Salt Thermal Testing in Heated Boreholes: Experiments and Simulations

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Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
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1. Introduction

Salt formations may be an ideal repository for heat generating nuclear waste (HGNW) due to their extremely low permeability, high thermal conductivity, self healing capability, and expansive existence in the USA. However, uncertainties associated with brine availability and composition near heat generating waste remains a focus for research (*Bourret et al., 2019, Kuhlman et al., 2018*). Heat sources within salt may establish so called "heat pipes" where the boiling of water vapor and subsequent condensing of steam within the formation create a multiphase convection system. While the presence of heated brine may corrode waste canisters the development of "heat pipes" may support storage efforts through the precipitation of salt around the canisters (*Johnson et al., 2019*, *Jordan et al., 2015*, *Kuhlman et al., 2013*). To reduce these uncertainties and improve model forecasts for HGNW storage in salt, heated borehole experiments have been proposed at the Waste Isolation Pilot Plant (WIPP) (*Stauffer et al., 2015*). Numerical models are being developed and calibrated at LANL to support the field test design.

Work conducted by LANL for Salt R&D during the first half of the 2019 fiscal year includes the development and implementation of the first phase of heated borehole experiments, numerical modeling for generic repository science with potential international applicability, and fundamental code development in support of the heated borehole experiments. This document focuses on the development of numerical models to support the experimental efforts and help design the larger Phase 2 experiments. A brief summary of the experimental progress is included but will be the focus of the annual experimental milestone in August 2019. Model development has been conducted using the porous flow simulator FEHM (Zyvoloski et al. 2012, https://fehm.lanl.gov).

Phase 1 of the heated borehole experiments was conducted as a “shakedown”. Its purpose was to learn the logistical challenges of working underground at WIPP while working through technical challenges in the field test design before the larger, and more expensive, Phase 2 experiment. The Phase 1 experiments began in July, 2018 and continued throughout the first half of the 2019 fiscal year. The most important aspects of the Phase 1 experiments for model development have been the implementation of three different heat sources and the monitoring of water production during the tests. Results from the Phase 1 experiments allowed LANL to develop and calibrate numerical models that were used to inform the design of the larger Phase 2 experiments. A detailed summary of Phase 1 of the heated borehole experiments can be found in *Kuhlman et al.* [2018]. Work has begun on the implementation of Phase 2, which will be detailed in a future milestone report.

Figure 1-1: Installation of an infrared heater in the WIPP underground.

2. Phase 1: "Shakedown" Experiments and Simulations

2.1 Field Experiments

During the Phase 1 experiments boreholes previously drilled in the WIPP underground were used to test different experimental setups. The initial test design relied upon the use of a stainless steel heater block which could be set to prescribed temperatures (Figure 2-1A). Besides the heated borehole (HB) temperature sensors were also deployed in two adjacent boreholes (Temp Hole – TB; and Small Temp Hole -TSB) to monitor the temperature distribution within the salt (Figure 2-1B).

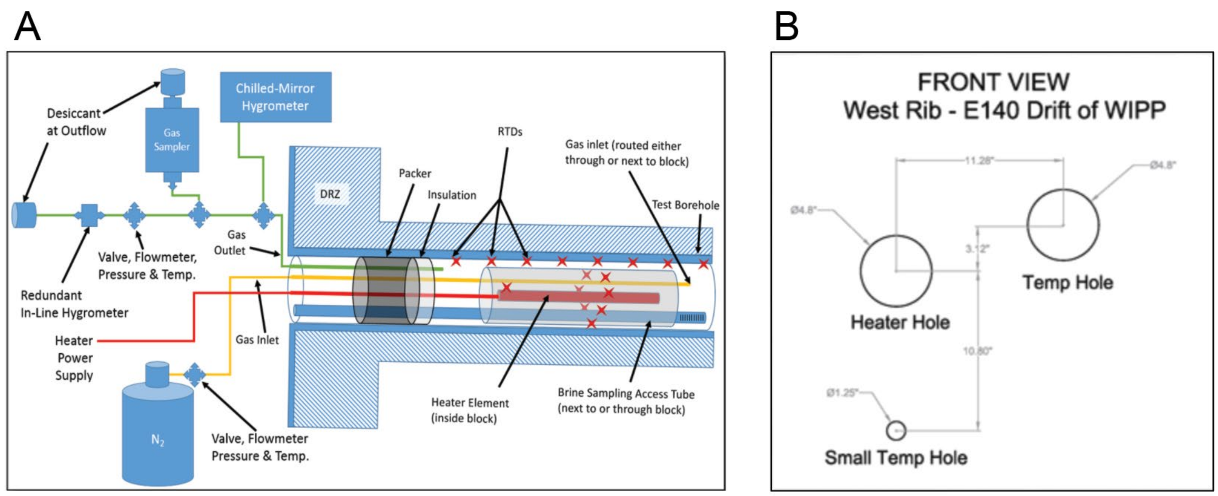

Figure 2-1: Detailed view of heated borehole instrumentation and B) Layout of heated borehole (HB) and two temperature monitoring boreholes temp hole (TB) and small temp hole (TSB).

With a goal of producing a temperature rise of 120° C within the salt, the heater block was set to 120° C. However, the air gap around the heater block insulated the formation from the heater creating a poor thermal coupling between the salt and heater. This resulted in observed temperatures within the temperature boreholes of only 35 °C, a 3.5°C degree increase from the background formation temperature. Although, the temperature rise was less than predicted these experiments provided valuable data for calibrating and developing numerical models.

2.2 Heater Block Modeling Development

To simulate the heater block experiments a three dimension mesh was generated that is approximately 3m x 3m x 7m (Figure 2-2) with the center of borehole laying at x=0, z=0. The mesh is highly refined near the borehole and the resolution decreases radially. This results in a mesh that includes 238,107 elements.

