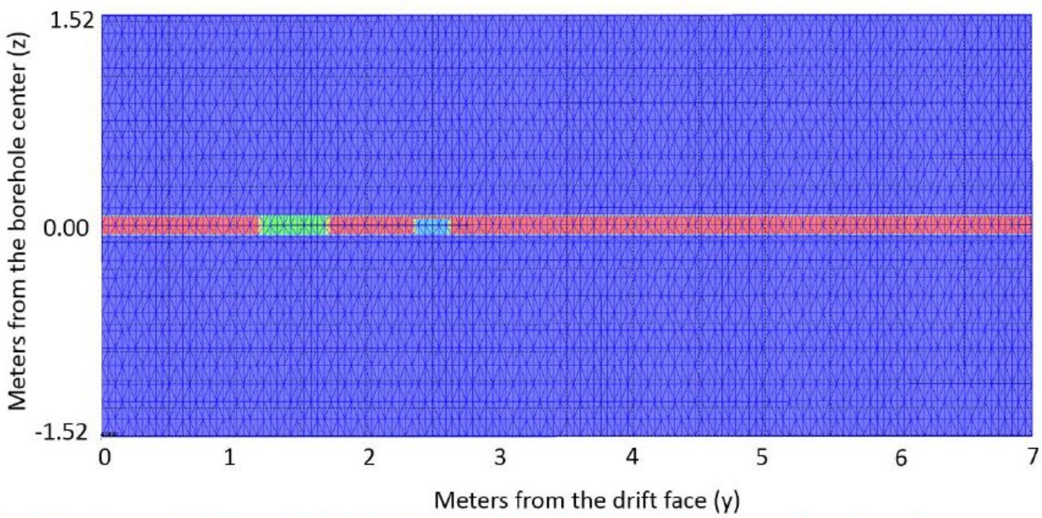

Fig. 4. Side view of the numerical mesh showing the borehole as red with the packer interval as green and the heater as light blue. Rock salt is dark blue.

RESULTS AND DISCUSSION

Air-injection Tests

To determine air permeability around the borehole, air-injection packer tests were performed, and these pressure decay measurements are compared to simulations. During the three injection tests performed in July and August of 2018, the ports connecting the packer to the moisture collection system are sealed, and the pressure of the packer set to 0.3 MPa (3 atm) while the pressure of the gas behind the packer is set to 0.2 MPa (2 atm) .

Once the pressure is stabilized at 0.2 MPa the nitrogen valve is shut to restrict flow, and a pressure transducer records the pressure decay, connected to the isolated interval behind the packer by a pass-through valve. Then, the injection test conditions were applied to the numerical model.

The simulations are run under isothermal conditions with a fixed, average background temperature of 31.5 °C. Pressure in the model is initially 0.1 MPa (1 atm), and the pressure is then increased in the borehole interval behind the packer (y = 1.5 - 7 m) to 0.3 MPa to represent the nitrogen injection. Multiple formation permeability values were simulated and compared to the measurements, and two cases are shown with the measured pressure decay curves in Fig. 5. Even with an unrealistically high permeability in the rock salt (10^{-14} m^2), the model does not predict the rate of decay nor the shape of the decay curve for pressure decay behind the packer, showing a much steeper curve shape and decay rate of the pressure behind the packer in early time (< 0.05 days) and much slower pressure bleed-off at late time (> 0.05 days). An additional case was simulated using an expected value for rock salt permeability (10^{-20} m^2) to test if leakage through the packer could explain the measured pressure decay behavior. For this simulation, the packer was assigned a low porosity (0.001) and a high permeability (10^{-11} m^2) to represent a small leak. Results from this simulation match well compared to the previous case, and the results suggest that the packer or other ports do not have an air-tight seal. A small leak may be due to issues with the epoxy seal around the wires passing through the central 2.54 cm (1 inch) diameter pipe. The formation permeability cannot be definitively determined by the air-injection tests, however, the assumption of very low permeability salt around the borehole, with a value of about 10^{-20} m^2 is not disputed by these results, and is the value used for further simulations; Table I shows the properties assigned to the model materials.

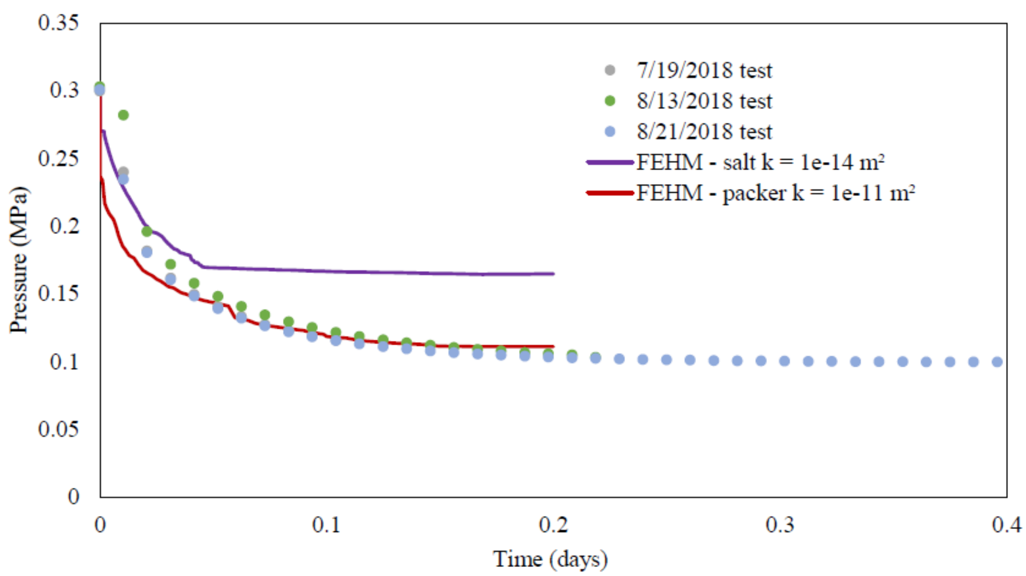

Fig. 5. Experimental pressure decay compared to simulation results.

TABLE I: Material properties of the simulations.

Material	Porosity	Density (kg/m^3)	Thermal conductivity ($W/(m \cdot K)$)	Heat capacity ($J/(kg \cdot K)$)	Permeability (m^2)
Rock Salt	0.001	2170	Variable	931	1×10^{-20}
Air	-	1	0.06	1000	1×10^{-12}
Packer	0.9	300	1	500	1×10^{-26}
Heater	0.001	8000	15	1000	1×10^{-12}

Simulations of Temperature Changes

Thermal properties of the formation salt can be determined through experimentation and modeling of time-dependent heat response to the heater in adjacent boreholes (TB and TSB shown in Fig. 1b). Initial simulations of the Phase 1 experiment assumed full coupling between the heater and the borehole wall in the HB. However, these preliminary simulations over predicted the transfer of heat into the formation when the heater is turn on to 120 °C. This result can be seen in Fig. 6, which shows the measured temperature in TB and TSB compared to simulated results. The featured thermistors TB0 and TSB0 are located on the same depth from the drift wall as the heater in the TB and TSB holes, respectively.

