Brine Availability Test in Salt: THMC Simulations of a Heated Borehole in Salt - 20239

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ABSTRACT

The Brine Availability Test in Salt (BATS) is a collaboration between Los Alamos, Sandia, and Lawrence Berkeley National Laboratories formed to reduce the uncertainties associated with long-term disposal of spent nuclear fuel (SNF) in a hypothetical bedded salt repository. Bedded salt formations may be an ideal location for disposal of nuclear waste due to their high thermal conductivity, extremely low permeability, and self healing capability. In this paper, we report on the first round of the BATS project with an emphasis on the supporting numerical modeling. The experiment was conducted at the Waste Isolation Pilot Plant (WIPP) and included heating previously drilled horizontal boreholes while monitoring nearby temperatures and water production to the borehole. We find due to the extremely low permeability of salt long term numerical simulations are necessary to develop the appropriate initial conditions. Testing with different heater designs reveals that a 750 W radiative heater within a borehole can achieve temperatures expected from waste packages. In addition, the inclusion of a damaged rock zone plays an important role in the pressure and saturation distribution at the start of testing and the lower saturations within this zone may dissipate the thermal pressurization when compared to simulations that do not include a damaged rock zone.

INTRODUCTION

While the future of the Yucca Mountain disposal facility remains unclear, the need for a high-level nuclear waste disposal facility continues to grow. To reduce the uncertainty associated with the long term storage of nuclear waste the US Department of Energy Office of Nuclear Energy's (DOE-NE) is developing and research program to examine the potential of storing nuclear waste in hypothetical argillaceous, crystalline, and salt formations [1]. Salt formations are considered a strong candidate for securely storing nuclear waste for because they have extremely low permeability, high thermal conductivity, and salt creeps under stress [2, 3]. The low permeability of salt prevents the advection of potentially contaminated groundwater away from the repository. The high thermal conductivity dissipates the energy from the nuclear waste into the formation, leading to lower repository temperatures and more stable conditions. Salt creeps (or flows) when exposed to differential stresses allowing the formation to "heal" any cracks or fractures induced by mining or heating.

Bedded salt deposits are relatively dry but do contain some water (less than 5% water by volume). This water exists as fluid inclusions, inter-granular porosity, and bound with hydrated minerals [4]. At the Waste Isolation Pilot Plant (WIPP) the bedded salt permeability is estimated at 10^{-21} to 10^{-22} m^2 [5, 6], however brine accumulations still occur within drifts and boreholes. Previous heater experiments at WIPP conducted in boreholes that intersect a clay layer have shown that heated boreholes produce more water than unheated boreholes [7, 8]. However, at the Asse II mine, a domal salt mine in Germany, heated boreholes produced much less water than expected with approximately 90% of it observed during the cool down period after the heater was shut off [9 , 10]. These tests leave uncertainty about the source and abundance of water in salt formations exposed to heating. These uncertainties could be reduced by investigations into the coupled thermal, hydrological, mechanical, and chemical (THMC) behavior of salt [11, 12].

Developing numerical simulations is important for ensuring the long-term stability of disposed HLW; however, simulating the strongly coupled processes in salt is computationally challenging. Simplifying the THMC couplings is difficult due to their interconnected relationships. This makes it difficult to understand the relative importance of different components. For instance, increased temperature drives thermal pressurization, which induces salt creep, which is itself dependent on temperature and humidity. By including the full physics as much as possible we can be sure that no unexpected behavior is missed in the simulations. In addition, the necessary scale of the experiments, large gradients, and boundary effects require a highly resolved three-dimensional mesh, further increasing the computational expense.

To develop these simulations and to reduce the uncertainties associated with brine availability to heat sources, a collaboration between Los Alamos, Sandia, and Lawrence Berkeley National Laboratories has been formed to conduct the Brine Availability in Salt Tests (BATS) experiments. These experiments are the first heated borehole salt experiments conducted underground at WIPP in almost 30 years. The goals of the first round of testing were to regain lost institutional experience working underground, test and troubleshoot equipment, and validate the coupled numerical simulations necessary to model the heat and brine transport with salt formations. The results from the first experiment have been used to develop a larger scale test conducted in freshly drilled boreholes, which is currently underway.