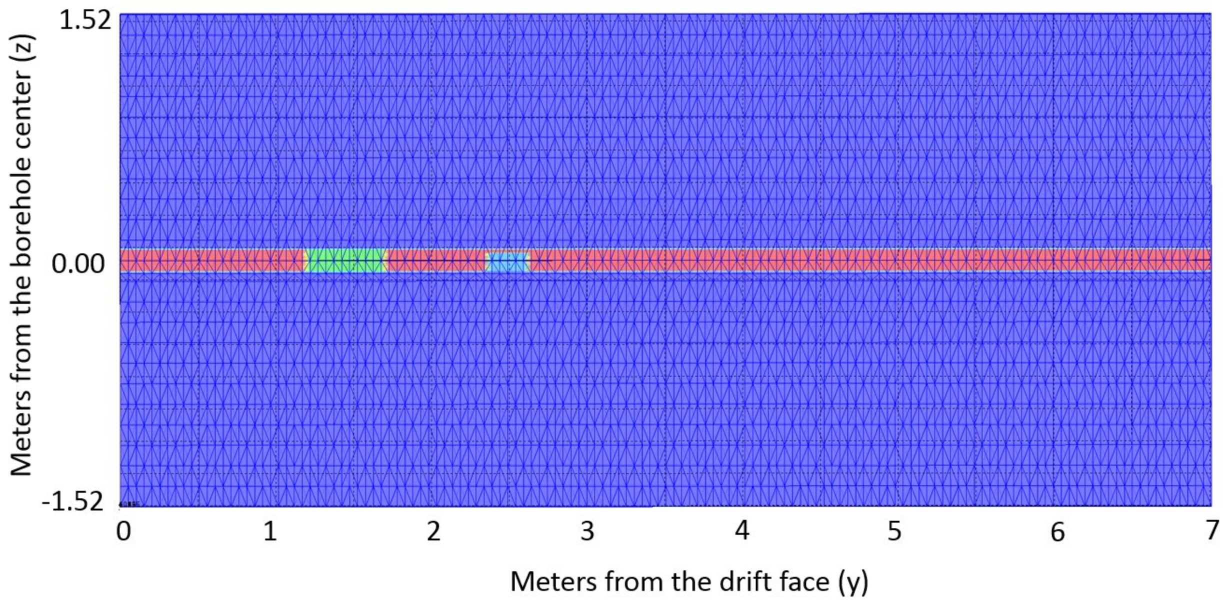

Figure 2-2: Cross section of the initial heater block mesh

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. 2-1b). 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. This result can be seen in Figure 2-3, 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.

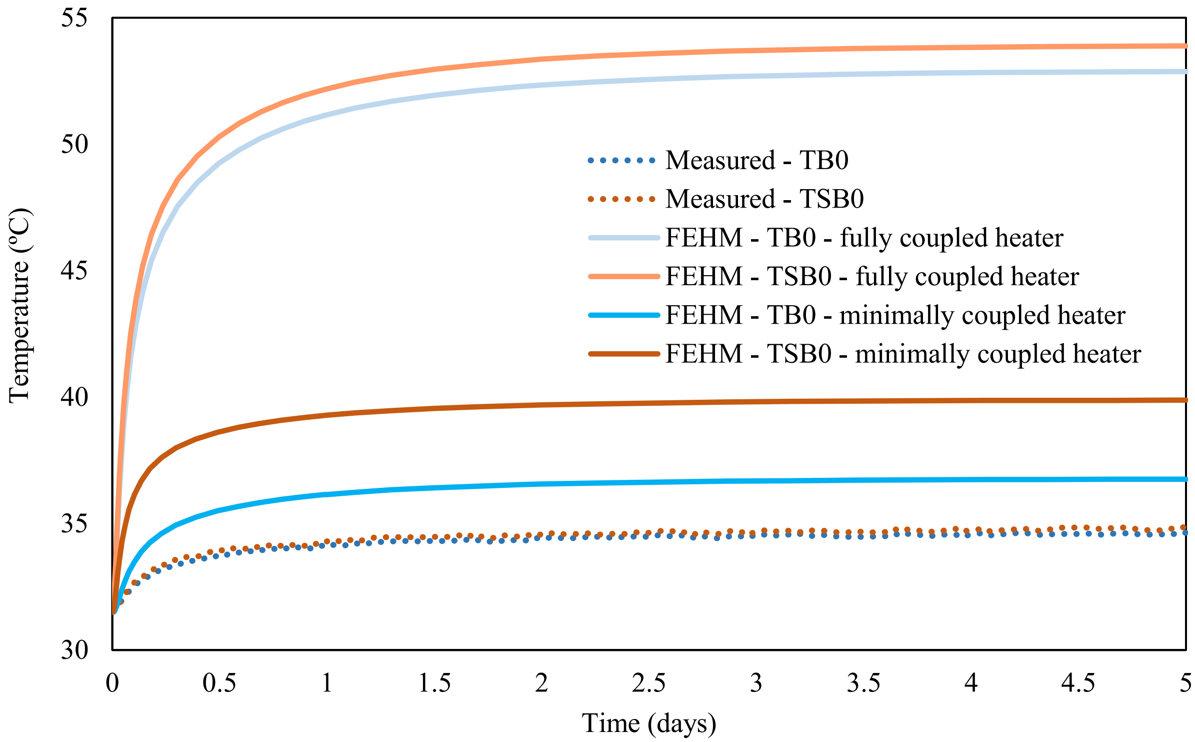

Figure 2-3: Measured and simulated temperature during a period where the heaters Cross section of the initial heater block mesh

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. 2-3 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.

To further improve the accuracy of the simulations a larger domain was developed. The original domain is highly refined around the borehole, but was limited in size due to computational expense (Figure 2-4a). However, the implementation of a larger, 20m x 20m x 10m model domain (Figure 2-4b) revealed that the boundary conditions in the smaller model were causing a feedback between the coupled temperature and thermal conductivity producing an over estimation of the temperature near the borehole.