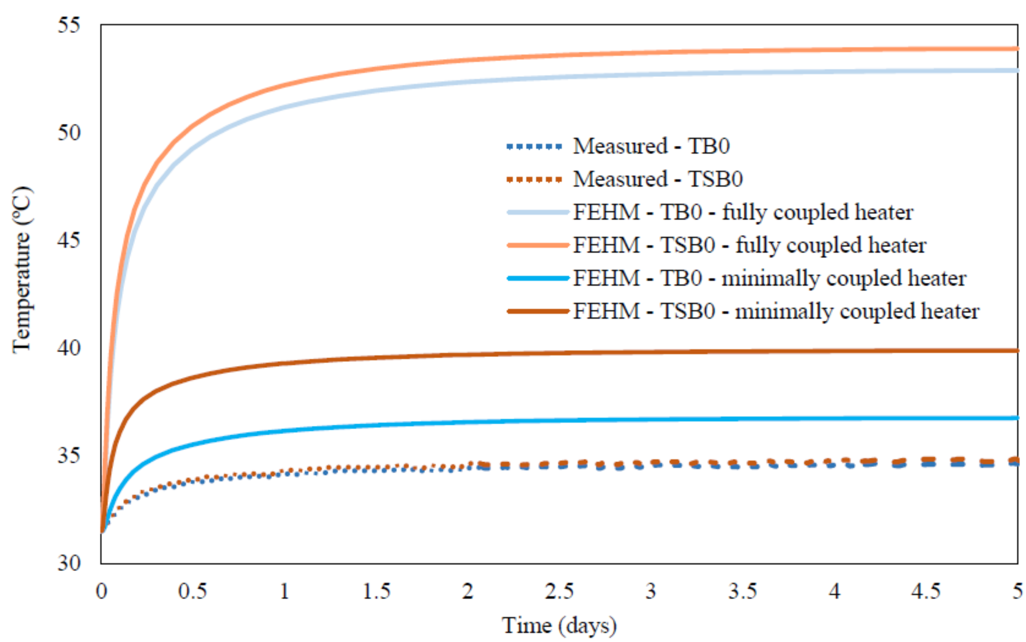

Fig. 6. Measured and simulated temperature during a period where the heater is turned on at TB0 and TSB0.

To address the discrepancy between the simulated and measured temperature results, the simulations were modified to add an air gap around the heater in the HB. While the fully-coupled simulation assumed full contact between the wall and heater, the minimally-coupled heater simulations assume only direct contact to the salt on the bottom of the HB where the heater rests. This allows for thermal insulation around the heater due to the low thermal conductivity of air in the HB. Fig. 6 includes the minimally-coupled simulation, and while this case still over predicts the temperature at TB0 and TSB0, the simulated transfer of heat is much more satisfactorily reproduced if an air gap is assumed to be present. Fig. 7 shows the simulated heat transfer for a cross-sectional slice through the heater when set to 120 °C for both the fully- and minimally-couple cases. The high temperature is clearly more isolated to the heater area as compared to the fully-coupled case, and appears to be a much better representation of the actual physical conditions of the Phase 1 experiment. However, the high temperature of the model prediction at TSB0 may suggest that irregularities in the HB may limit the heaters contact with the walls, and that even less coupling is realistic at the bottom of the borehole. To address this issue in Phase 2, an infrared heater approach is planned to be used in order to heat the surrounding borehole more evenly if contact with the borehole walls is limited due to poor fit of the heater or heterogeneities from drilling.

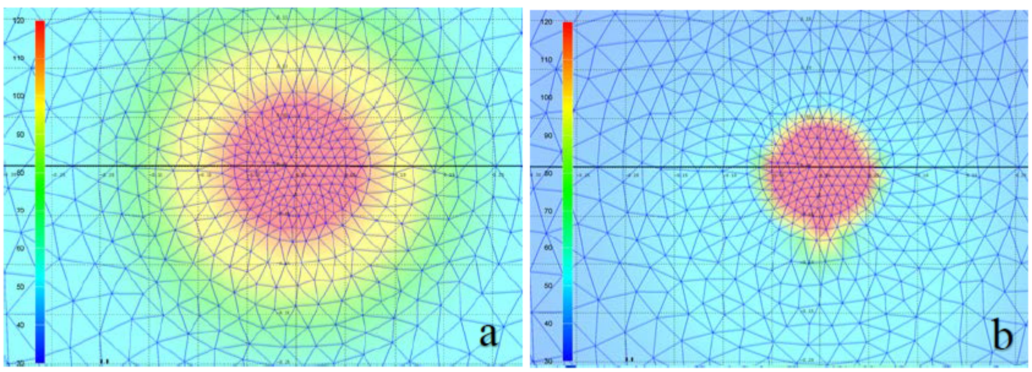

Fig. 7. Simulated temperature in cross-sectional view for the (a) fully-coupled heater and (b) minimally-coupled heater simulations.

Vapor Phase Water Removal

Finally, the rate of moisture removal in the vapor phase is evaluated with experimental and modeled results. During the experiment, nitrogen gas flowed into the borehole at a fixed rate of 200 mL per minute, and gas flowed to an outlet connected to a desiccant container (Fig. 2). The mass of the desiccant was measured daily to quantify water mass removal in the vapor phase from the HB. To simulate moisture removal, two nodes located in the HB are identified to represent the nitrogen inlet and gas outlet as implemented in the experiment. The inlet node (101,068) is located behind the packer, in the center of the heater borehole, 3 m from the drift face (y = 3.0 m). The gas outlet node (66,812) is located just past the downhole face of the simulated packer at y = 1.98 m. A fixed gas flow rate of 3.33×10^{-6} kg/s (200 mL/min) is applied to the inlet node. The inlet node relative humidity is set to 0.001 to allow for inflow of very dry air. The outlet node is specified to maintain the original pressure of 0.1 MPa (1 atm) and any gas leaving the domain will carry with it the water vapor and thermal energy associated with the temperature and relative humidity of the outlet node.

Table I includes the properties used in the moisture removal simulation, however two simulations cases are compared to measured data in Fig. 8: (1) the rock salt permeability is 1×10^{-20} m^2 and (2) 1×10^{-19} m^2.

The initial rate of water removal during the first 2 to 3 days in the simulation over predicts the mass removal for both simulated cases, however, the $k = 1 \times 10^{-20}$ m^2 simulation removes less water vapor than expected following about 5 days since the experiment start. The $k = 1 \times 10^{-19}$ m^2 case has a far better fit to the 25-day experiment results. This result suggest that the salt has a very low permeability that controls the rate that brine can reach the HB during the heater experiments. The rock salt walls of the borehole likely have higher permeability due to damage induced by drilling. Increased permeability in the rock salt surrounding the borehole could allow water to migrate toward the borehole where it would be available for evaporation by the dry nitrogen. We plan to explore a series of additional simulations to determine what parameters may lead to better long term match to the experimental data.

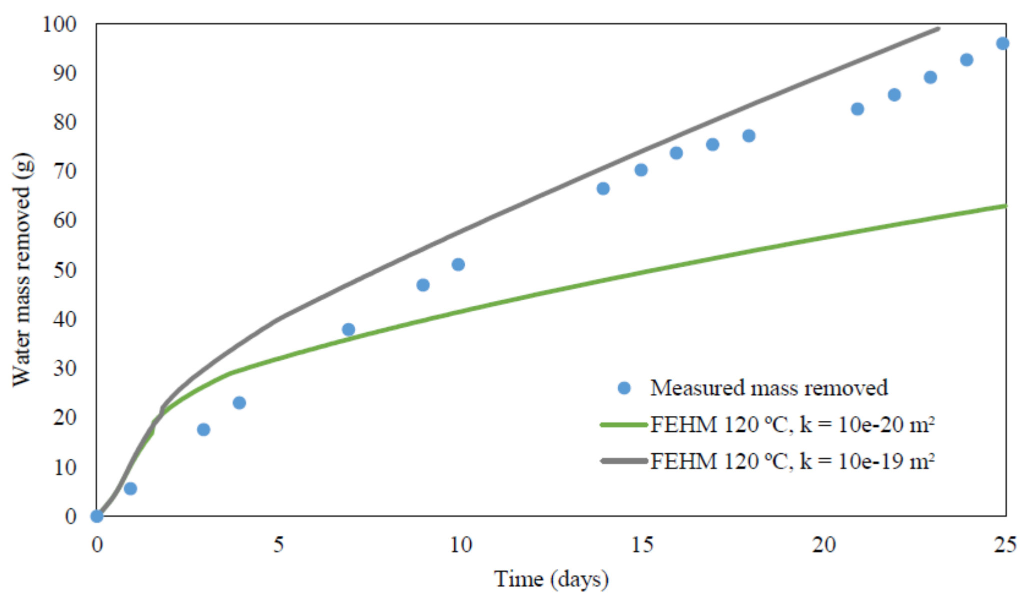

Fig. 8. Measured and simulated results of water mass removal through the nitrogen flow system.

