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

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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 ºC (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.

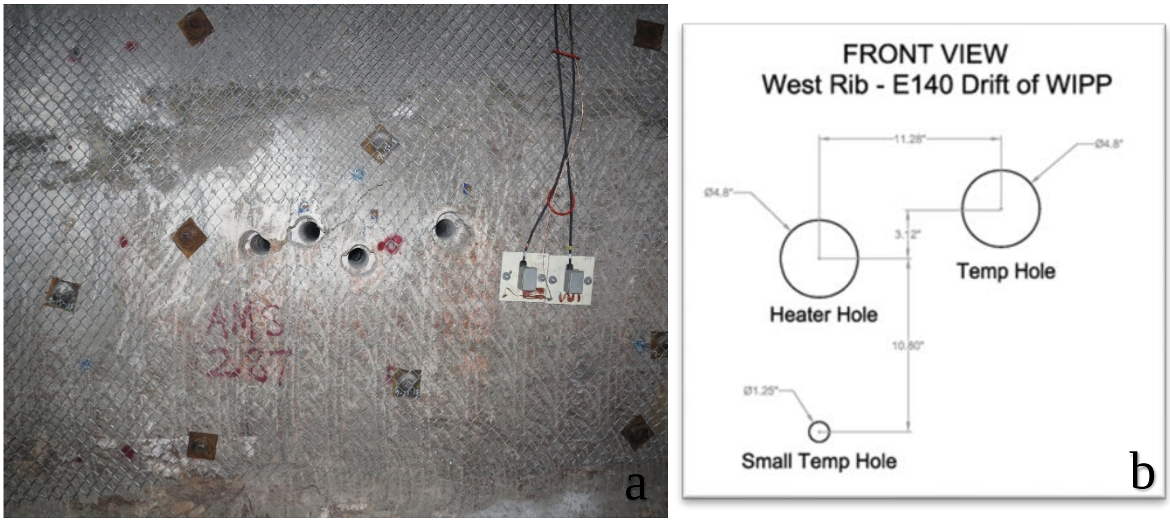

Fig. 1. (a) The face of the wall on which the horizontal boreholes are located for Phase 1 experimentation. Also seen in this picture are the rock bolts and chain link fence used to secure the drift face and reduce the likelihood of rock falls. The image predates the majority of instrument installation, 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).

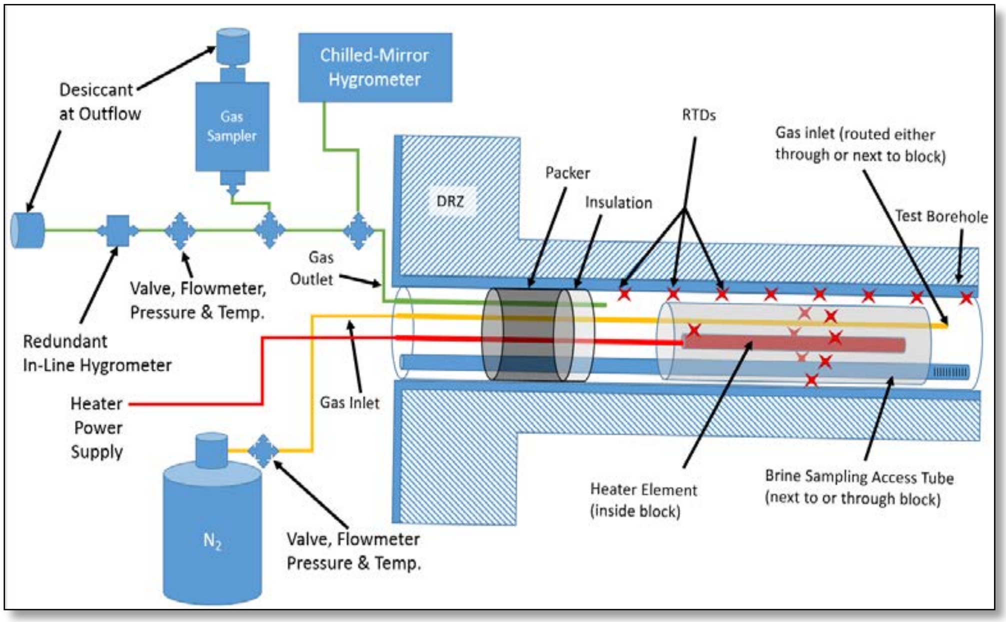

Fig. 2. Detailed view of the borehole and instrumentation to perform a heater test.

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.