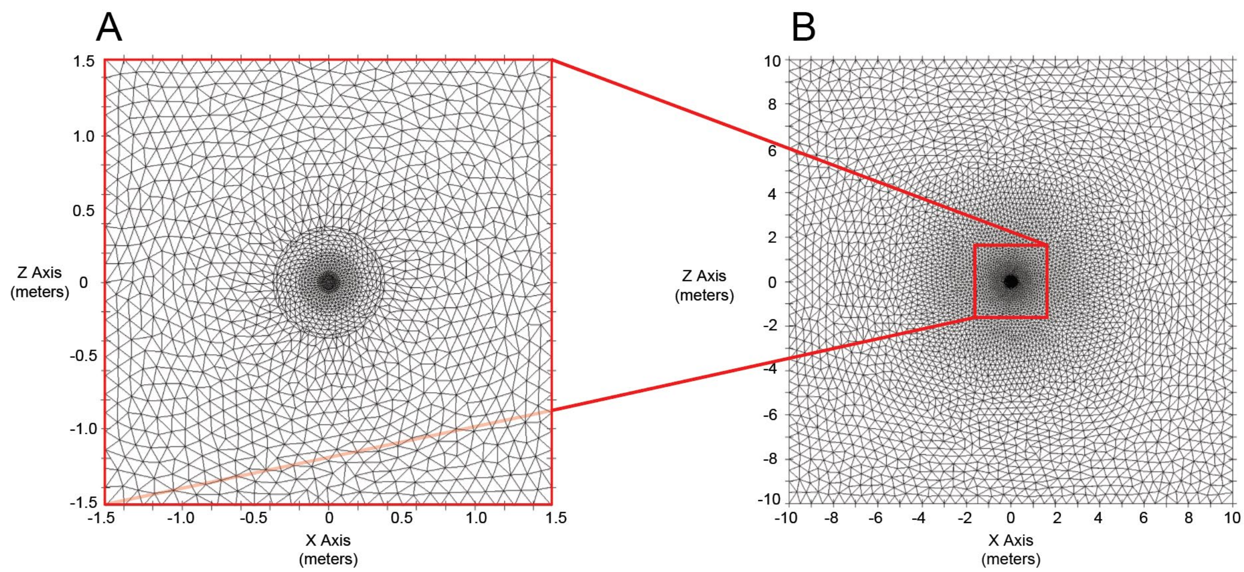

Figure 2-4: Cross section of model domains. A) Smaller 3m x 3m x 7m domain. B) Larger 20m x 20m x 10m domain.

To accurately model the complex thermo-hydro-mechanical-chemical processes associated with the heater tests many coupled processes must be included in the model. These coupled processes can sometimes result in non-intuitive model behavior which leads to a better understanding of the system. By moving the 31.5 °C temperature boundary condition due to the background formation temperature further away from the borehole a more accurate temperature profile is produced (Figure 2-5).

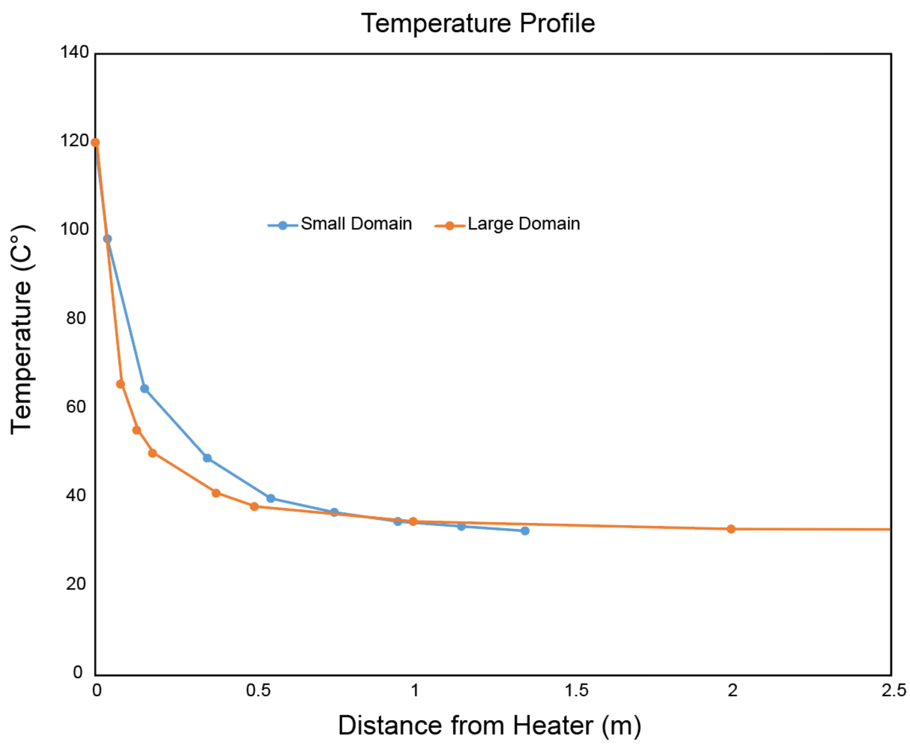

Figure 2-5: Temperature profile along the axis of the heater.

2.3 Model Initialization and Simulation of Heater Block

Beginning with accurate initial conditions is critical to model accuracy. Table 3-1 displays the initial properties of the intact salt used during the simulations. These properties are dependent upon each other and vary throughout model. For instance, porosity changes due to the dissolution of salt drive changes in permeability; whereas, temperature changes from the heater drive changes in thermal conductivity. The implementation of these coupled processes in FEHM have been developed over the years with some recent work on the variable thermal conductivity and permeability of salt being covered in the previous modeling milestone (*Johnson et al., 2018*)

Table 2-1: Important Initial parameters used for Phase 1 salt simulations

Parameter	Value
Salt initial porosity (-)	0.001
Salt initial permeability (m^2)	10^{-21}
Salt initial thermal conductivity (W/m K)	5.25
Initial formation pressure (MPa)	12
Initial formation temperature (°C)	31.5
Residual saturation (-)	0.1

Due to the extremely low permeability of intact salt, field measurements of formation pressure are difficult. Previous work indicates that in the undisturbed salt near WIPP the formation pressure is approximately 12 MPa (Beauheim 1999). Using this information and knowledge of the mining activities at WIPP we developed an estimated pressure distribution at the location of the heated borehole in the E140 drift. First, the model is initialized at 12 MPa throughout the domain, this represents the formation prior to the excavation of the mine (Figure 2-6). Next an atmospheric boundary condition is applied along one side, this represents the initial mining of the E-140 drift in 1982, and the model is allowed to equilibrate for 30 years. After 30 years of model time, the domain is further updated to include the heated borehole, this corresponds to the drilling of these boreholes in 2012. Next the model is run for an additional 6 years to arrive at the pressure conditions within the formation at the start of the Phase 1 testing. This final condition is then used as the initial pressure distribution condition for each of the Phase 1 simulations.

