Thermal Energy Storage Using High Temperature Borehole Heat Exchangers in Unconsolidated Materials

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THERMAL ENERGY STORAGE USING HIGH TEMPERATURE BOREHOLE HEAT EXCHANGERS IN UNCONSOLIDATED MATERIALS

A Thesis
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Hydrogeology

by
Kayla Bicknell
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Accepted by:
Dr. Ronald Falta, Committee Chair
Dr. Lawrence Murdoch
Dr. Brady Flinchum
ABSTRACT

Thermal energy storage is a potential method for storing excess energy produced when supply is greater than demand. The use of the subsurface for storing thermal energy has become more recognized as a viable alternative to conventional methods of energy storage. However, high temperature borehole thermal energy storage has yet to be researched in-depth. Therefore, the goal of this project is to determine the feasibility of using the subsurface to store thermal energy at relatively high temperatures.

The focus of this work is to determine what design elements would make a borehole thermal energy storage system most effective and produce the most power. To do so, laboratory experiments assessing different borehole heat exchanger designs as well as analytical and numerical models were used to evaluate different parameters. Once important parameters were understood, a numerical model was built in TOUGH2.1-EOS3 to determine an estimated power production from both small-scale and pilot-scale systems. The borehole thermal resistance (BTR) represents the sum of the resistances inside the borehole between the circulating fluid and the soil (Zhang et al., 2015). The BTR is valuable when designing the BTES system because it can have a significant effect on the system performance and should be minimized to see the best results (Gehlin, 2002). Therefore, by constructing several different models for each size BTES system, the effects of varying borehole spacing, and borehole thermal resistance (BTR) values could be established.

The results show that when borehole heat exchangers are in direct contact with unconsolidated sediment, the BTR is between 0.10 and 0.13 m°C/W. However, when the annulus of the borehole is filled with a thermally enhanced grout the BTR value for the U-bend falls to approximately 0.03 m°C/W. The radial temperature drop required for a unit of heat flux
between the BHE and the formation is proportional to the BTR, so a design with a low BTR is more efficient than one with a higher BTR.

Varied BTR values were used within the TOUGH multiphase flow simulations to determine the impact they would have on each system. In the pilot scale simulation, the production of power at the end of a 30-day production cycle was between 30 and 60 W/m. The lower thermal power output correlated with the system that had a higher BTR value and vice versa. Therefore, the BTR is highly important and design choices should be made to keep it as low as possible.
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1 INTRODUCTION

Since the beginning of the industrial revolution, fossil fuels have played a large role in energy generation as well as the global economy. Climate change caused by increased carbon dioxide emissions has been the main motivator for the push to renewable sources of energy production. With carbon emissions being the leading cause of climate change, research into alternative energy sources has also ramped up (IPCC, 2023). However, as of 2021, the U.S. Energy Information Administration (EIA) reported that natural gas and coal were still the leading providers of energy, producing more than 60% of the nation’s demand. Meanwhile, renewable energy accounted for only about 20%; divided between solar, wind, geothermal, hydroelectric, and biomass energy production. An additional 19% of energy production was provided by nuclear sources (US EIA, 2022). Conventional energy production methods across the United States costs consumers approximately $0.12/kWh (EIA, 2023).

While solar only accounts for approximately 2.8% of total U.S. electricity generation, with 79,000 Terawatt years (TWyr) of solar energy hitting the earth’s surface annually it constitutes the largest, readily accessible energetic resource available on earth (Perez and Perez, 2022). Perez and Perez (2022) found that solar power is capable of meeting 100% of extant global primary energy demand 12x over even after considering reasonable constraints posed by land use and conversion efficiency.

While solar energy seems to have a promising future, solar irradiation differs throughout the day as well as seasonally. Depending on the latitude of the solar collectors, there is the potential for long periods of time without sunlight. This presents the issue of how to store the energy produced when supply exceeds demand in a way that limits increased costs to the consumer. According to the US Office of Energy Efficiency & Renewable Energy (EERE), the
most common form of energy storage is pumped hydropower followed by electrochemical storage (batteries), thermal storage, and compressed air storage (www.energy.gov/eere/renewable-energy).