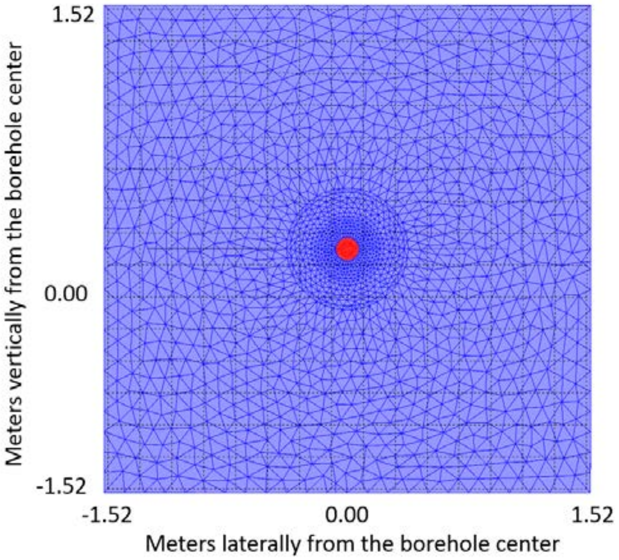

Fig. 3. Drift face view of the numerical mesh showing the borehole as red with the rock salt as dark blue.

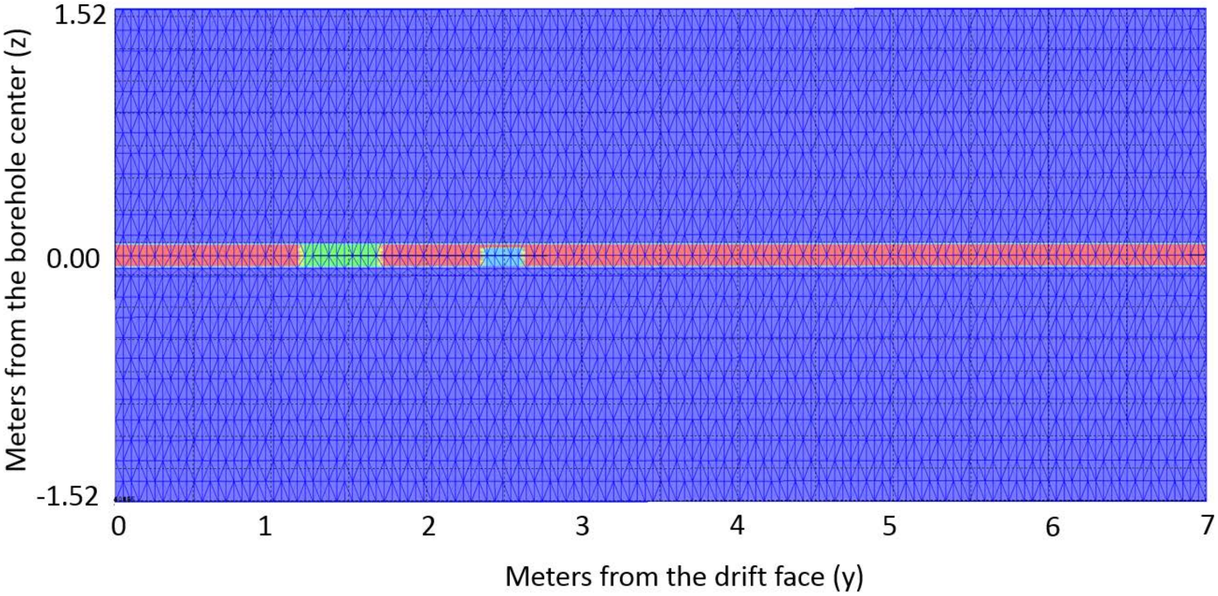

Fig. 4. Side view of the numerical mesh showing the borehole as red with the packer interval as green and the heater as light blue. Rock salt is dark blue.

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.