DESCRIPTION

Experimental Setup

The first phase of the BATS experiments was conducted on horizontal boreholes completed in the drift face for core collection in 2012 (Figure 1).

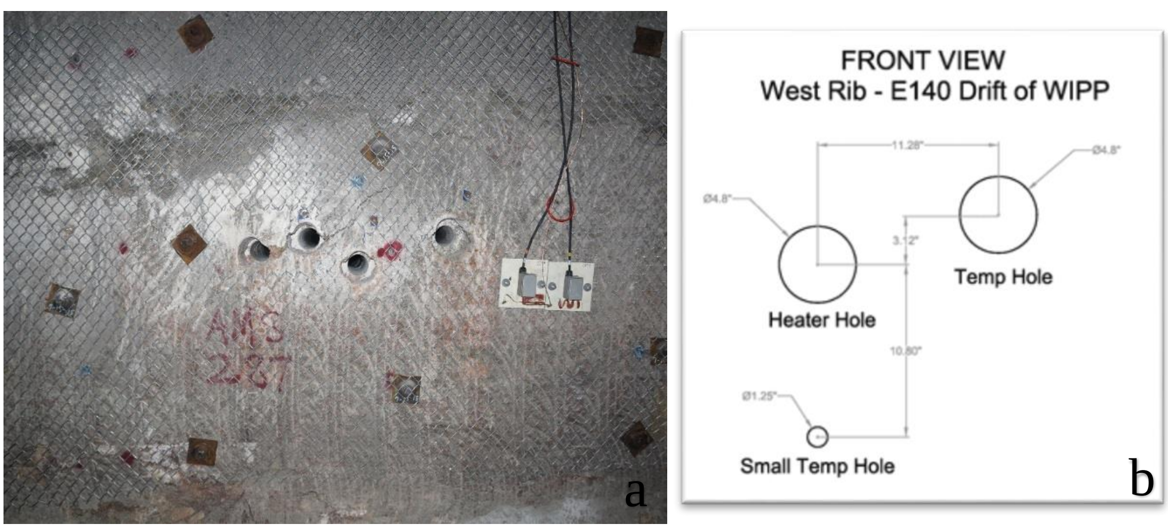

Fig. 1. (a) The face of the wall on which the horizontal boreholes are located for experimentation. Also seen in this picture are the rock bolts and chain link fence used to secure the drift face and reduce the likelihood of rock falls. The image predates the majority of instrument installation, however the power supply junction boxes can be seen to the right of the existing boreholes. The boreholes used in testing

shown in schematic view in (b) that includes the heater borehole (HB), a temperature borehole (Tb), and a small temperature borehole (Tsb).

A heater was isolated within a borehole (heater hole) behind an inflatable packer. Temperature sensors were installed within the heater hole, as well as the small temp hole (Tsb) and the temp hole (Tb). Dry nitrogen gas was circulated behind the packer where it could pick up water vapor and carry it out of the borehole through desiccant canisters of Drierite® which were weighed periodically to quantify water removal. A flowmeter, humidity, pressure, and temperature sensor was located in line before the dessicant containers and was used to verify the water removal measurements. Three different heaters were ultimately installed: a stainless steel resistive block heater, a 260 W radiative heater, and a 750 W radiative heater. A schematic of the experiment is shown if Figure 2.