Pumped-storage hydropower employs the same methodology as hydroelectric power i.e., water flowing downhill spins a turbine to produce electricity. This can be used as a storage method because in this case, the excess electrical energy produced from solar when demand is low can be used to pump water up into a reservoir. The water pumped into storage is then released when demand is higher than the supply. EERE states that this technology has been in use since 1929, however, the areas where this technology can be used must have a suitable landscape and natural reservoir areas (www.energy.gov/eere/renewable-energy). A 100 MW pumped-storage hydropower plant with ten hours of storage is estimated to cost approximately $260/kWh (Mongird et al., 2020).

Another viable option is electrochemical storage, typically in the form of lithium ion or lead acid batteries (EIA, 2022). These are large-scale batteries capable of storing electricity until it is needed later. This is done by a series of reactions within the battery itself. When the electricity enters the battery, a chemical reaction occurs which allows for the energy to be stored effectively. Therefore, when it is time to discharge the battery, the chemical reaction is reversed, and a voltage is created across the two contacts which allows current to flow out. This option tends to be quite expensive, costing approximately $350 to $400/kWh with ten hours of storage (Mongird et al., 2020). Therefore, consumers are hesitant to switch from the conventional energy sources that are available on demand.

Compressed air energy storage (CAES) is also an option that has been considered. According to the Pacific Northwest National Lab or PNNL (2019), the idea of a CAES is to store
compressed air in suitable geologic structures underground or large vessels aboveground when electrical supply is greater than demand. The high-pressure air would then be returned to the surface where it can expand and be used to spin a turbine when additional electricity generation is necessary. Once again, if utilizing natural geologic formations, the possibility of installing a CAES will be highly location dependent as it would require the use of a reservoir of some sort with sufficiently low permeability to act as the cap rock. Otherwise, like pumped storage hydropower the implementation may be cost prohibitive with a cost of approximately $120/kWh with four hours of storage (Mongird et al., 2020).

Thermal energy storage (TES) typically refers to a technology where a fluid or other material is used to store heat in an insulated tank until energy is needed (EERE, 2023). Storing heat at relatively high temperature (greater than 200°C) is important because it can be recovered and used to generate steam which drives a turbine to produce electrical power. This thesis aims to look at the feasibility of storing heat in the subsurface rather than in an insulated tank aboveground. Most subsurface thermal energy storage projects operate at relatively low temperatures, like the Drake Landing Solar Community (DLSC) located in Okotoks, Alberta where 800 solar panels are used for space and water heating for 52 homes (https://www.dlsc.ca/). Only a few power plants in the world have tested high temperature thermal energy storage systems above 120°C none of which are known to utilize the subsurface as their storage mechanism (Marc Medrano et al., 2009).

While the aboveground methodologies for TES have been successfully implemented across the globe, only one is located in the US: the Solana Generating Station located in Pheonix, Arizona which is a 250 MW parabolic trough concentrating solar power plant with a molten salt TES system (https://www.energy.gov/lpo/solana). While aboveground storage has proven
viable, it may be possible that the natural subsurface could also be effective in storing thermal energy. Natural earth materials have a combination of high heat capacities and moderate to low thermal conductivities compared to other elements and metals which could potentially allow for the storage of large amounts of heat and eliminate the need to purchase a chemical battery or use other forms of energy storage (Falta et al., 2021).

This thesis examined a high temperature borehole thermal energy storage system (ht-BTES) that will reach temperatures in the 200 to 300°C range. Temperatures in this range are too low for traditional Rankine cycle power production and so an Organic Rankine cycle (ORC) will need to be utilized to generate power from the system. An ORC differs by using an organic working fluid that maximizes thermal efficiencies for the temperature range that the system intends to operate at (Yamada et al., 2012). While the temperature of the heat from the system plays a part in efficiency, the efficiency of the ORC is heavily dependent on the working fluid that is chosen as well as the heat sink temperature (Daniarta et al., 2023).