CONCLUSIONS

Shakedown testing of the field equipment for the thermal borehole testing at the WIPP has proven to be extremely valuable for design and installation of a planned Phase 2 in FY2019. The integration of numerical simulations has allowed us to explore unexpected results, such as lower than expected temperatures in surrounding boreholes. The lower simulated temperatures are likely caused by poor coupling of the heater block to the rock salt, leading us to adopt a new infrared approach for heating. Simulations also confirmed a probable leak in the packer system, likely caused by bundling many wires through a 2.54 cm pass-through pipe that was sealed with epoxy. The team is working to alleviate the leakage problem by using a different pass-through design and fewer wires behind the packer. Lessons learned will allow the team to move with much greater confidence and speed for Phase 2.

ACKNOWLEDGEMENTS

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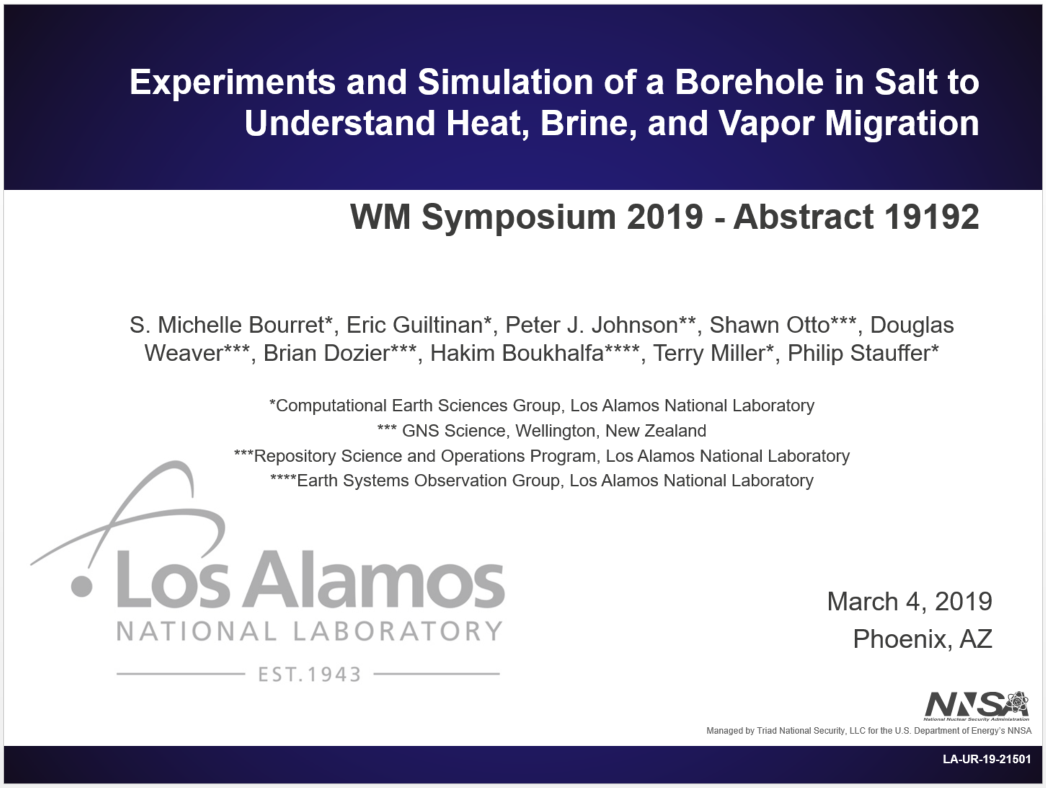

Outline

The face of the wall on which the horizontal boreholes are located for shakedown experimentation.

Los Alamos
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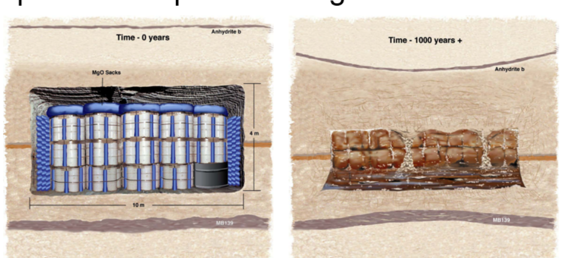
EST. 1943

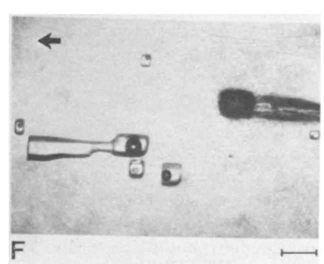
- Background
- Research objectives/motivation
- Coupled processes - **T**hermo/**H**ydro/**M**echanical/**C**hemical
- Methods – FEHM models of experimental results
- Modeling results

Is Disposal in a Salt-Base Repository the Answer?

- Salt is an attractive geological medium due to its impermeability and self-sealing features.
- The response of salt to decay heat from the waste must be well understood.
- There are small amounts of water in salt. This water could be liberated and mobilized, leading to alteration of the salt mechanical properties and potential degradation of the waste package system.



Erickson and Dials, RadWaste Solutions, Jan.-Apr., 24-34, 2011.



Fluid inclusions migrating under a thermal gradient - Carter and Hansen, Technophysics, 93, 1983.

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- Water sources in bedded salt:
  - **Intracrystalline** (brine inclusions)
  - **Intercrystalline** (e.g., mobile “pore fluid”)
  - Water associated with **clay minerals** and polyhalite
- Water may be liberated from brine inclusion migration and clay dehydration (above 65^{o}C)
- Relative humidity of ventilation air

Photo: H. Boukhalfa

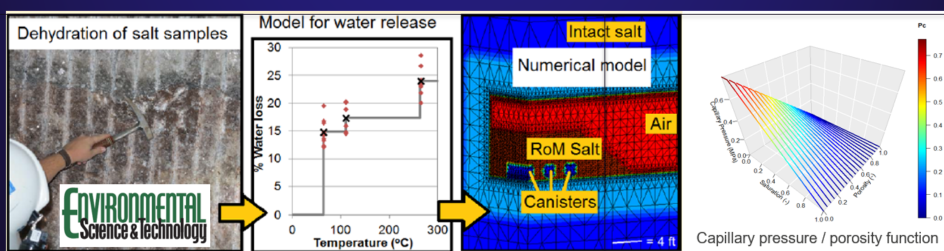

Photo: D. Weaver

Process-level Modeling Goals

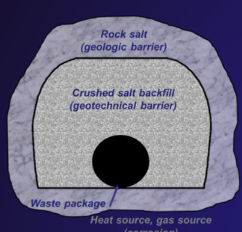
- Simulation tools demonstrate understanding of repository processes
- Gain confidence in long-term predictions
- Explore uncertain processes and inputs prior to designing new experiments to reduce uncertainty
- Integrate process-level physics into the generic Generic Disposal System Analysis (GDSA) performance assessment (PA) tool