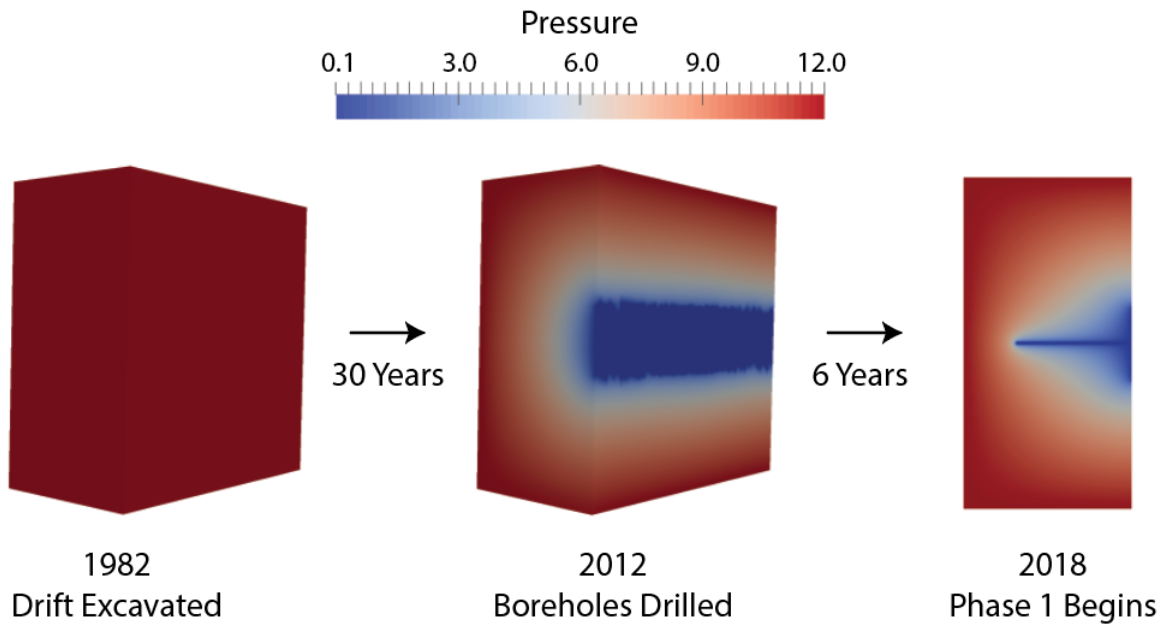

Figure 2-6: Pressure distribution development for Phase 1 simulation initialization

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The final constant 120 °C Phase 1 heater simulation temperature results are shown in Figure 2-7. The model is able to accurately represent the temperature at the monitoring locations to within 2 degrees. Some error associated with measuring the precise locations of the temperature sensors within boreholes that are not entirely straight is considered a likely reason for this discrepancy.

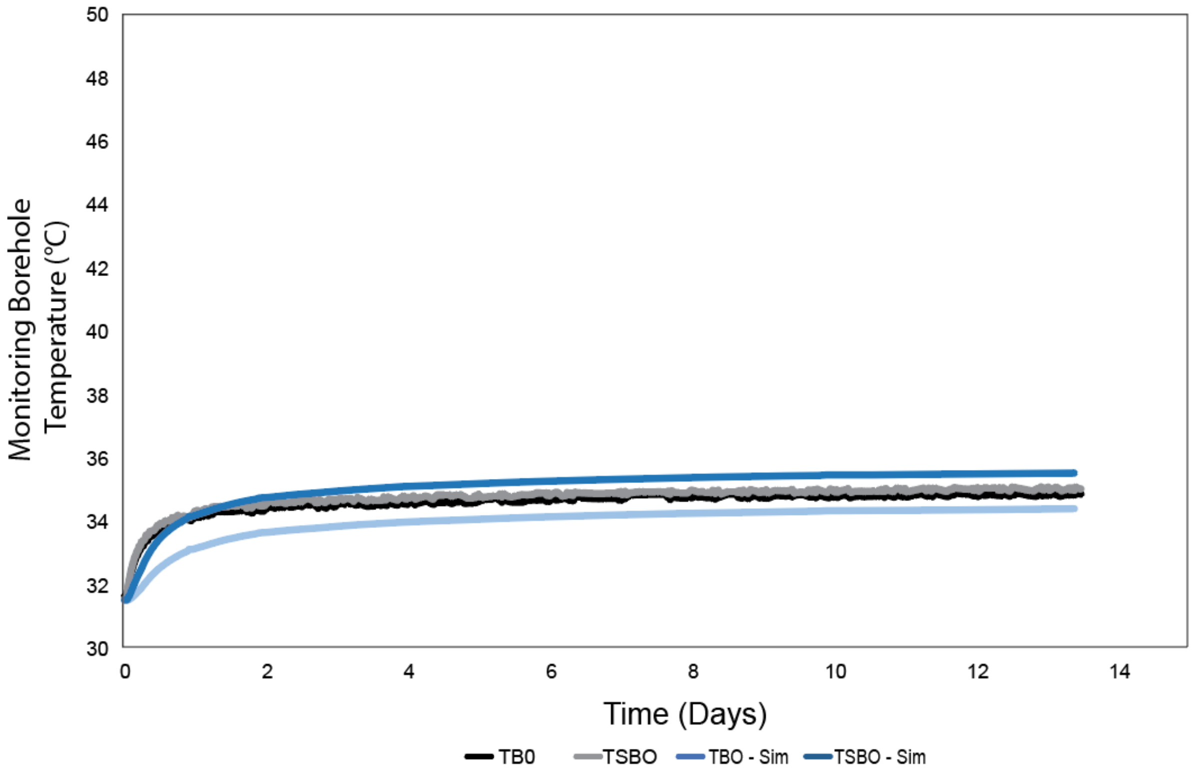

Figure 2-7: Final Simulation of the 120 °C heater block experiment

During this experiment water vapor was extracted from behind the packer by circulating nitrogen throughout the test. We find that a permeability of 1e-21 m^2 produces a fairly accurate simulation of the water production (Figure 2-8), but the match would likely be better with a slightly lower permeability. Permeability in the damaged zone around the boreholes is likely significantly higher than 1e-21, but because these boreholes were drilled 6 years prior to the Phase 1 testing they have equilibrated and the water flow is now likely controlled by the permeability of the intact salt. The much smaller than expected temperature change means the thermal expansion of the water in the formation had little effect on the flow. The Phase 2 testing, which will use freshly drilled boreholes and significantly more heat will explore brine availability during these tests.

