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.

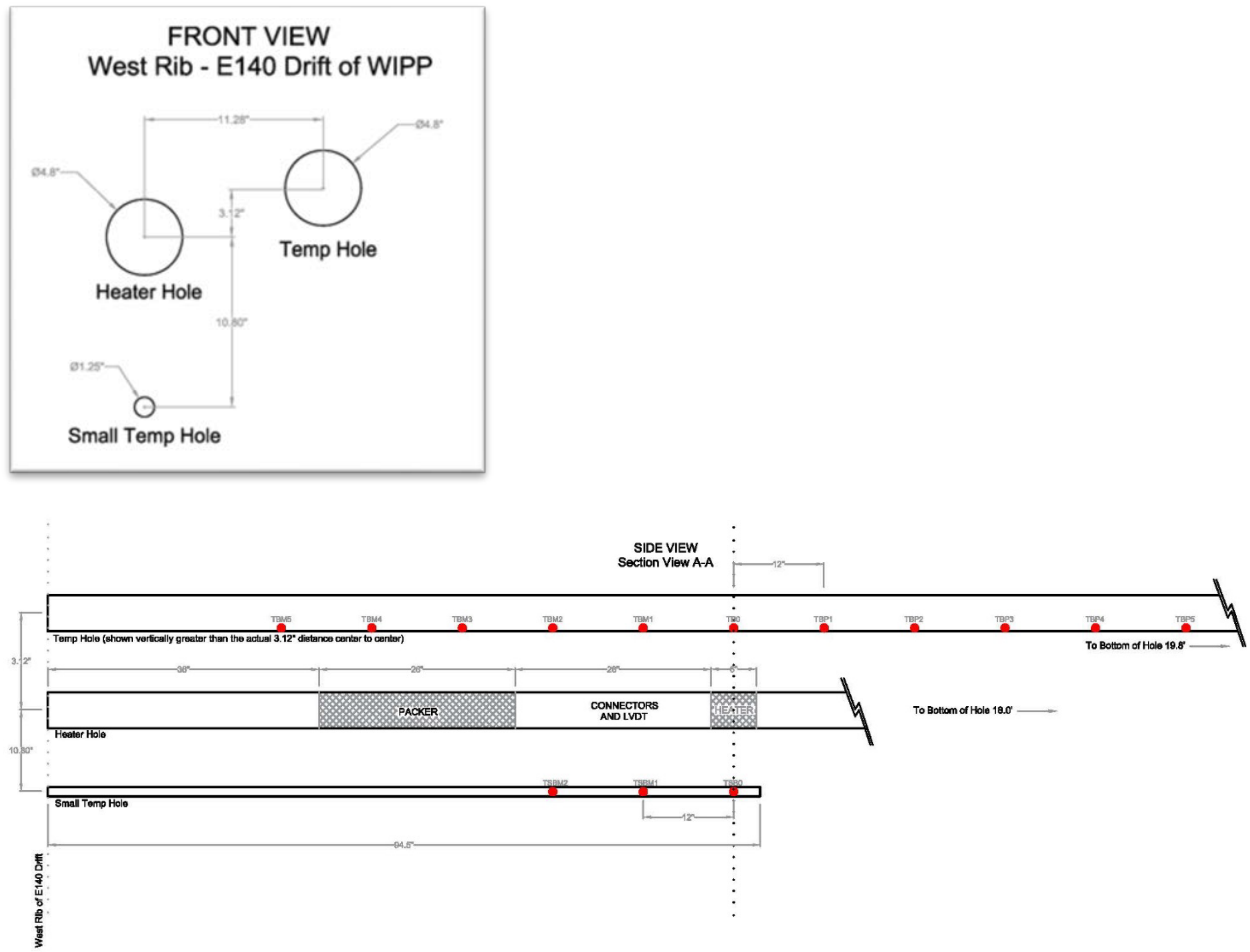

Figure 1. Schematic representation of the positions of the heater assembly and boreholes used positions in the heater test. The top schematic representation shows the front view of positions of the different boreholes looking from the drift area towards the drift wall. The bottom representation show 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.