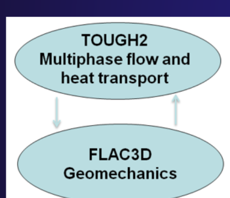
Salt THMC Couplings

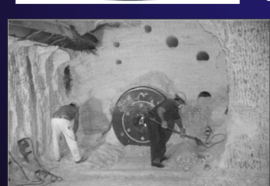
- *Deformation* — ***F****(temperature, stress, time, saturation)*
- *Vapor pressure lowering* — ***F****(capillary pressure, salinity)*
- *Porosity* — ***F****(dissolution, precipitation, stress, strain)*
- *Thermal conductivity* — ***F****(temperature, porosity, saturation)*
- *Permeability* — ***F****(porosity, saturation)*
- *Capillary pressure* — ***F****(porosity, saturation, temperature)*
- *Water vapor diffusion* — ***F****(porosity, saturation, temperature)*
- *Clay dehydration* — ***F****(temperature)*



Importance of THMC Processes





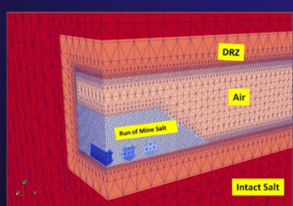


- Performance Assessment
  - Development of DRZ, a potential path for transport
  - Compaction, sealing and healing (solidification)
- Safety Case
  - Post-closure SA [4.2], including barrier / safety function
  - Post-closure FEPs [3.3], including host rock / DRZ
  - Confidence enhancement [4.3], including validation
- Roadmap
  - THMC model development
  - Validation against field (WIPP) and lab experiments
  - THMC model demonstration (long-term, GDSA)
- International
  - Salt constitutive model development and validation with Clausthal Technical University (Germany)
  - Access to field test data in various salt types (e.g. bedded vs. domal salt in Asse Mine URL, possible WIPP contributions)

7

THMC Process-Level Modeling

- Thermal-Hydrological-Mechanical-Chemical (THMC)
- FEHM numerical model simulates small-deformation THMC
- Isolating specific processes allows more rapid validation
- Some processes are validated using analytical solutions (simple) and experiments (complicated)



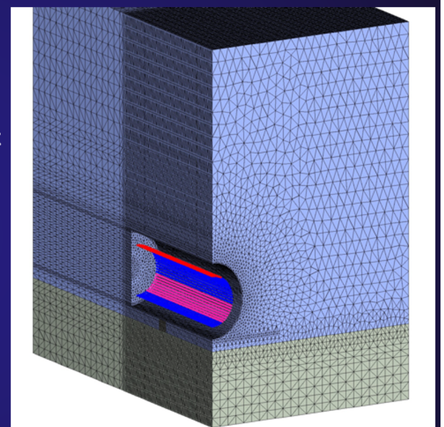
Overview of Activity

Examine heat/brine/vapor/salt interactions related to heat generating nuclear waste

- Improve numerical modeling capabilities (https://fehm.lanl.gov)
  - Validate reactive transport model functions for salt against all available data
  - Identify any gaps in capabilities
  - Improve existing model functions
- Design and execute experiments : generate data to compare to simulations
- Benchmark with other numerical codes PFLOTRAN/TOUGH3

Modeling THMC Processes with FEHM

- **Model physical processes controlling near-field thermo-hydrological-mechanical-chemical (THMC) changes in salt**
  - safe design of experiments and waste disposal
- **FEHM code development (Finite Element Heat and Mass)**
  - FEHM developed at Los Alamos 30+ years
  - Used for 150+ peer reviewed articles
    fehm.lanl.gov/pdfs/FEHM_references_list.pdf
  - Fully coupled thermal, mechanical, chemical, multiphase (gas, water vapor, water, rock)
  - Uses LaGriT: Powerful 3-D grid generation tool