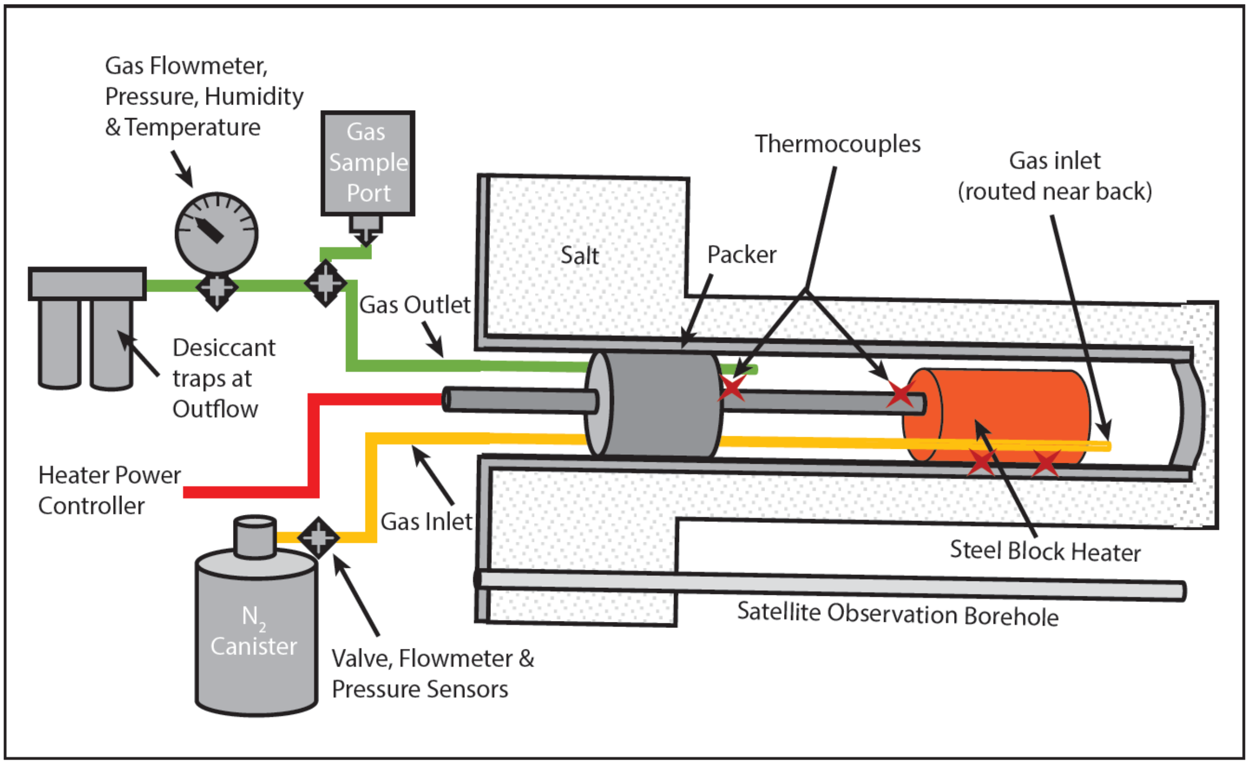

Figure 2: Detailed view of heated borehole instrumentation with a steel block heater installed behind an inflatable packer.

To reach the desired temperature of 120 °C at the borehole wall a stainless steel resistive heater block was installed in the heated borehole and set to 120 °C. Due to the insulating air gap around block heater the temperature at the monitoring boreholes only reached 35 °C. Next the block heater temperature was raised from 120 to 155 to 185 and finally 220 °C although the desired temperatures were not reached these experiments provided valuable data for model development. To overcome the insulating air gap an infrared radiative heater was selected (Helios Quartz ® I.R. Twin Tube Medium Wave). First, a 260 W heater was installed and later a 750 W version. The infrared heaters reached approximately 42 and 58 °C degrees in the monitoring borehole Tb (Figure 3). Which the 750 W radiative heater reaching the desired temperature the experiment was concluded.