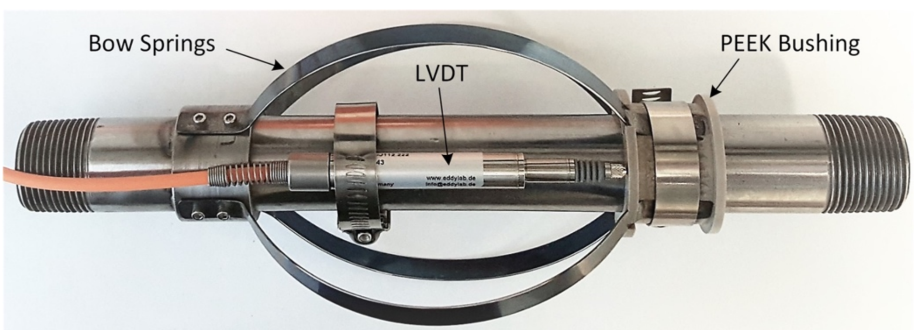

Figure 2. Picture of the Phase 1 LVDT device constructed to measure borehole closure

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.

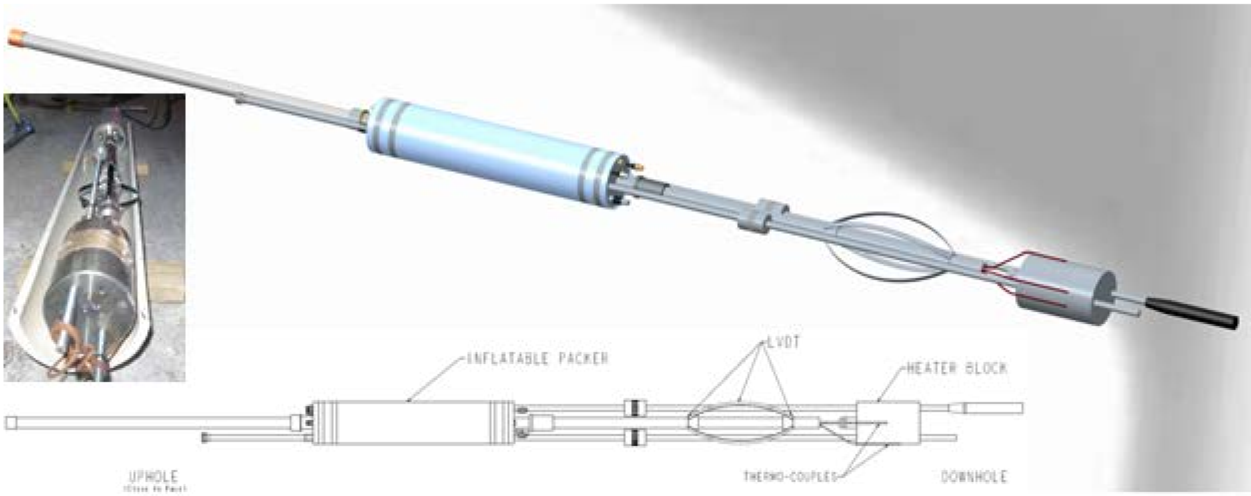

Figure 3. Schematic representation of the heater packer assembly. As-built rendering of Phase 1 heater/packer assembly.

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.