If the BTES can achieve these temperatures and ultimately produce thermal power that can be turned into electricity, it has the potential to act as a resilient energy reserve in the case of a disruption to the electrical supply. Additionally, the estimated costs associated with the TES system are expected to be in the $5-10 kWh range, making it more financially appealing than the other methods of energy storage discussed above.
2 RESEARCH OBJECTIVES

Through my research, I aim to:

1) Evaluate the fundamental earth thermal properties that favor a BTES system by comparing dry sand and granite.

2) Determine effective BHE spacing for different size BTES systems.

3) Measure the borehole thermal resistance (BTR) for prototype BHE designs in the laboratory.

4) Determine the field performance of BTES systems by using multiphase flow heat transfer models.
3 APPROACH

3.1 OPEN AND CLOSED SYSTEMS

Depending on the system application, there are two major subsurface thermal energy storage systems that are typically used: open systems and closed systems. In an open system, a well is installed which allows for a heated substance (typically water) to be injected into the formation (Eklof & Gehlin, 1996). The system can be reversed if the opposite effect is desired. In a closed system, the borehole typically contains either one or several U-bends or coaxial pipes in which neither of the pipes are open to formation (Eklof & Gehlin, 1996). In a closed system heating or cooling of the fluid within the borehole heat exchanger is completed primarily by conduction to or from the formation. For the purposes of this project, the closed system method was utilized.

This system requires the installation of closed loop BHEs beneath the earth’s surface at a determined depth. The BHEs proposed installation locations are either in a shallow, unconsolidated formation above the water table or in an unfractured crystalline rock matrix that can be situated either above or below the water table. The unconsolidated formation requires that the BHEs be above the water table so that the area around the BHEs is not constantly being infiltrated by groundwater recharge, which will expend the energy stored by boiling the water, rather than reaching the desired temperatures.

A BTES system in an unfractured crystalline rock formation can be below the water table due to minimal porosity and permeability of this rock type. Therefore, as the rock is heated during the preliminary heating period, the water is unlikely to be able to penetrate back into the system. However, there are additional complications that could occur with the increased thermal
conductivity of the crystalline rock compared to dry unconsolidated materials. This thesis will evaluate both scenarios but will focus on whether a BTES system is feasible in an unsaturated, unconsolidated formation.

3.2 BTES SYSTEM CONCEPTS AND SET UP

The full-scale high-temperature thermal energy storage (ht-BTES) system to be discussed in this thesis would work by pumping a food-grade thermal fluid through pipes attached to solar thermal collectors that heat the fluid. The fluid would then be pumped through a closed loop borehole heat exchanger (BHE) array which will conduct heat outward into the surrounding formation. The formation will undergo an initial heating event prior to power production to heat the entirety of the volume between BHEs to a desired temperature. This will be accomplished by pumping a hot thermal fluid through the BHE array.

The evaluation of a ht-BTES system in the form of a thermal battery is the goal of this thesis. A thermal battery refers to the process of heating up a volume of the subsurface, or charging, then withdrawing, or discharging, that heat therefore, storing energy and functioning similar to a battery. When discharging the system, the hot thermal fluid would be used to flash a working fluid into steam and drive a turbine for electricity generation.

If the appropriate amount of energy has been stored and there is no additional demand, the system could run as a regular power plant would to generate electricity while maintaining the amount in storage. Therefore, the potential benefits are high if a solar thermal, or other, power plant was able to be successfully joined with a ht-BTES system, especially when the resiliency of the system is compared to current means of electricity generation (Falta et al., 2021). A schematic of the workflow can be seen in Figure 1.
This thesis focused only on the subsurface storage of heat and does not require the energy stored to be produced by renewable sources; therefore, electric water heaters were used during laboratory experiments. The main elements included BHEs and initially a 100-W electric inline water heater for heating in the laboratory. This heater will eventually be upgraded to a 24-kW hot oil heater for further testing. The design of the BHEs to be used in the field are dependent on the lab results discussed in Section 6.
4 DETERMINING THE MAGNITUDE OF HEAT LOSSES DURING STORAGE

4.1 BACKGROUND

It is helpful to investigate the energy storage of the system as a function of the heat transfer properties and storage volume. The method chosen for estimating the heat losses from the BTES system was a spherical analysis for heat conduction. This method can be used to determine the feasibility of using different formation types as well as the impact of using different volumes. The spherical system was chosen for this order of magnitude analysis because it is the simplest model that captures the dominant volumetric effects.