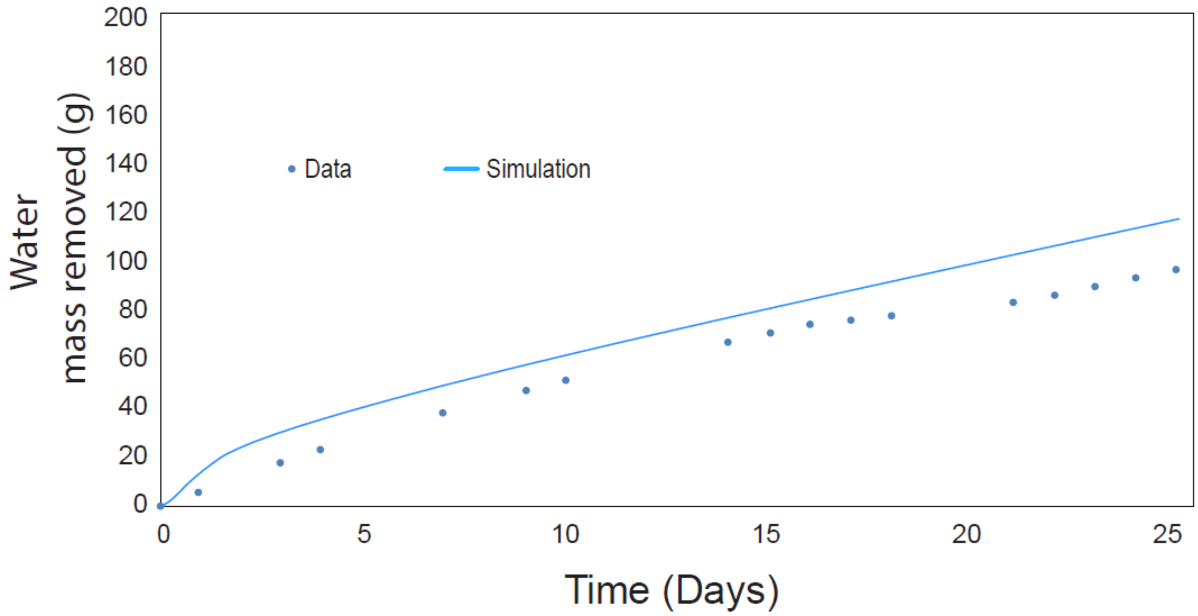

Figure 2-8: Water production during the 120 °C heater block experiment

2.4 Variable Temperature Heater Block Simulations

In an attempt to reach the target formation temperature of 120 °C the heater block temperature was raised in stepwise fashion while monitoring the temperature in the monitoring boreholes. The heater block was subsequently set at 120, 155, 185, and 222 °C over the course of 10 days (Figure 2-9).

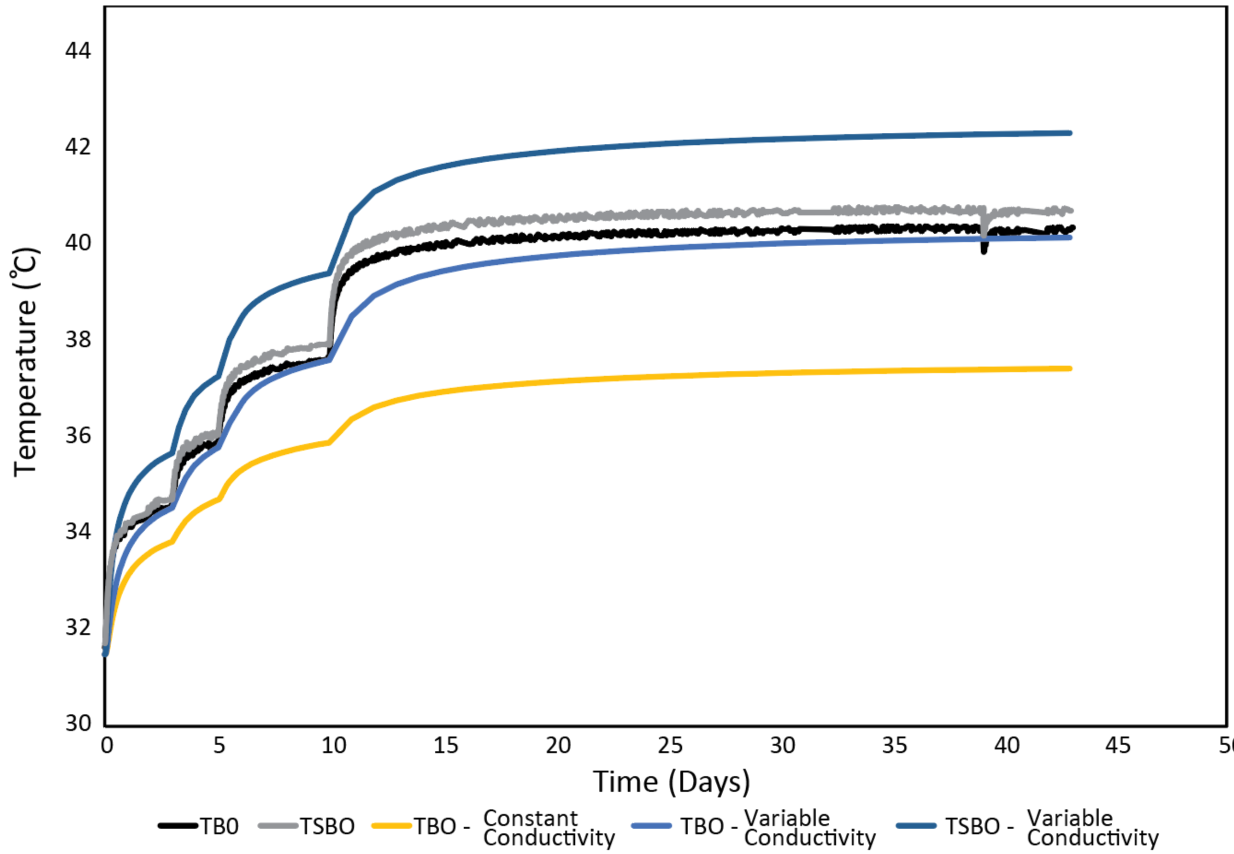

Figure 2-9: Variable temperature heater block simulation

Using the same constant thermal conductivity for the insulating air around the heater block we found the simulations to underestimate the borehole temperatures by a few degrees (yellow line, Figure 2-9). In order to accurately produce the higher temperatures associated with this experiment a new variable conductivity algorithm was added to the FEHM source code. This update to vcon.f, allows for the energy from black body radiation between two nodes to be accounted for through an adjustment of the thermal conductivity. The energy flux due to black body radiation is proportional to the difference in the temperature to the fourth power (Eq. 1)