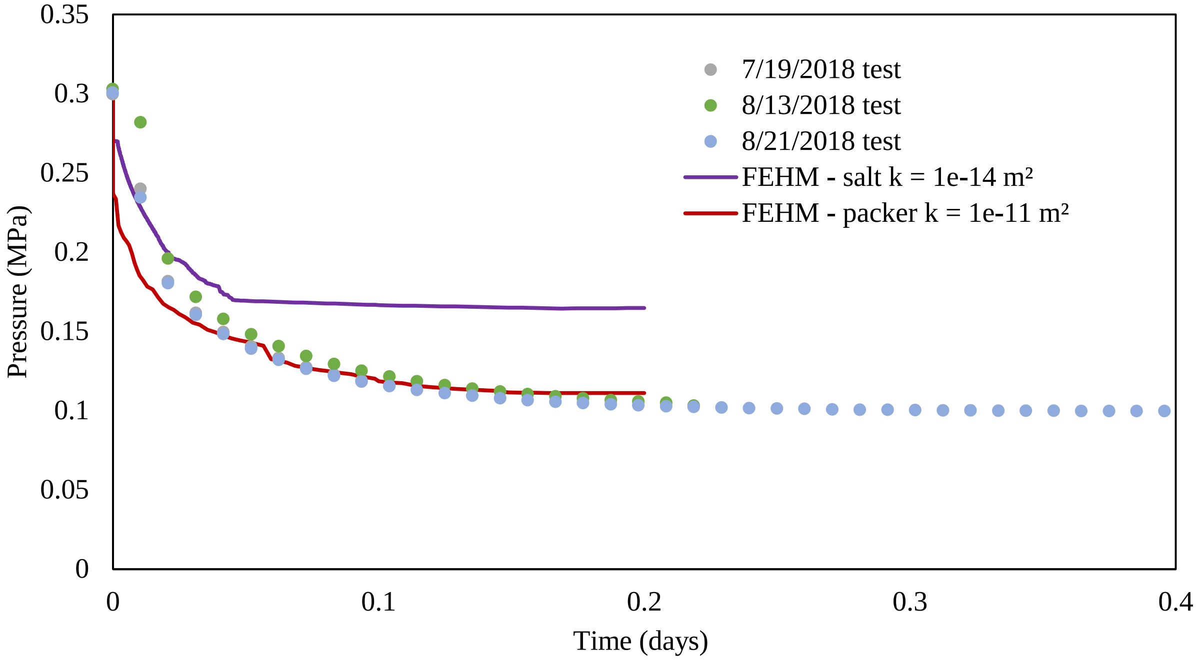

Fig. 5. Experimental pressure decay compared to simulation results.

TABLE I: Material properties of the simulations.

Material	Porosity	Density (kg/m^3)	Thermal conductivity (W/(m·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}

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 ºC. 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.

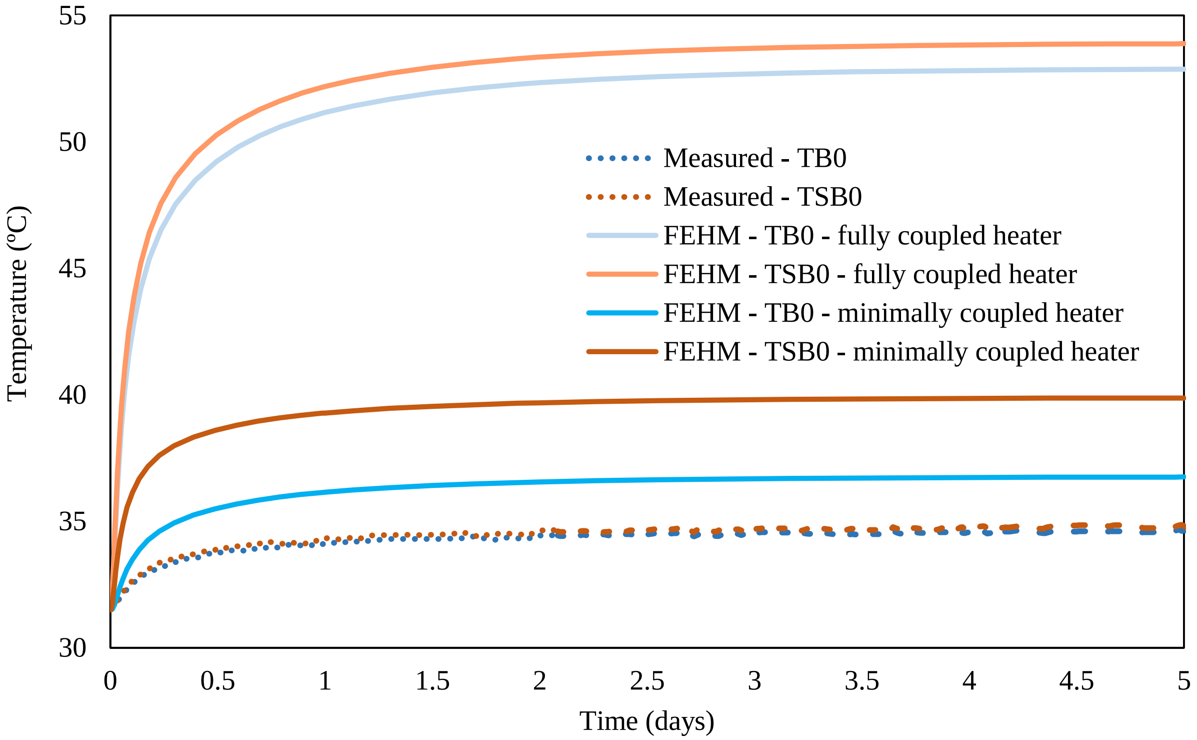

Fig. 6. Measured and simulated temperature during a period where the heater is turned on at TB0 and TSB0.

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.