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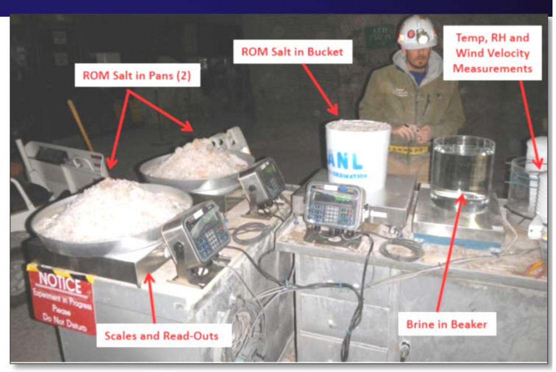
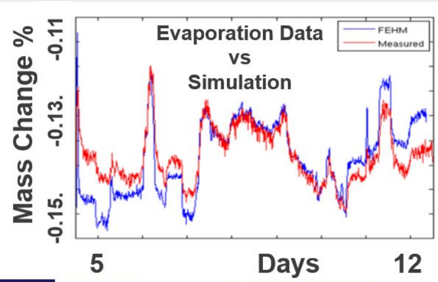
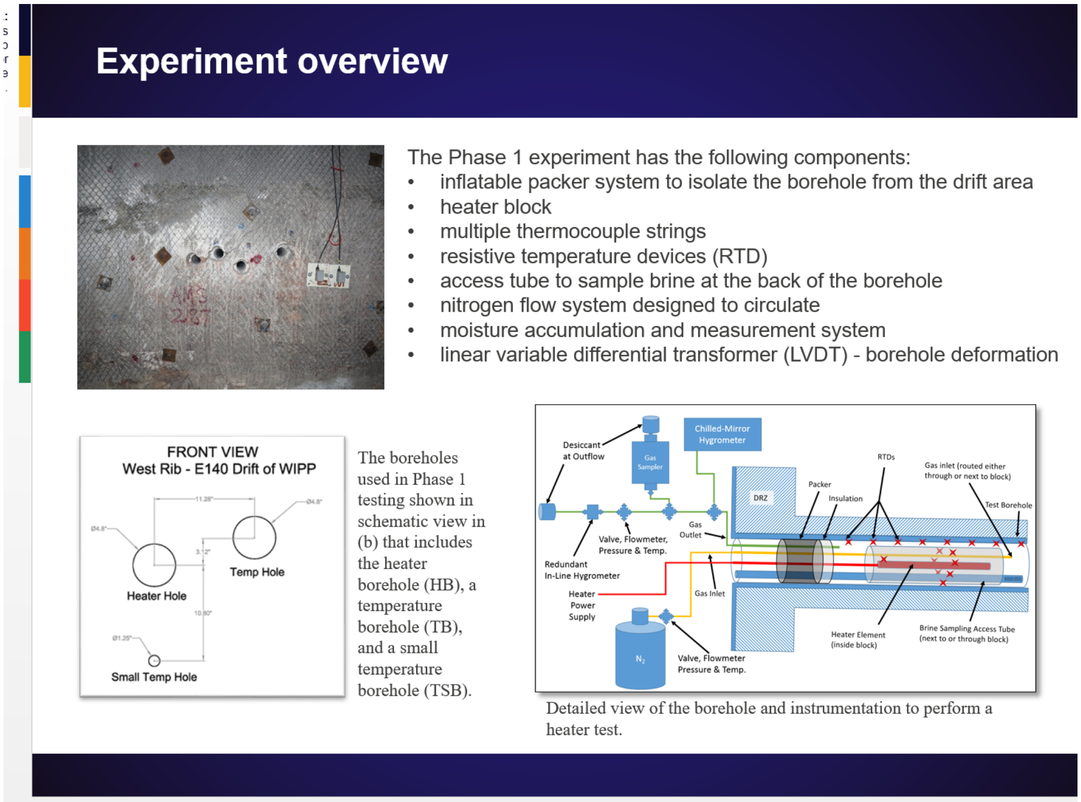
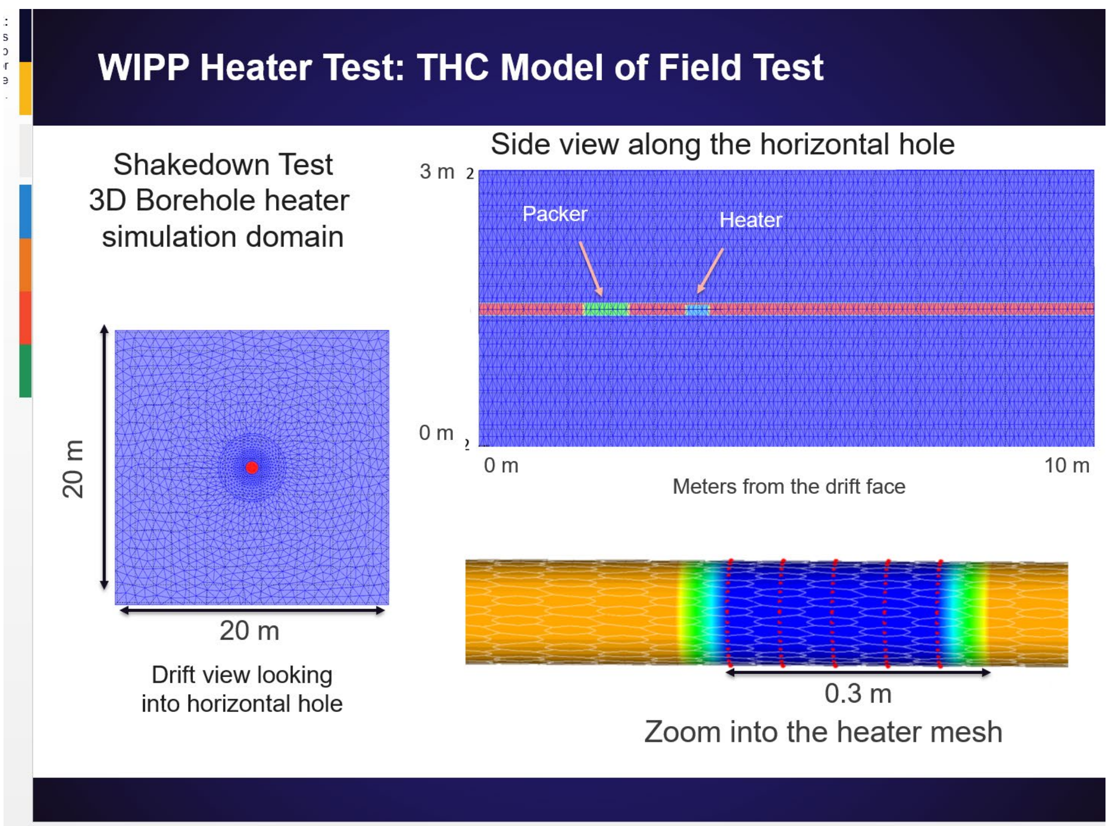
THC Couplings : Evaporation example

- WIPP evaporation experiment
  - Joint DOE-EM / DOE-NE
  - Ran in WIPP underground by LANL Carlsbad
- Simulated using FEHM
  - Implemented a new time-dependent FEHM relative humidity (RH) boundary condition
- Mine ventilation (RH) impacts better included in future test simulations

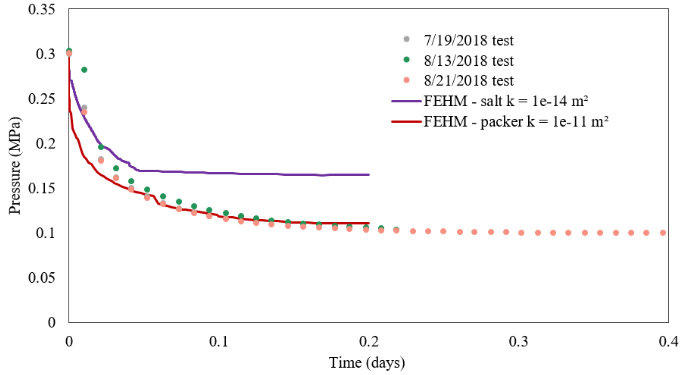





Experiment overview
The Phase 1 experiment has the following components:
• inflatable packer system to isolate the borehole from the drift area
• heater block
• multiple thermocouple strings
• resistive temperature devices (RTD)
• access tube to sample brine at the back of the borehole
• nitrogen flow system designed to circulate
• moisture accumulation and measurement system
• linear variable differential transformer (LVDT) - borehole deformation
FRONT VIEW
West Rib - E140 Drift of WIPP
Heater Hole
Temp Hole
Small Temp Hole
The boreholes used in Phase 1 testing shown in schematic view in (b) that includes the heater borehole (HB), a temperature borehole (TB), and a small temperature borehole (TSB).
Chilled-Mirror Hygrometer
Desiccant at Outflow
Gas Sampler
RTDs
Packer
Insulation
DRZ
Test Borehole
Valve, Flowmeter, Pressure & Temp.
Gas Outlet
Redundant In-Line Hygrometer
Heater Power Supply
Gas Inlet
Heater Element (inside block)
Brine Sampling Access Tube (next to or through block)
Valve, Flowmeter Pressure & Temp.
Detailed view of the borehole and instrumentation to perform a heater test.


WIPP Heater Test: THC Model of Field Test
Shakedown Test
3D Borehole heater simulation domain
20 m
20 m
Drift view looking into horizontal hole
Side view along the horizontal hole
3 m
0 m
Packer
Heater
0 m
10 m
Meters from the drift face
0.3 m
Zoom into the heater mesh

Field and modeling parameters



Comparison of packer injection test to modeling results in field-scale model parameters

Leak in packer system indicated by raid pressure decay

Experimental pressure decay compared to simulation results

Material	Porosity	Density (kg/m^3)	Thermal conductivity (W/(m·K))	Heat capacity (J/(kg·K)	Permeability (m^2)
Rock Salt	0.001	2170	Variable	931	1×10^{-20}
Air	-	1	0.06	1000	1×10^{-12}
Packer	0.9	300	1	500	1×10^{-26}
Heater	0.001	8000	15	1000	1×10^{-12}

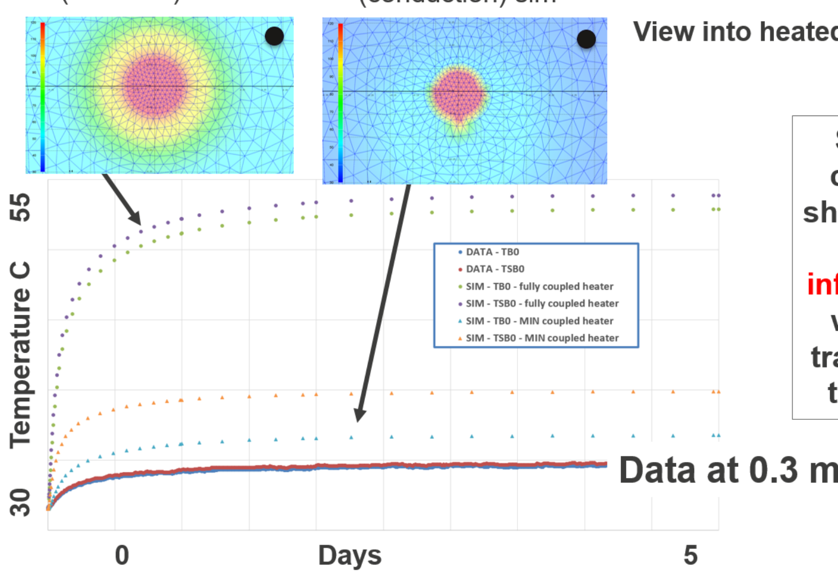
Material properties of the simulations.