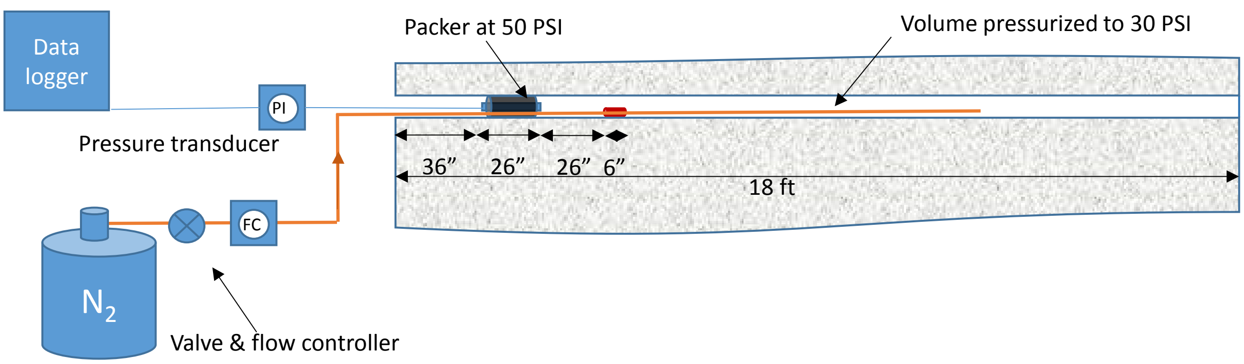

Figure 4. Simplified diagram showing the moisture collection and gas permeability measurement systems.

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).

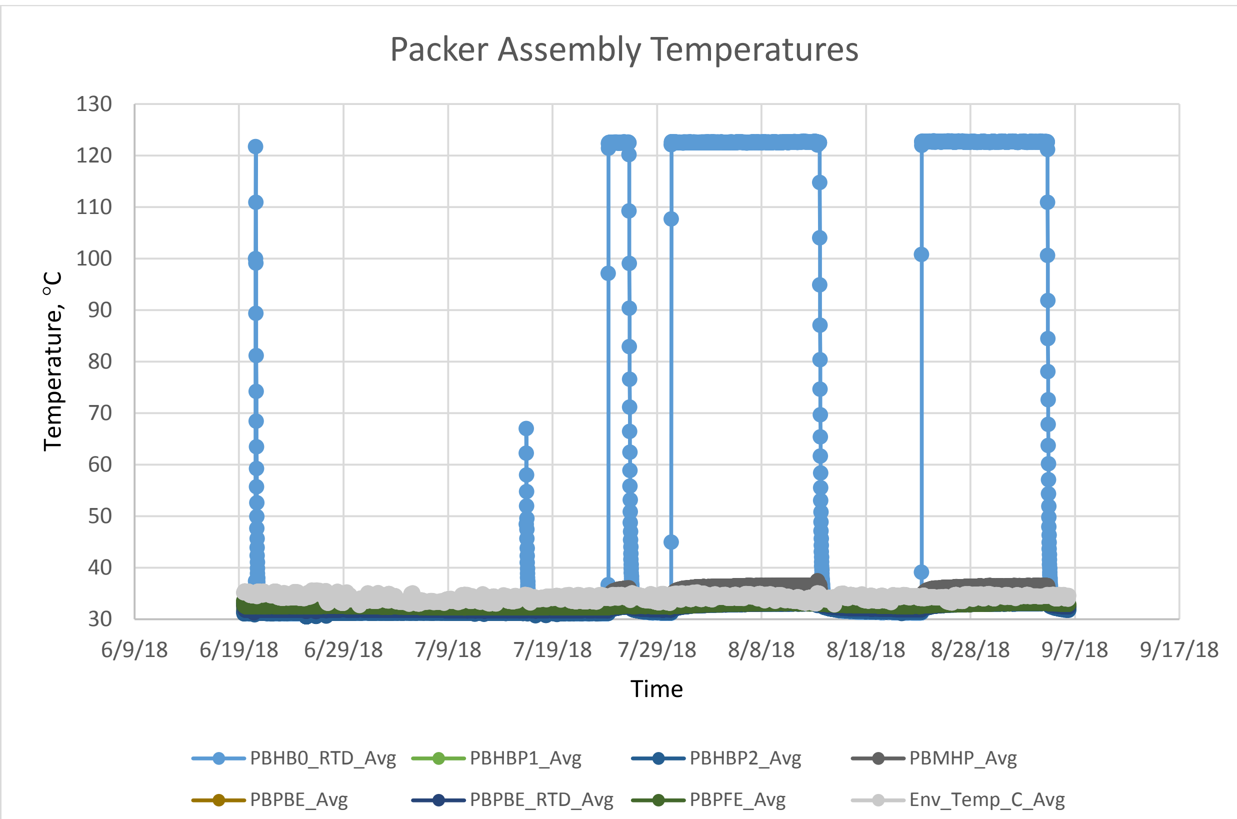

Figure 5. Temperature profiles recorded by thermocouples and RTDs during the heater test in the heated packer borehole. The different colored lines represent individual thermocouples and RTDs positioned at different distances from the heater.