4.2 DESCRIPTION OF SPHERICAL ANALYSIS METHOD

This analysis uses one-dimensional spherical heat conduction away from the storage volume to estimate the magnitude of heat losses out of the BTES system. To do so, the steady state differential equation for spherical heat conduction is used and is described below as Equation 1.

\[
\frac{d}{dr} \left( r^2 \frac{dT}{dr} \right) = 0
\]

The storage volume has a radius of \( r_{st} \) and is assumed to have a uniform and constant temperature. The constant temperature boundary at \( r_e \) is maintained at a temperature \( T_e \) while the average temperature inside the storage volume is represented as \( T_{st} \). As a special case, \( r_e \) may be located infinity far away. For this analysis, several assumptions were made to allow the use of Equation 1. It was assumed that the system is at steady state, is isotropic and homogeneous, and there is no heat generation taking place. With these assumptions, the boundary conditions for integrating the equation are \( T=T_{st} \) at \( r=r_{st} \) and \( T=T_e \) at \( r=r_e \) represented in Figure 2. When
integrated twice using the boundary conditions to solve for the constants of integration Equation 2 becomes:

\[ T = T_{st} + \left(\frac{T_e - T_{st}}{\frac{1}{r_{st}} - \frac{1}{r_e}}\right) \left(\frac{1}{r_{st}} - \frac{1}{r}\right) \]

Fourier’s Law can be used to determine the conductive heat flux, in W/m², leaving the spherical storage volume at \( r_{st} \).

\[ \text{heat flux} = -\lambda \frac{dT}{dr}\bigg|_{r_{st}} = \frac{\lambda(T_{st} - T_e)}{\left(\frac{r_{st}}{r_{st}^2} - \frac{r_{st}^2}{r_e}\right)} \]

Thermal conductivity is represented as \( \lambda \) and is measured in W/m°C. By multiplying the heat flux by the area of the sphere at \( r_{st} \), the heat flow out of the storage volume, in watts, can be determined.
\[ A_{\text{st}} = 4\pi r_{\text{st}} \]

\[ \text{heat flow} = \frac{4\pi\lambda(T_{\text{st}} - T_e)}{\left(\frac{1}{r_{\text{st}}} - \frac{1}{r_e}\right)} \]

To calculate the storage capacity of the spherical volume, the volumetric bulk heat capacity, \( C_b \), can be estimated by multiplying the rock grain density, \( \rho_R \) (kg/m\(^3\)), the rock grain heat capacity (by mass), \( C_R \) (J/kg °C), and the fraction of rock or sediment present after accounting for porosity, \( \varphi \), assuming dry conditions. Dry conditions are used because the BTES system will have undergone an initial preheating period to reach the initial storage temperature greater than the boiling point of water prior to cycling. During the preheating process, any residual water within the pores would have been boiled away to create a dry system. The bulk heat capacity, in J/°C m\(^3\), is:

\[ C_b = (1 - \varphi)\rho_R C_R \]

Finally, the storage, in Joules, of the spherical system can be determined using:

\[ \text{heat storage} = \frac{4}{3}\pi r_{\text{st}}^3 C_b \Delta T \]

The approximate amount of time that the heat can be stored by the spherical storage volume is estimated by taking the ratio of heat storage to heat flow:
maximum heat storage time \(= \frac{heat \ storage}{heat \ flow} = \frac{r_{st}^3 \left( \frac{1}{r_{st}} - \frac{1}{r_e} \right) C_b \Delta T}{3\lambda(T_{st} - T_e)} \)

The constant temperature boundary at radius, \(r_e\), plays a major role in how well the formation can store heat. In a perfect system \(r_e\) would be very large and would approximate an infinite system. This would be the best-case scenario for the BTES system, excluding the possibility of an insulated system, and would represent a system that was infinite. However, it is unlikely that this system will be infinite. The radius, \(r_e\), must be larger than the storage radius, \(r_{st}\), but can be located at any distance outside of \(r_{st}\). A very small \(r_e\) value will give the worst-case scenario for the BTES system in terms of heat loss by conduction within the subsurface. In a real BTES system, the constant temperature boundary would be located near the ground surface, at the water table, etc. Therefore, it is more realistic to treat spherical analysis as a finite system.