WIPP Heater Test: Simulations Assist Design

Full contact (radiation) sim

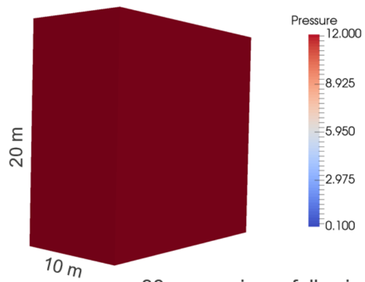
Small contact (conduction) sim

View into heated borehole

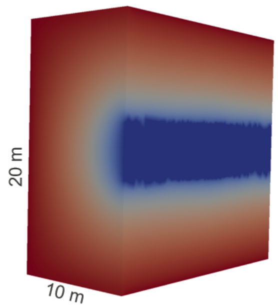


Simulations compared to shakedown data show that infrared heating would better transfer heat to the rock salt.

Establishing initial conditions - Pressure

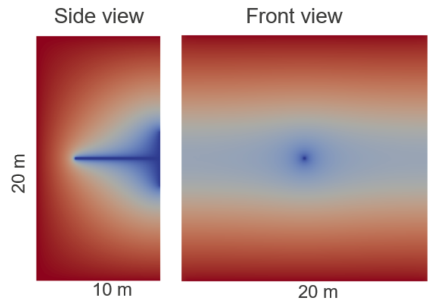


30-year spin up following drift excavation



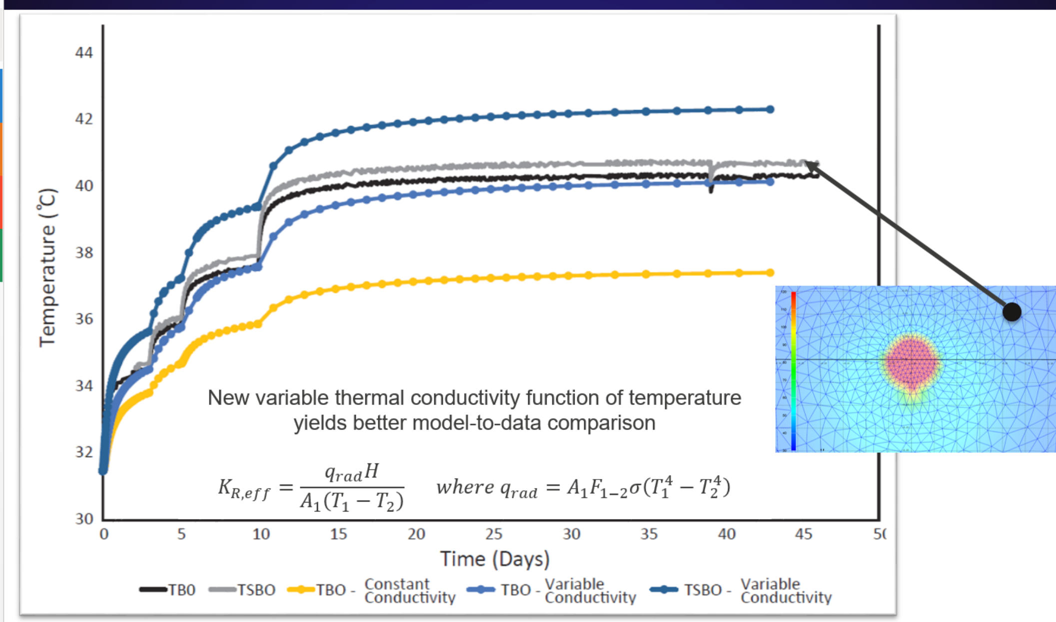
Establishing initial pressure and saturation conditions:

- Pressure and saturation gradients change following excavation and drilling
- Changes to water and heat flow during experiment
- Fresh holes in Phase 1 expected to have different results

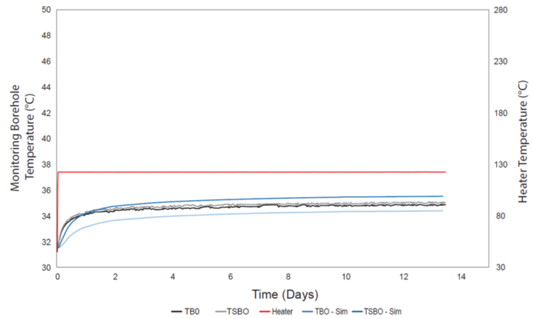


Boreholes drilled and open for ~6 years

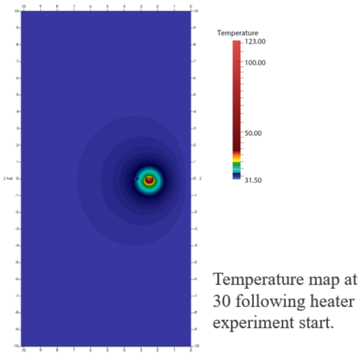
WIPP Heater Test: Modeling Thermal Step Test



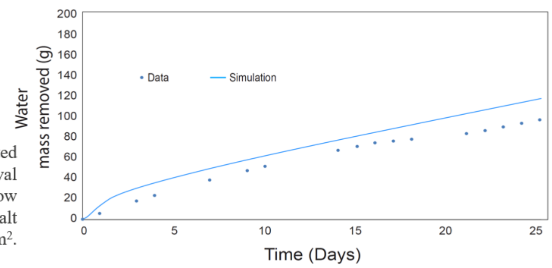
Heater experiments 123 C



Measured and modeled temperature for heater and water removal experiment.

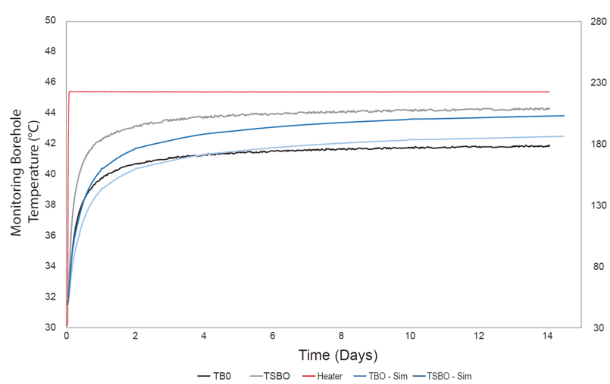


Temperature map at 30 following heater experiment start.

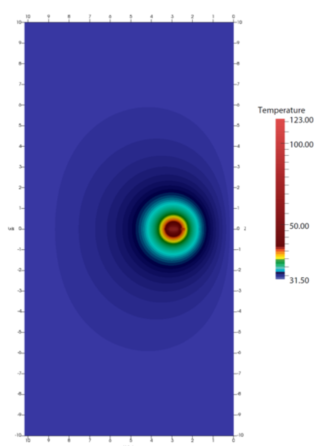


Measured and simulated results of water mass removal through the nitrogen flow system using salt permeability of 1e-21 m^2.