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.

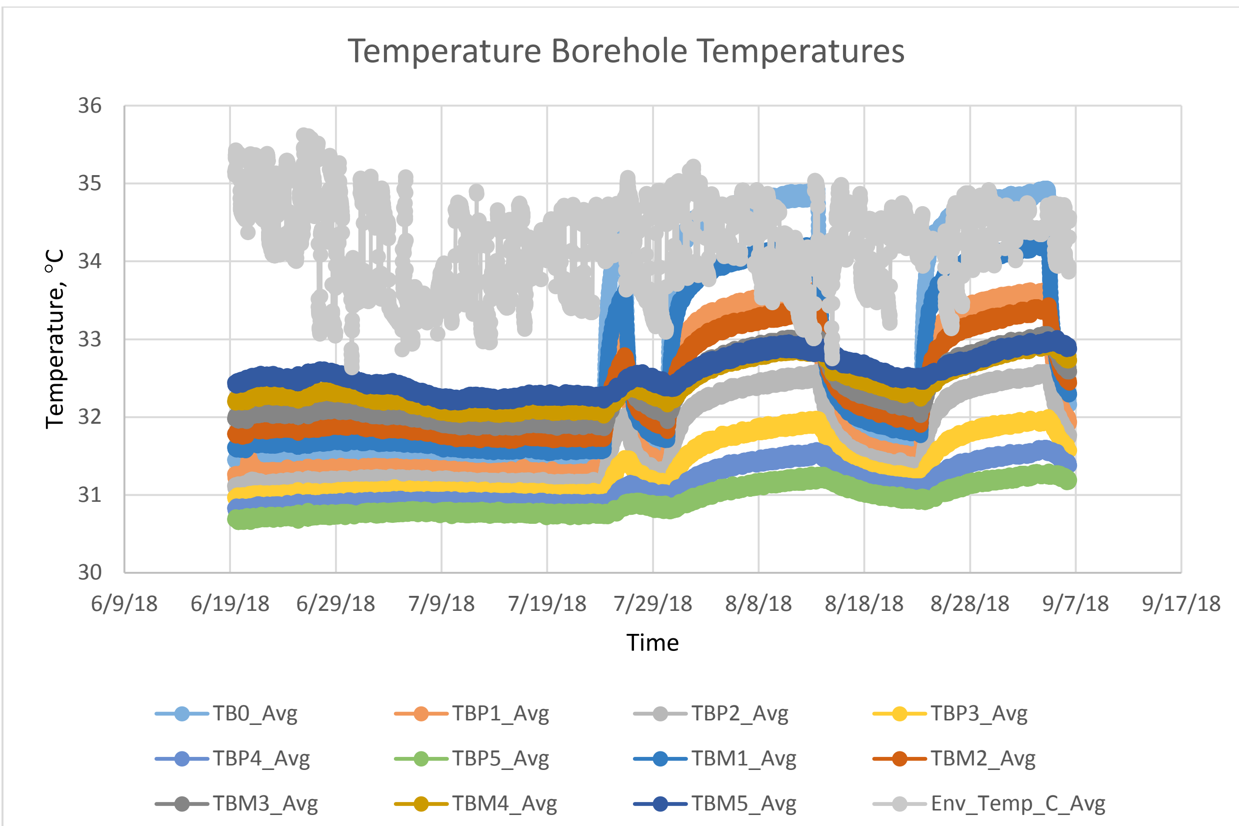

Figure 6. Temperature profiles recorded by thermocouples and RTDs during the heater test in the temperature borehole. The different colored lines represent individual thermocouples and RTDs positioned at different distances from the heater. Exact positions of the individual heaters are shown in Figure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