4.3 ESTIMATING HEAT LOSSES BY SPHERICAL VOLUME

4.3.1 THERMAL PROPERTY INPUTS

The thermal properties of two different formation types were used to estimate the heat losses. All thermal properties were estimated based on the thermal properties of either dry sand or granite. By looking at both sand and granite cases, the feasibility of each could be determined. Following the determination of which formation would be a better fit for a BTES system, the outer radius, \(r_e\), could be varied. By varying the outer radius, a comparison between a worst-case and best-case scenario for heat losses within the system could be completed. The thermal property inputs can be seen below in Table 1.
### Model Input

<table>
<thead>
<tr>
<th>Model Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Thermal Conductivity, $\lambda_{\text{sand}}$ (W/m°C)</td>
<td>0.5</td>
</tr>
<tr>
<td>Dry Thermal Conductivity, $\lambda_{\text{granite}}$ (W/m°C)</td>
<td>3</td>
</tr>
<tr>
<td>Bulk Volumetric Heat Capacity, $C_{b,\text{sand}}$ (J/m$^3$ °C)</td>
<td>1.7E6</td>
</tr>
<tr>
<td>Bulk Volumetric Heat Capacity, $C_{b,\text{granite}}$ (J/m$^3$ °C)</td>
<td>2.7E6</td>
</tr>
<tr>
<td>Ambient Temperature, $T_e$ (°C)</td>
<td>21</td>
</tr>
<tr>
<td>Average Storage Temperature, $T_{st}$ (°C)</td>
<td>240</td>
</tr>
<tr>
<td>Cycling Temperature Range (°C)</td>
<td>35</td>
</tr>
</tbody>
</table>

*Table 1 - Thermal properties of for estimating 1-D spherical heat conduction out of the BTES system.*

#### 4.4.2 HEAT LOSS RESULTS

The volume of a storage sphere is shown below in Table 2.

<table>
<thead>
<tr>
<th>Storage Radius (m)</th>
<th>Storage Spherical Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>113</td>
</tr>
<tr>
<td>4</td>
<td>268</td>
</tr>
<tr>
<td>5</td>
<td>524</td>
</tr>
<tr>
<td>6</td>
<td>905</td>
</tr>
<tr>
<td>7</td>
<td>1,437</td>
</tr>
<tr>
<td>8</td>
<td>2,145</td>
</tr>
<tr>
<td>9</td>
<td>3,054</td>
</tr>
<tr>
<td>10</td>
<td>4,189</td>
</tr>
<tr>
<td>11</td>
<td>5,575</td>
</tr>
<tr>
<td>12</td>
<td>7,238</td>
</tr>
<tr>
<td>13</td>
<td>9,203</td>
</tr>
<tr>
<td>14</td>
<td>11,494</td>
</tr>
<tr>
<td>15</td>
<td>14,137</td>
</tr>
<tr>
<td>16</td>
<td>17,157</td>
</tr>
</tbody>
</table>

*Table 2 - Volume of heat storage in a spherical volume.*

Based on the storage volumes, the amount of thermal energy that can be stored within the storage volume (storage capacity), and heat losses for each volume can be calculated. The storage capacity is a linear function of the storage volume while the heat losses vary in a nonlinear way with volume. Therefore, the storage capacity will remain a linear function of the storage volume in both the infinite and finite cases. However, the heat losses from the system
depend heavily on the distance to the constant temperature boundary at \( r_e \). A plot of the storage capacity as a function of volume and formation type is displayed below as Figure 3. Figure 4 displays the heat losses of volumes with different radii to the constant temperature boundary based on the two different formation characteristics.

**Figure 3** - Sand storage capacity as it varies with the spherical storage volume.

**Figure 4** - Heat loss from the system as it varies with storage volume and distance to the constant temperature boundary.
Figure 4 shows that the formation characteristics dominate the heat loss magnitude. The distance to the constant temperature boundary further affects the heat losses. While the granite system has a storage capacity of 1.6 times greater than the dry sand system, the heat losses from the granite system are consistently 6 times larger than the dry sand at any given volume. Therefore, while granite can store more heat it will also lose that heat more quickly than a dry sand system.