$$q_{rad} = A_1 F_{1-2} \sigma (T_1^4 - T_2^4) \qquad \text{Eq. 1}$$

where A_1 is the surface area of the heater, T_1 is the temperature of the heater, T_2 is the temperature of the salt adjacent to the borehole, $F_{1\text{-}2}$ is a shape factor, and σ is the emissivity of the stainless steel heater. In this case, since all of the radiation from the heater impacts the salt our shape factor is 1. Using this energy flux we can determine the change in thermal conductivity necessary to account for this radiation, K_R as:

$$K_R = \frac{q_{rad} H}{A_1 (T_1 - T_2)} \qquad \text{Eq. 2}$$

where H is the size of the air gap in the borehole. Finally, the effective thermal conductivity is simply the sum of the thermal properties of the air and those due to radiation:

$$K_{eff} = K_R + K_{Air} \qquad \text{Eq. 3}$$

Applying this variable thermal conductivity model we achieve a satisfactory match to the experimental data (Figure 2-9). Some error is likely be due to the location of the temperature sensors as well as the selection of an appropriate emissivity factor which varies by material, temperature, and over time. Unfortunately, even with the heater set to 222 °C, we still only achieve about 40 °C at the temperature boreholes.

2.5 Radiative Heating Experiments and Simulations

In an attempt to increase the thermal coupling between the heater and the formation a 22 inch long quartz infrared heater was selected (Figure 2-10).

Figure 2-10: Infrared heater being tested on the floor of the mine at WIPP prior to installation

This heater overcomes the insulating layer of air by emitting infrared radiation directly into the formation. The first experiment utilized a 260W heater which achieved 44 °C at the temperature boreholes. This type of heater is accurately modeled using an energy flux boundary condition in FEHM (Figure 2-11).

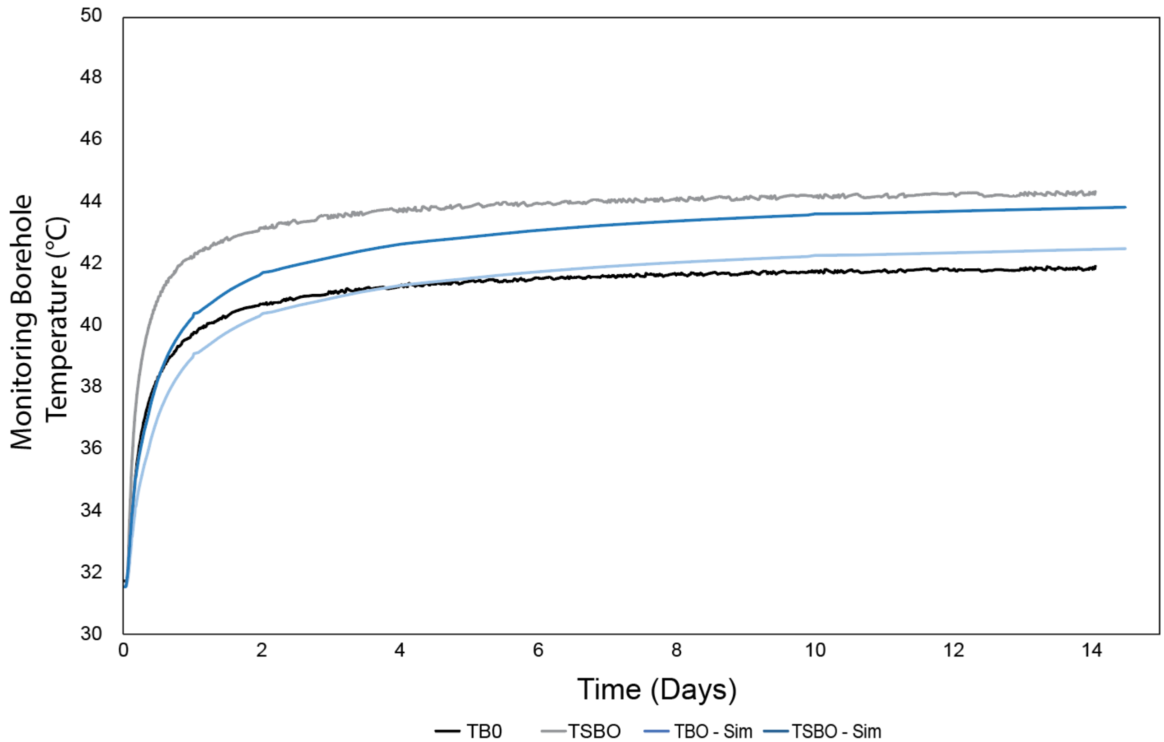

Figure 2-11: Simulation of 260W infrared heater experiment

Successful simulations of the 260W heater experiment provided confidence in the model allowing for the selection of a heater with a specific wattage to achieve the targeted temperature goals. Simulations showed that 750W would achieve approximately 140 °C at the borehole wall and ** at the temperature boreholes. At the time of this writing the 750W has achieved 144 °C at the borehole wall and data from the temperature boreholes is not yet available. With this heater achieving the desired temperatures the Phase 1 experiments are complete. The boreholes for Phase 2 are currently being drilled and the modeling and experiments from them will be the subject of future milestones.

3. Phase 2 Experiments and Simulations

The borehole pattern for the Phase 2 experiments is currently being drilled in the WIPP underground. The Phase 2 experiments will include electrical resistivity measurements, acoustic emission monitoring, more temperature monitoring locations, and tracer injection and sampling locations (Figure 3-1).