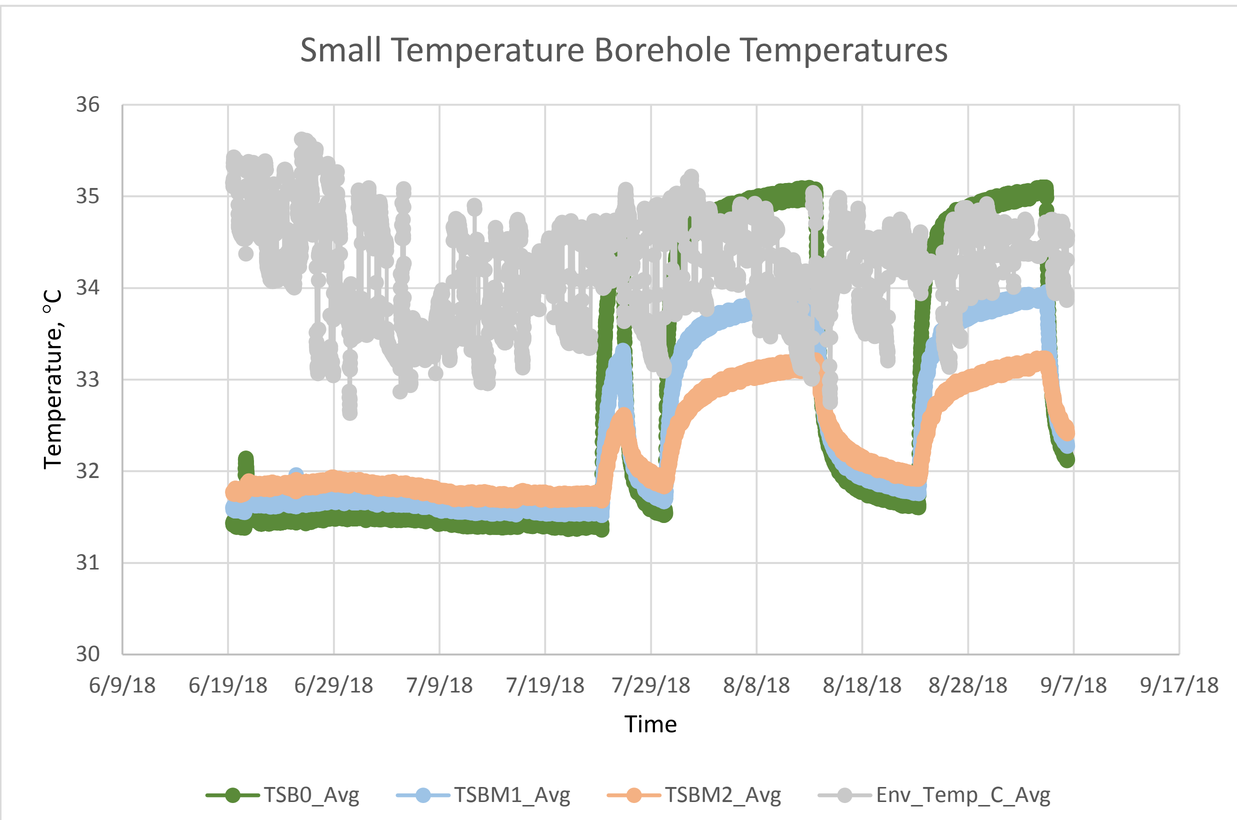

Figure 7. Temperature profiles recorded by thermocouples and RTDs during the heater test in the small temperature borehole. The location of the temperature probe is shown in Figure 1.

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.