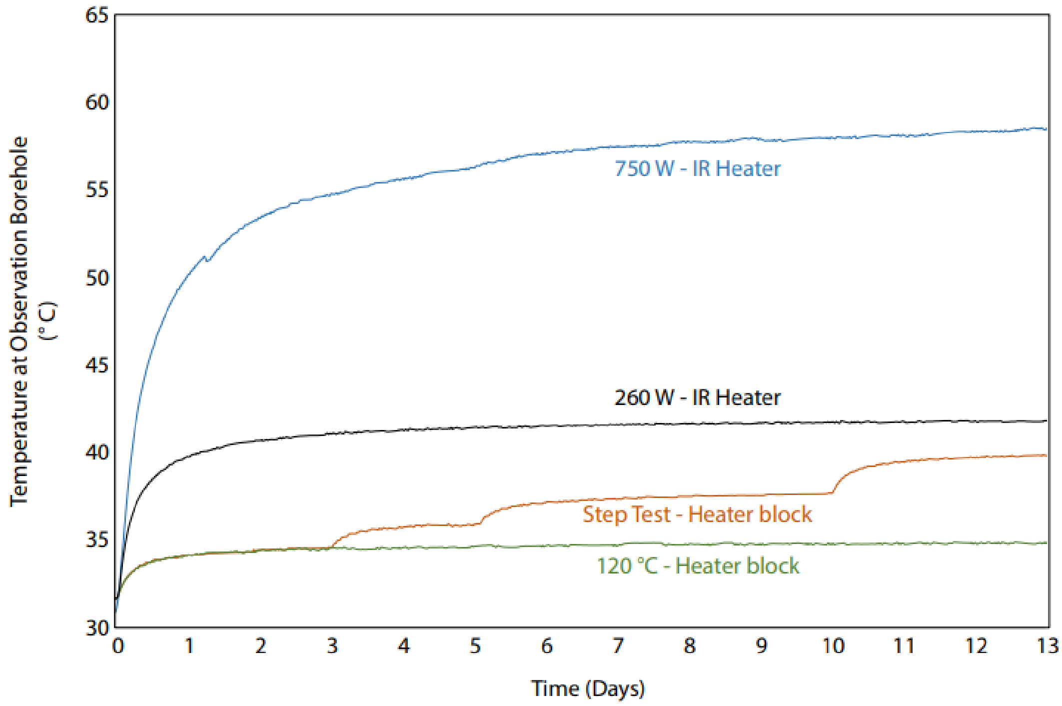

Figure 3: Temperature at Tb vs. time since heating began during each heater test. Tb is located approximately 0.3 m away from the heated borehole.

Model Setup

Model development was conducted using the porous flow simulated FEHM [13, 14] A 20 m X 20 m X 10 m three dimensional mesh was generated using LaGriT [15]. The mesh is highly refined around the heated borehole to resolve the high temperature, saturation, and pressure gradients near the borehole. Resolution is decreased radially to reduce computational expense. A higher permeability DRZ layer surrounds the borehole with a thickness of 0.08 m (3 inches). The size of the DRZ is dependent on the nearby excavations and ranges from 0.5 to 1.5 m around a 5 m drift excavation [16]. Given a borehole diameter of 0.24 m the DRZ falls within the appropriate range of observations. A schematic of the model is shown in Figure 4 while a table of relevant parameters is presented in Table 1.

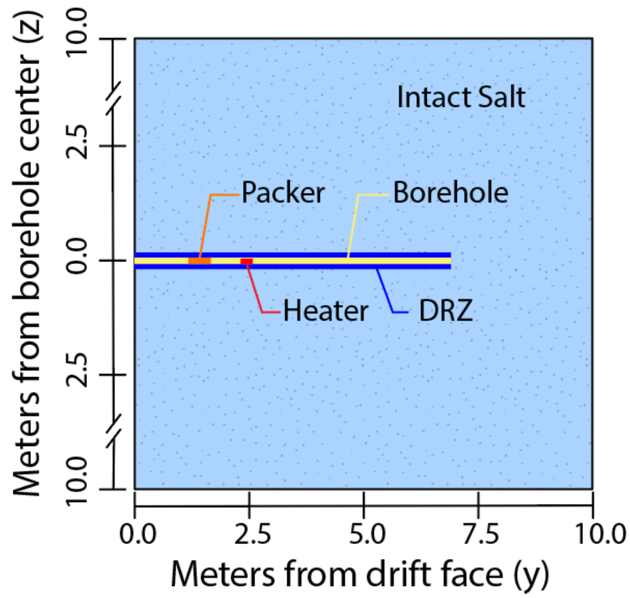

Figure 4: Cross-section of the model geometry, showing the 0.12 m radius borehole in yellow, packer in orange, heater in red, the 0.08 m thick damaged rock zone in dark blue, and the background salt in light blue. The full mesh is 20 m × 10 m × 20 m and is composed of 1,003,995 elements.