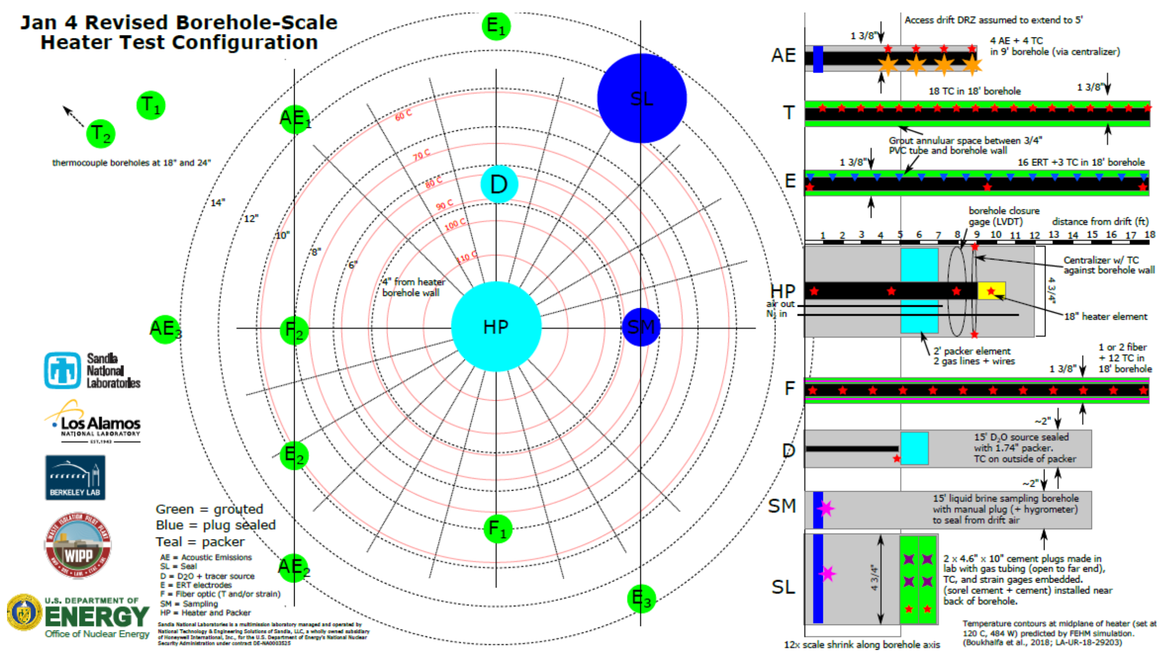

Figure 3-1: Experimental configuration for Phase 2 experiments. Red contours indicate the temperature simulations from numerical models.

The red contours on Figure 3-1 indicate the temperature contours from the numerical simulations developed during the first half of fiscal 2019 at LANL. These simulations have been critical to the selection of a 750W infrared heater and the final borehole configuration for the Phase 2 experiments.

The drift where the Phase 2 experiments are being installed was excavated in early 2012. The pressure distribution was developed similarly to the Phase 1 simulations; however, because the boreholes are being freshly drilled the pressure distribution is not allowed to equilibrate around the boreholes (Figure 3-2). Characterizing the water availability in freshly disturbed boreholes is an important aspect of the Phase 2 experiments and simulations.

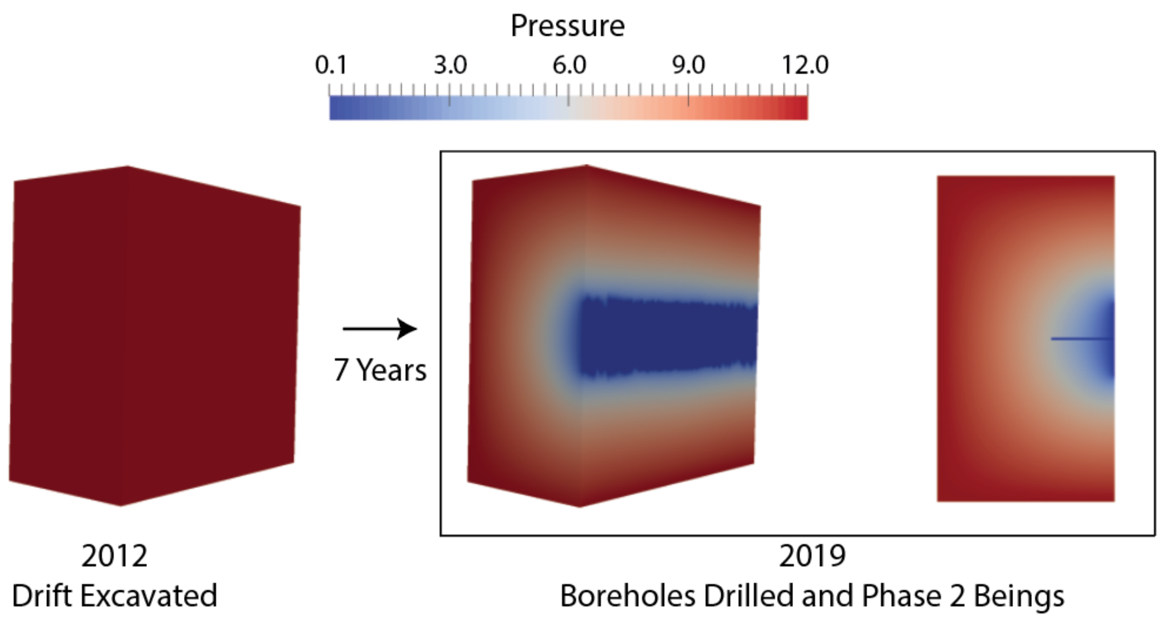

Figure 3-2: Pressure field development for the Phase 2 simulations. Unlike the Phase 1 pressure distributions, the simulations do not equilibrate to the freshly drilled boreholes.

The 750W heater selected for the Phase 2 experiments is expected to raise the temperature significantly more than the Phase 1 experiments. The simulations predict the area around the borehole to approach 140 °C with the temperatures reaching approximately 65 °C as far out as the Phase 1 temperature boreholes (Figure 3-3). As far as 1 meter away from the heated borehole temperatures are forecast to still be above 40 °C. This significant increase in temperature will allow for the study of the thermal effects on water availability that were not observable during the Phase 1 experiments.