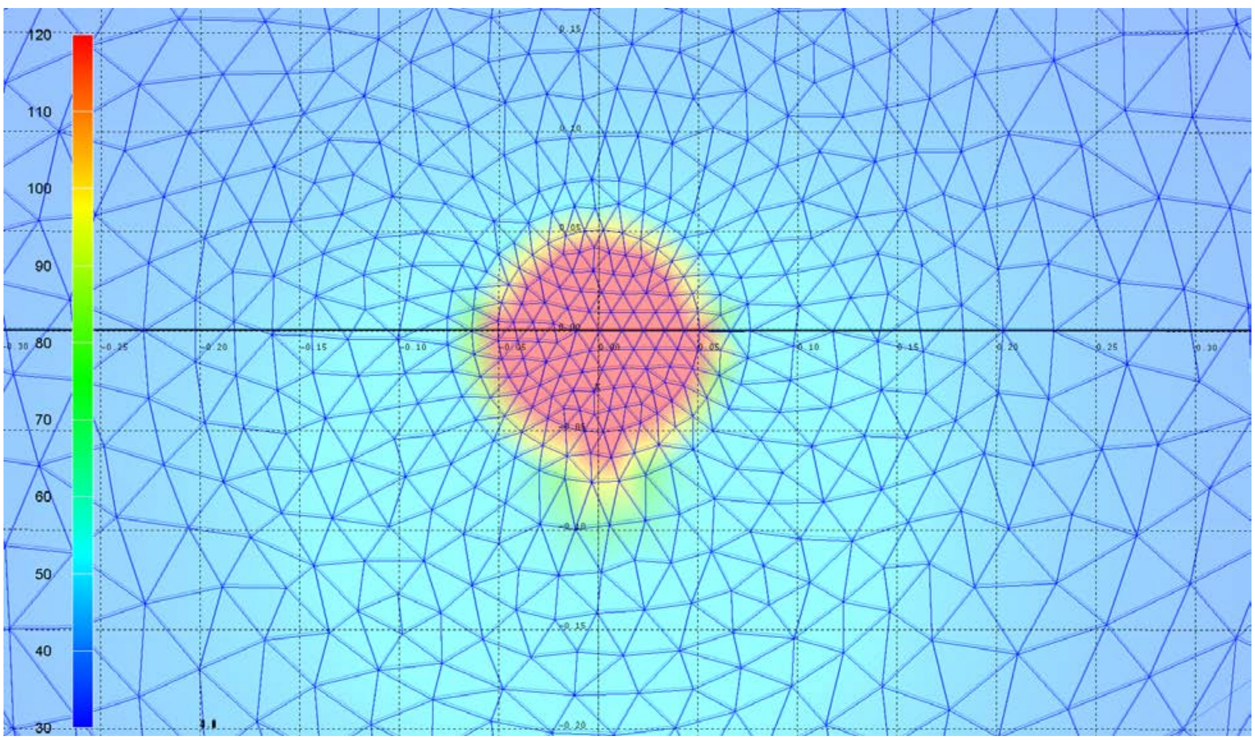

Figure 8. Figure showing simulated temperatures in the rock salt with minimal heater coupling to the rock salt.

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.