TABLE 1: Key initial parameters used for heated borehole simulations

Parameter	Value
Salt initial porosity (-)	0.001
Salt initial permeability (m^2)	10^{-21}
Damaged rock zone permeability (m^2)	10^{-18}
Damaged rock zone thickness (m)	0.08
Air permeability (m^2)	10^{-12}
Salt thermal conductivity at 31.5 ºC (W/m K)	5.25
Air thermal conductivity (W/m K)	0.03
Initial formation pressure (MPa)	12
Initial formation temperature (°C)	31.5
Air source behind heater (kg/sec)	3.83×10^{-6}
Residual saturation (-)	0.1
Maximum capillary pressure (MPa)	1.0
Saturation at which capillary pressure is zero (-)	1.0

The porosity, thermal conductivity, and permeability are not static within the model. For instance, porosity changes due to the dissolution of salt, which causes changes in permeability; whereas, temperature changes from the heater drive changes in thermal conductivity. These coupled processes in FEHM have been developed over the past 8 years and are covered in detail in previous work [17, 18, 19, 20]. A linear relative permeability model is used for the intact salt and DRZ with capillary pressure varying between 0 MPa when fully saturated and 1 MPa at a theoretical zero saturation. During the experiment dry nitrogen was injected behind the heater at 200 ml/min, the nitrogen picked up moisture and exited through an outlet in the packer. We simulate this as dry air source located approximately 0.2 meters past the heater with an equivalent flowrate of 3.83×10^{-6} kg/sec. The dry air picks up humidity and exits the model at a node located at the packer surface with an atmospheric pressure condition.

The initial pressure and saturation distributions are developed using long-term simulations (Figure 7). The models are began in 1982, when the drift was first excavated. An atmospheric pressure and dry condition are applied at the drift face to represent the presence of the drift. After 30 years, the borehole and DRZ are included in the model and the pressure and saturation distribution continue to evolve for another 6 years. This represents the initial condition for our models.

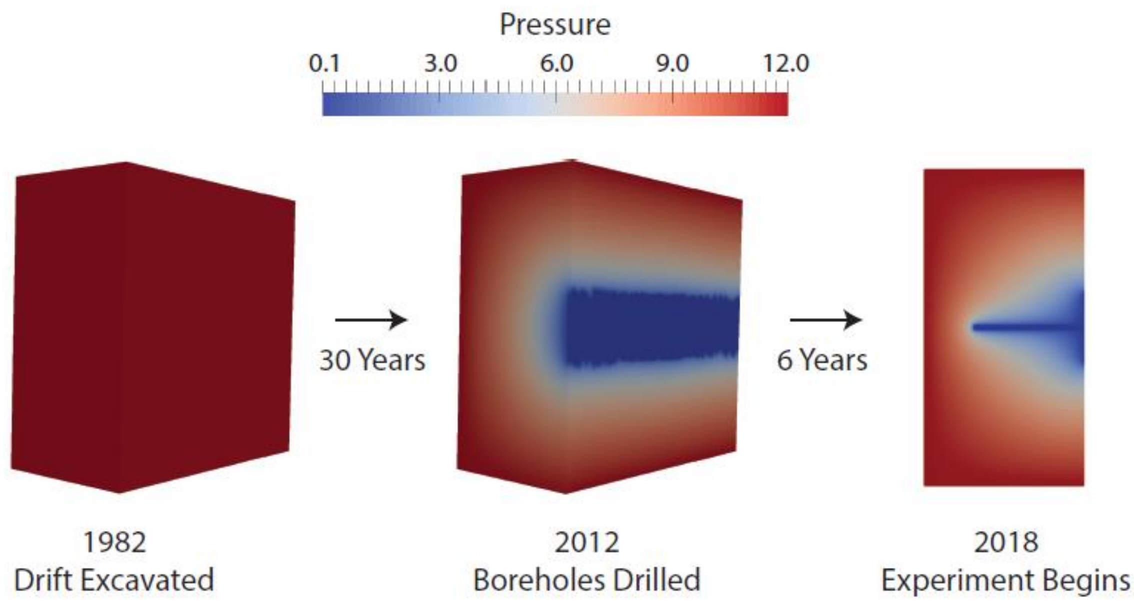

Figure 5: Brine pore pressure (in MPa) distribution development for simulation initialization. Domain is 20 m × 10 m × 20 m.