Heater experiments 260 W

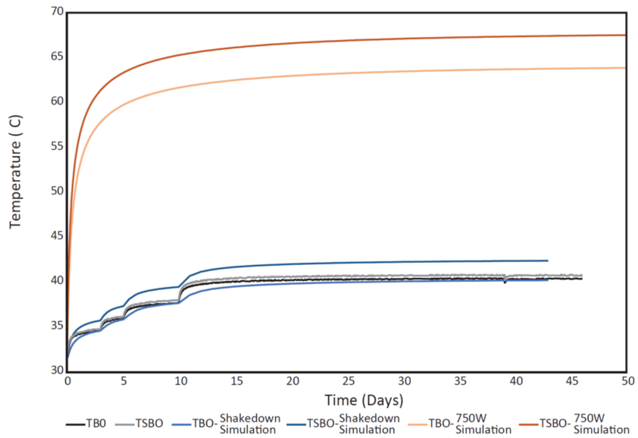


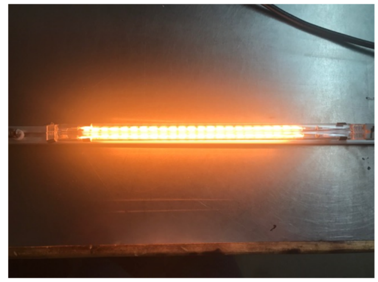
- Because of heater voltage, the heater could only reach under 230 C during the experiment
- A new heater with different design was swapped in for ongoing experiments to comply with WIPP



Temperature map at 30 following heater experiment start.

Projections for Phase-1 experiment

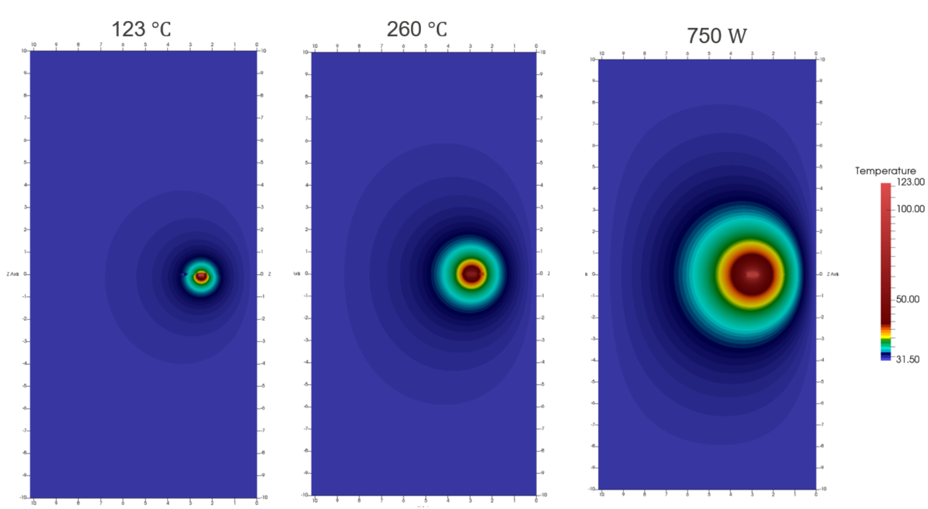


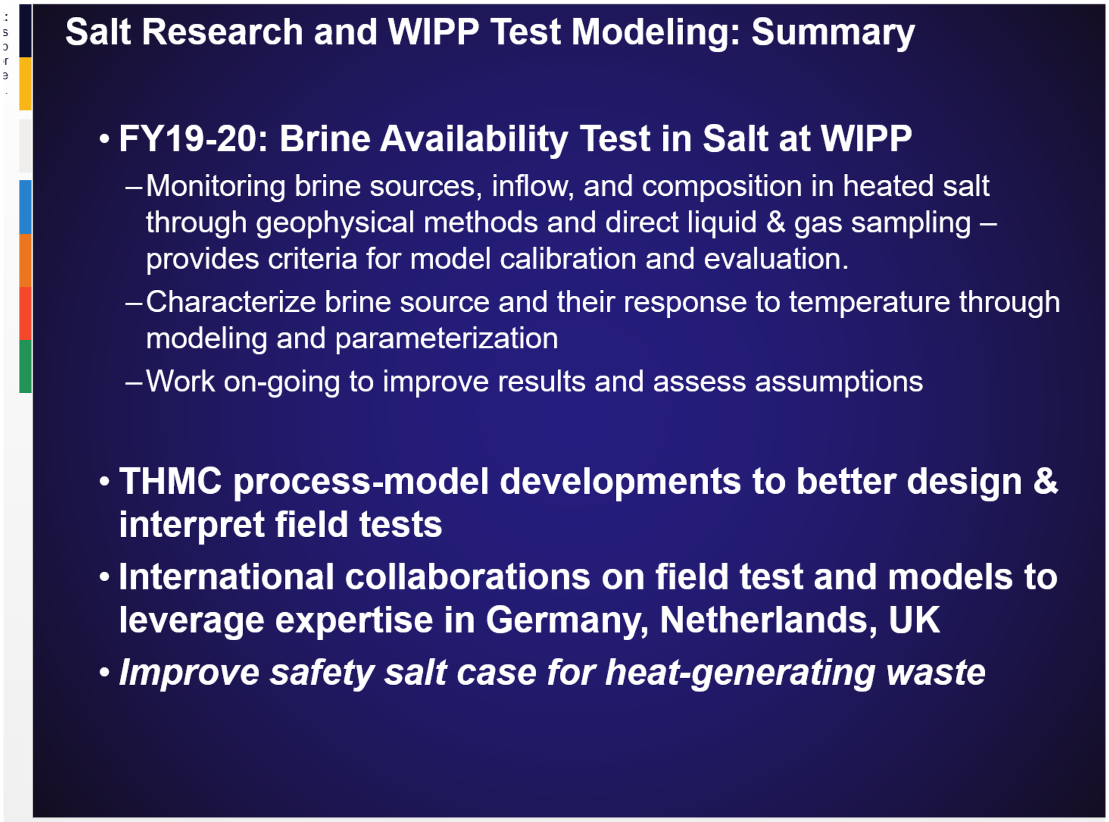


New 110 V, 750 W heater installed February

- New radiative heater placed into borehole Feb. 20
- Modeling matches temperature conditions with 750 W heater
- Variable heat conductivity capability appears to representing physical conditions well.

Comparison of modeled temperature results using different heaters




Salt Research and WIPP Test Modeling: Summary
• FY19-20: Brine Availability Test in Salt at WIPP
– Monitoring brine sources, inflow, and composition in heated salt through geophysical methods and direct liquid & gas sampling – provides criteria for model calibration and evaluation.
– Characterize brine source and their response to temperature through modeling and parameterization
– Work on-going to improve results and assess assumptions
• THMC process-model developments to better design & interpret field tests
• International collaborations on field test and models to leverage expertise in Germany, Netherlands, UK
• Improve safety salt case for heat-generating waste

4. WM2019 Poster – 19286

The next two slides are reproductions of WM2019 poster 19286 "Field Scale Experiments and Simulations of Heat Generating Nuclear Waste in Salt". This poster was presented March the 6th in the afternoon session on a board at the entrance to the oral session hall. Because of the location we got excellent visibility and interactions with many international attendees. We also had interaction with the NTWRB staff who were in attendance. This poster was re-used for the April 24-25 NTWRB meeting in San Francisco, a meeting that focused on international collaboration.