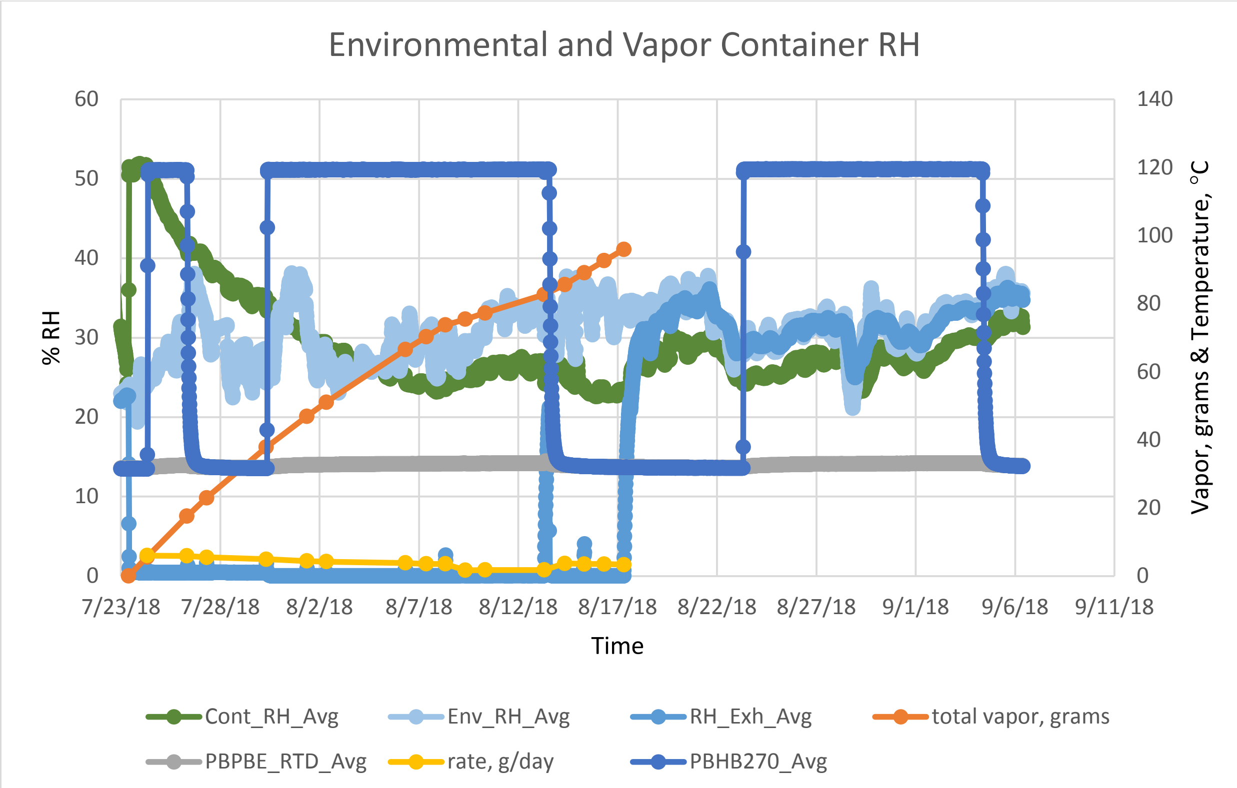

Figure 9. Plot showing water extraction by nitrogen circulation through the isolated interval of the borehole.

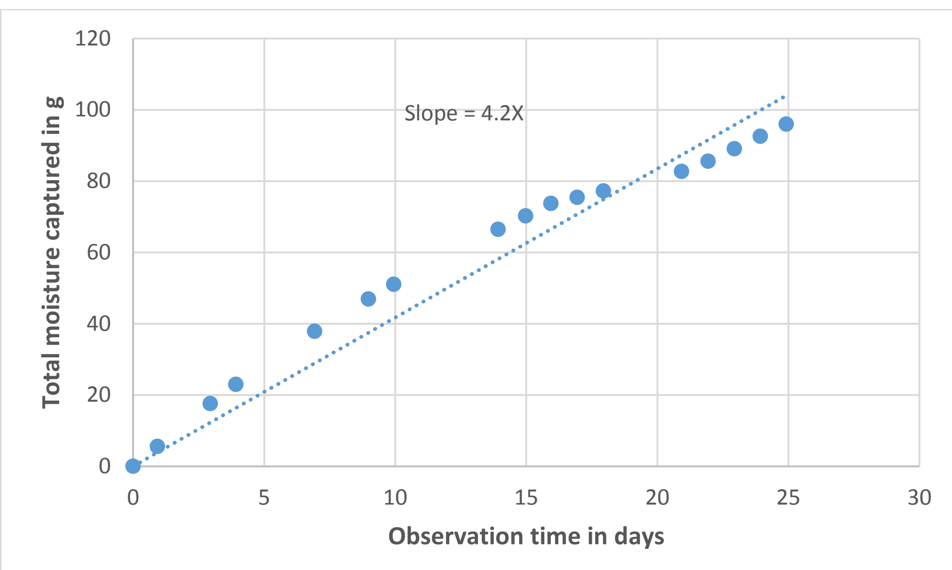

Figure 15. Plot of the total moisture captured by the desiccant cartridges as a function of observation days (Phase 1).

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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