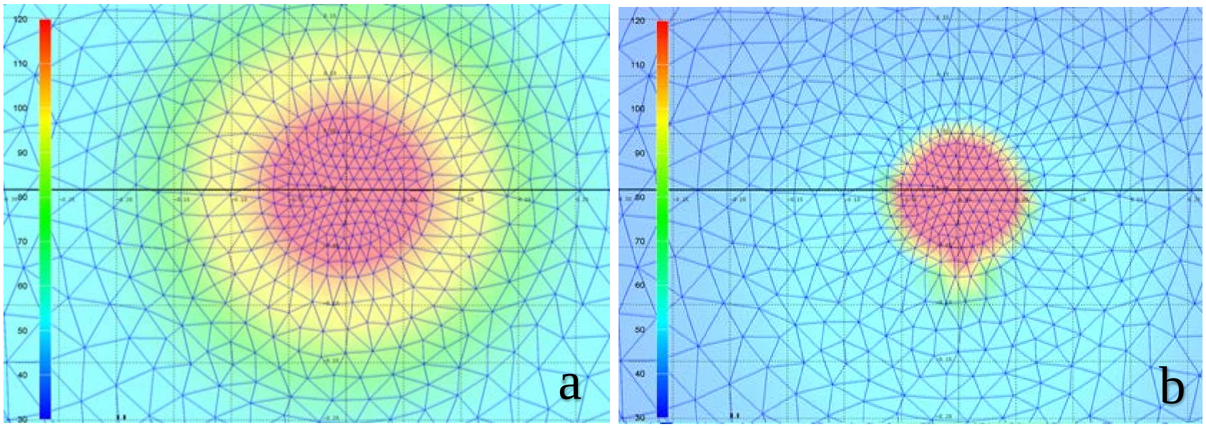

Fig. 7. Simulated temperature in cross-sectional view for the (a) fully-coupled heater and (b) minimally-coupled heater simulations.

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 x 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 x 10^{-20} m^2 and (2) 1 x 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 x 10^{-20} m^2 simulation removes less water vapor than expected following about 5 days since the experiment start. The k = 1 x 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.

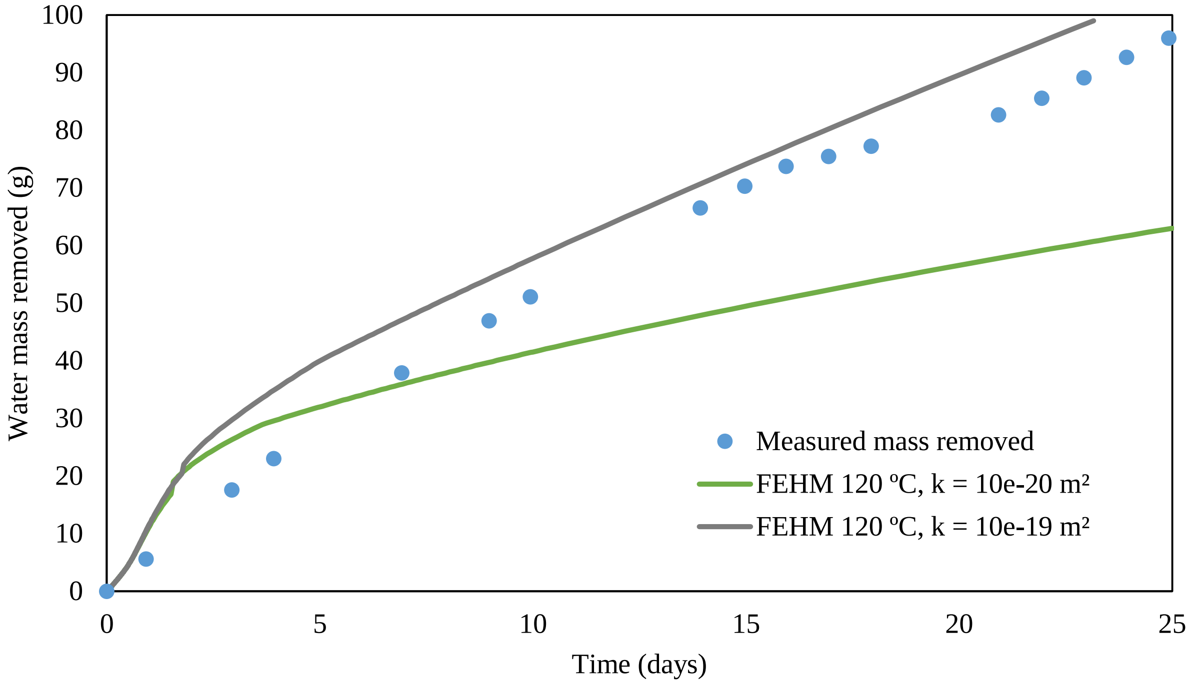

Fig. 8. Measured and simulated results of water mass removal through the nitrogen flow system.

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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