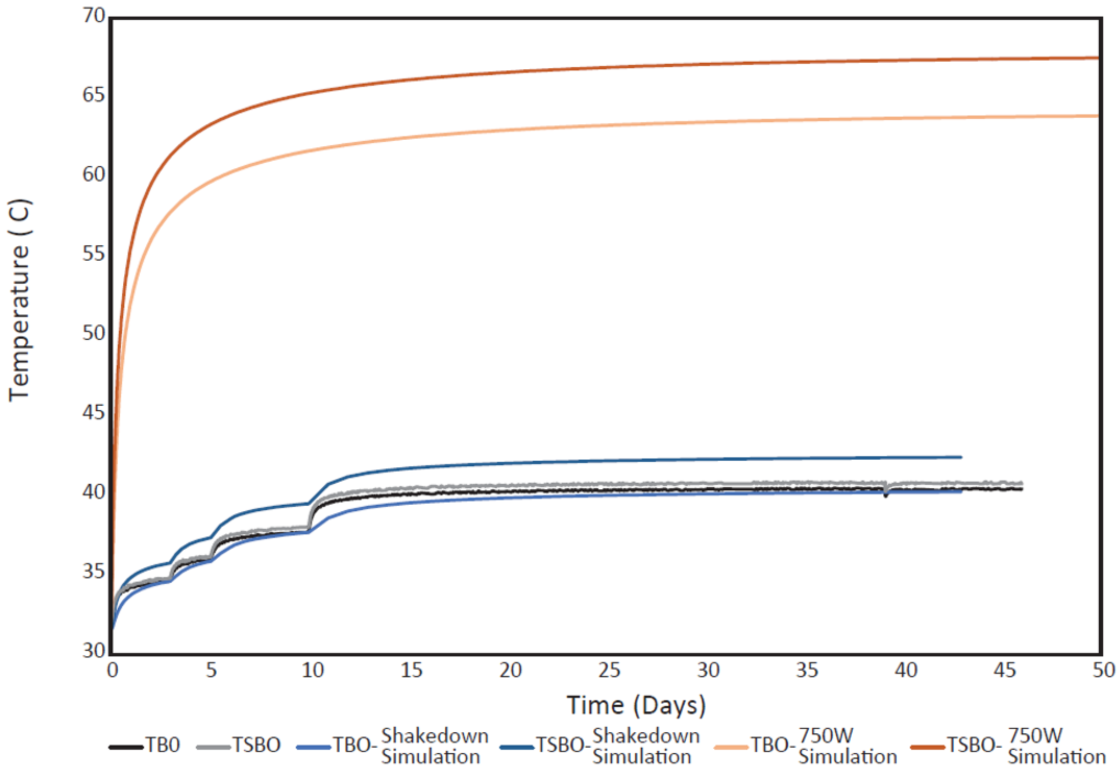

Figure 3-3: Comparison of the temperatures observed and simulated during the Phase 1 (shakedown) experiments and those predicted by the 750W heater to be used during the Phase 2 experiments

The Phase 1 experiments have provided an excellent opportunity for model development and calibration and provided confidence in the successful implementation of the Phase 2 experiments and modeling. The FEHM simulations accurately represent the temperature of the salt formation and the simulated pressure distributions and permeability are able to recreate the observed water production. The Phase 2 experiments will begin shortly and the results of the experiments and simulations will be the focus of the next modeling milestone.

4. References

Beauheim, R. L., P. S. Domski, and R. M. Roberts (1999), *Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Final Report*, Sandia National Laboratory, Report: SAND--98-2537

Bourret, S. M., E. J. Guiltinan, P. J. Johnson, S. Otto, D. J. Weaver, B. Dozier, H. Boukhalfa, T. A. Miller, and P. H. Stauffer (2019), *Experiments and Simulation of a Borehole in Salt to Understand Heat, Brine, and Vapor Migration*. Waste Management 2019 Proceedings

FEHM (2019), FEHM Website, https://fehm.lanl.gov/ accessed March 20th, 2019.

Johnson, P. J., P. H. Stauffer, G. A. Zyvoloski, and S. M. Bourret (2018), *Experiments and Modeling to Support Field Test Design*, Los Alamos National Laboratory, Report: *LA-UR-18-28189*

Johnson, P. J., S. Otto, D. J. Weaver, B. Dozier, T. A. Miller, A. B. Jordan, N. G. Hayes-Rich, and P. H. Stauffer (2019), *Heat-Generating Nuclear Waste in Salt: Field Testing and Simulation*, Vadose Zone Journal, 18(1), doi: 10.2136/vzj2018.08.0160

Jordan, A.B., Boukhalfa, H., Caporuscio, F.A., Stauffer, P.H. *Brine Transport Experiments in Granular Salt* (2015), Los Alamos National Laboratory, Report: LA-UR-15-26804.

Kuhlman, K. L., M. M. Mills, and E. N. Matteo (2017), *Consensus on Intermediate Scale Salt Field Test Design*, Sandia National Laboratory, Report: *SAND2017-3179R*

Kuhlman, K. L., M. M. Mills, C. G. Herrick, E. N. Matteo, P. Stuaffer, P. Johnson, H. Boukhalfa, D. Weaver, J. Rutqvist, and Y. Wu (2018), *Project Plan: Salt in Situ Heater Test*, Sandia National Laboratory, Report: *SAND-2018-4673R*

Kuhlman, K.L., Malama, B (2013), *Brine Flow in Heated Geologic Salt*, Sandia National Laboratory, Report: SAND2013-1944

Stauffer, P.H., A. B. Jordan, D. J. Weaver, F. A. Caporuscio, J. A. Ten Cate, H. Boukhalfa, B A. Robinson, D. C. Sassani, K. L. Kuhlman, E. L. Hardin, S. D. Sevougian, R. J. MacKinnon, Y. Wu, T. A. Daley, B. M. Freifeld, P. J. Cook, J. Rutqvist, and J. T. Birkholzer, (2015). *Test proposal document for phased field thermal testing in salt*. Los Alamos National Laboratory, Report: FCRD-UFD-2015-000077

Zyvoloski, G.A., B. A. Robinson, Z. V. Dash, S. Kelkar, H. S. Viswanathan, R. J. Pawar, P. H. Stauffer, T. A. Miller, S. P. Chu (2012), *Software users manual* (UM) for the FEHM Application Version 3.1-3.X, Los Alamos National Laboratory, Report: LA-UR-12-24493