DISCUSSION

Temperature

Using a constant thermal conductivity for the air surrounding the stainless steel resistive heater the simulations under predicted the temperatures at the observation boreholes (Figure 6, yellow line). However, once an effective variable thermal conductivity that accounted for the black body radiation between the heater and the borehole was implemented the predictions agreed closely with observations. Some error associated with uncertainty about the exact locations of the temperature sensors within the observation boreholes is expected.

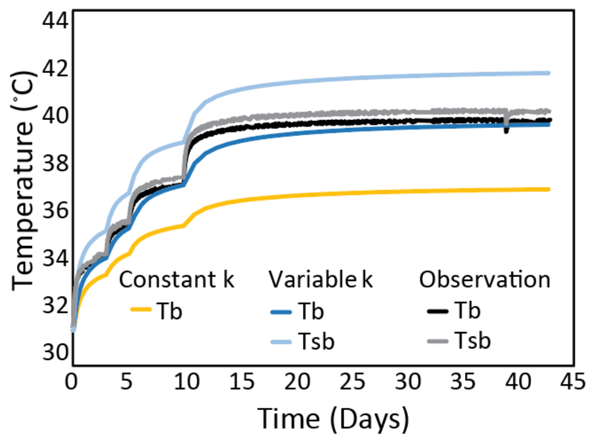

Figure 6: Simulated and observed Temperatures at Tb and Tsb during heating with the stainless steel resistive heater block. In yellow, the original model prediction before accounting for black body radiation between the heater and borehole wall.

The 260 W and 750 W radiative infrared heaters dramatically increased the energy transfer to the nearby formation. The simulations were able to accurately model of the observed temperatures (Figure 7). During the 750 W heater experiment the heater was placed deeper within the heater borehole. This resulted in the Tsb sensor being out of the plane with the heater resulting in a significant decrease in temperature compared to the Tb temperature. The ability of the simulations to accurately model the radiative heater experiments gives the BATS team confidence in their ability to model future experiments which will utilize this style of heater.

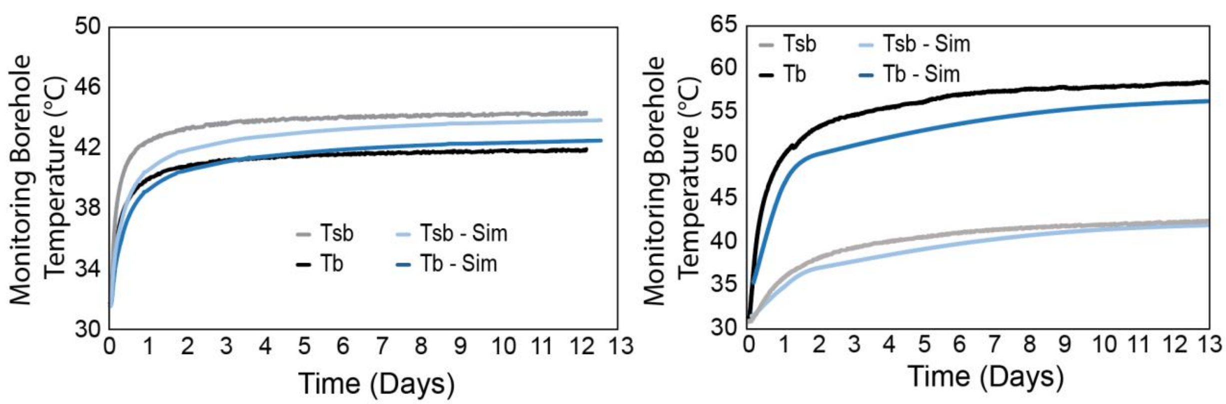

Figure 7: Simulated and observed temperatures at Tb and Tsb during heating with a 260 W Heater (left) and 750 W heater (right). During the 750 W heater experiment the heater was placed further into the borehole. The Tsb temperature sensor was no longer in plane with the heater resulting in a significant decrease in temperature compared to the Tb sensor.