The poster consists of two panels, meant to be viewed from left to right starting with the first image below.

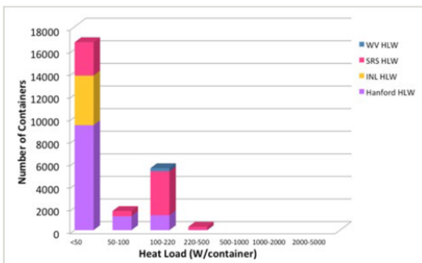
Field Scale Experiment and Simulations of Heat Generating Nuclear Waste in Salt - 19286

Background

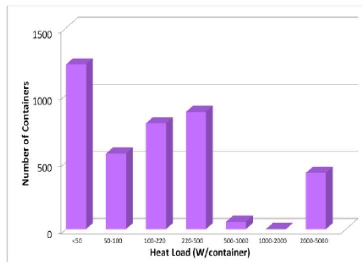
Can we make a safety case for storing DOE managed high-level nuclear waste (HLW) and Spent Nuclear Fuel (SNF) in bedded salt?

- US Department of Energy (DOE)
- Generic repository research
- Collaboration with DOE Office of Environmental Management

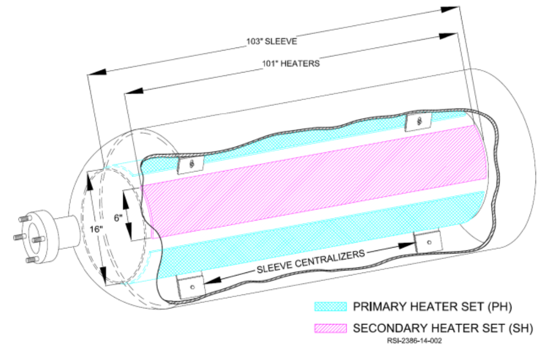
High-Level Waste



DOE Spent Nuclear Fuel



Full size waste canister mock-up tested before underground deployment in the Waste Isolation Pilot Plant (WIPP)

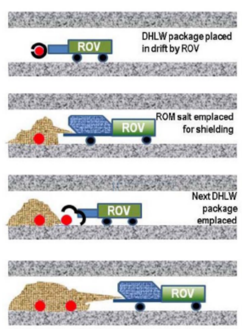


3 m canister

0.6 m diameter

In-drift disposal concept for salt repository

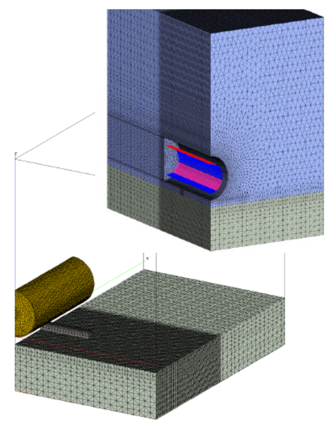
Simple lower cost method. Backfill is readily available in salt formations



Hardin et al., FCRD-UFD-2012-000219

DOE/CBFO-12-3485

Above Ground Canister Testing including canister simulations (Oct 2014 - May 2015)



LA-UR-19-21737

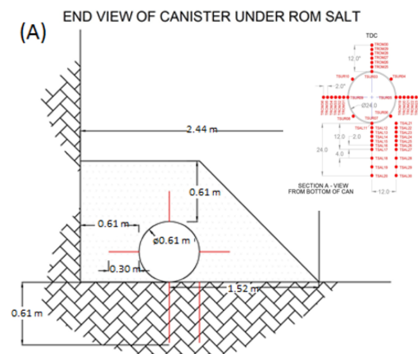
P.H. Stauffer[1], P.J. Johnson[2], T.A. Miller[1], M. Bourret[1], D. Weaver[3], S. Otto[3], B. Dozier[3], E. Guiltinan[1]

1 - Los Alamos National Laboratory, EES-16 Computational Earth Science
2 - GNS Science, Wellington, New Zealand
3 - Los Alamos National Laboratory Carlsbad Field Office

Canister buried under run-of-mine salt (ROM Salt) in WIPP

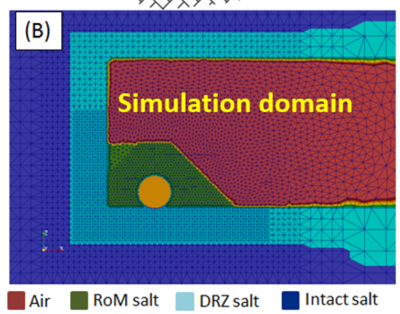
Experiment details

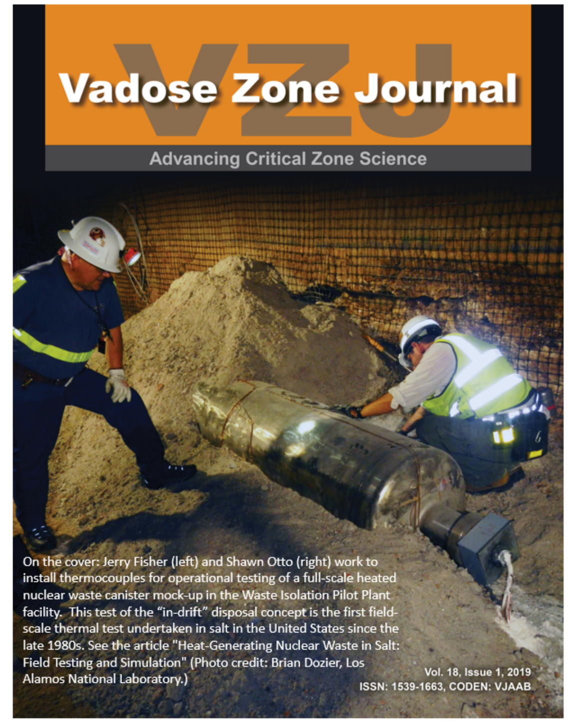
34 thermocouples
2 humidity sensors in the pile.
Mine air temperature and humidity.

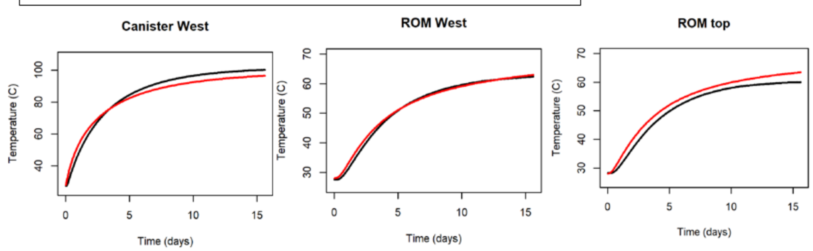


Simulation details (fehm.lanl.gov)

- Mass and energy conservation,
- Relative permeability for unsaturated flow
- Thermal effects on solubility
- Water vapor pressure lowering (capillary and solute)
- Porosity and temperature effects thermal conductivity
- Vapor and non-condensable gas diffusion
- Permeability changes with porosity
- Porosity changes from precipitation/dissolution
- Mine air relative humidity boundary condition







Temperature in the ROM salt pile : Field data versus simulation

Conclusions

A field-scale experiment and numerical simulations confirm salt backfill behavior.

Simulations closely match temperature around and under the piled salt backfill.

Limited dissolution–precipitation reactions around the canister.

Alteration of backfill is unlikely if the drift is allowed to dry before emplacement.

Los Alamos National Laboratory EST. 1943 — Waste Isolation Pilot Plant WIPP — LA-UR-19-21737 — Earth & Environmental Sciences — U.S. Department of Energy Office of Environmental Management — National Nuclear Security Administration

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