Water Production

Through successive simulations it was determined that an initial permeability of 10^{-21} m^2 for intact salt and 10^{-18} m^2 for the borehole DRZ accurately reflects the water production during the experiments (Figure 8). Previous work at WIPP estimates the permeability of halite to fall between 3 ×

10^{-16} to 2×10^{-23} m^2 [6]. The water production increases with temperature as the heater increases the vapor pressure within the formation and drives water vapor into the borehole. Long term simulations show that the DRZ remains partially saturated for longer than 3 years. Data during the 750 W heater test was not available during this experiment but this data will be gathered during the next round of experiments. The next round of experiments will be conducted in freshly drilled boreholes. Simulations suggest these experiments will produce more water and more thermal pressurization due to beginning with a fully saturation DRZ. With the successful implementation of a 750 W radiative heater and the accurate simulation of both temperature and water production the first phase of the BATS experiment is concluded.

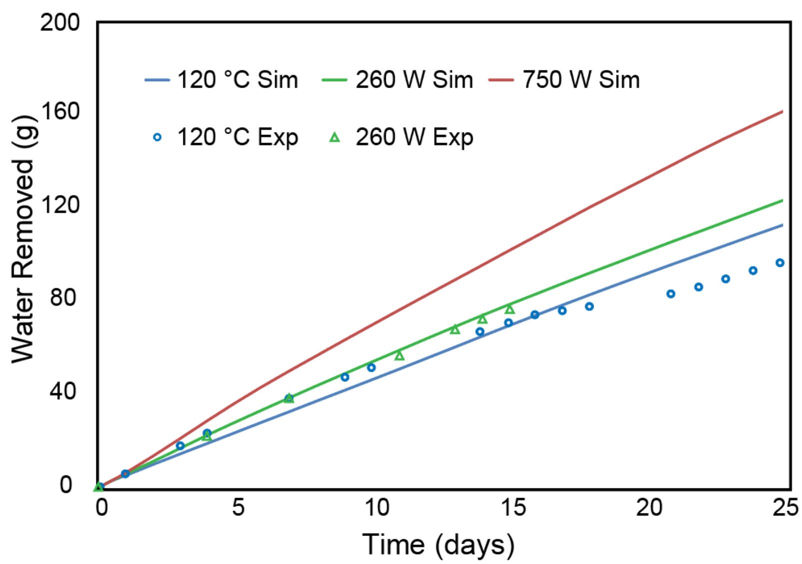

Figure 8: Water production during the 120 °C heater block and 260 W radiative heating experiment compared to simulations. Observations from desiccant are points while simulations are lines.

CONCLUSIONS

A collaboration between Sandia, Los Alamos, and Lawrence Berkeley national lab has been established to conduct the Brine Availability Test in Salt (BATS) experiments. The goal of these experiments is to reduce the uncertainty associated with brine origin and abundance in bedded salt near heat generating nuclear waste. The first phase of the experiment began in 2018 and included a series of borehole heater tests conducted in previously drilled boreholes at the Waste Isolation Pilot Plant. The results showed that a 750 W infrared heater was capable of reproducing the temperatures expected from a heat generating nuclear waste canister. Thermo-hydro-mechanical-chemical coupled simulations conducted using FEHM accurately reproduce the temperature and water production from the dry boreholes. Simulations show the importance of conducting long-term simulations based on the history of activity at the WIPP site to establish the initial pressure and saturation conditions. These simulations give the BATS team confidence in their ability to model the next round of larger experiments to be conducted in freshly drilled boreholes.

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