The heat losses of both materials could also be compared as across different constant temperature boundaries, $r_e$. For both materials, the ratio of heat losses at the finite constant temperature boundary of 5 meters to the infinite constant temperature boundary was determined to be approximately 1.4 greater at a volume of 34 m$^3$. However, the ratio also increased with volume and at the largest spherical storage volume evaluated, 17,157 m$^3$, the ratio was approximately 4.2 times greater when $r_e$ is located 5 meters from the storage volume.

Since the materials have different heat capacities, we can also look at the storage time of each formation. Since storage time is heat storage divided by the heat flow out of the system, the storage time also increases as storage volume increases. However, this is also a function of the material, and to a lesser extent, $r_e$, the constant temperature boundary. This can be seen in Figure 5.
Figure 5 shows that the worst-case for a sand BTES system has a comparable maximum storage time to the best-case scenario maximum storage time of a granite system. This once again shows that it is not likely feasible to use granite as a storage formation for our purposes. This is because, while the storage times may increase with larger storage volumes, the ratio of the sand to granite storage time is always the same; equal to the ratio of the bulk volumetric heat capacity, $C_b$, to the thermal conductivity, $\lambda$, of each formation. Therefore, the sand storage time is almost always worse than the dry sand.

Additionally, the one-dimensional spherical analysis of different storage volumes has shown that the amount of heat stored in the formation and the length of time which that heat can be stored is vastly improved by increasing the volume of the system. Therefore, it is in our best interest to maximize the volume of the BTES while keeping the spacing tight enough that the BHEs and surrounding formation can be properly charged and discharged during each cycling event.
5 ONE DIMENSIONAL RADIAL NUMERICAL MODEL ANALYSIS

5.1 BACKGROUND

This numerical modeling tool was chosen to help determine what spacing between BHEs would be effective for power production. This simulation represents an idealized internal symmetry element from a repeated BHE pattern. However, it must assume that the system is dry from the beginning because it cannot account for multiphase flow. Therefore, it neglects any water present in the system which would initially require being boiled away prior to cycling events. The result of this is that the initial preheating period may get the system to an initial temperature more quickly than is possible in reality. The heat up period including boiling and multiphase flow is described in Chapter 7.

To obtain an understanding of the effects these might have on the system, a strategy for testing the heating process needed to be adopted. It was decided that the best fitting conceptual model of heating the subsurface with a BHE is line source pure conduction heating. This model uses an insulated outer boundary condition at a radius of \( r_e \) to simulate the interference that would result from a repeated pattern of closely spaced borehole heat exchangers. This effect can be seen below in Figure 6. In that case, the system symmetry and superposition of heat sources produces a temperature profile that is approximately equivalent to a radial system with an insulated outer boundary. By varying \( r_e \), the effect of borehole spacing can be tested.
5.2 DESCRIPTION OF THE NUMERICAL MODEL

This 1-D radial finite difference model for conduction heating is written in Visual Basic code. This numerical modeling tool allows for the user to specify a temperature at the borehole wall and will calculate the temperature at each change in radius that is specified at every time step until the end time is reached. This allowed for repeated simulations of varying thermal conductivities, volumetric heat capacities based on rock/soil type, borehole radius spacing, initial temperature, and cycling temperatures. Equation 9 is the governing equation that was implemented into the numerical model (Arpaci, 1966) where $T$ is the temperature of the subsurface material ($^\circ$C), at time, $t$ (s), at a radius, $r$ (m). The thermal diffusivity of the subsurface, $\alpha$ (m$^2$/s), is the thermal conductivity, $\lambda$ (W/m$^\circ$C) divided by the product of the soil/rock density, $\rho$ (kg/m$^3$) and the specific heat capacity, $C$ (J/kg$^\circ$C) which is the dry bulk volumetric heat capacity, $C_b$ (J/$^\circ$C m$^3$), described previously in Equation 6.

*Figure 6 - Image showing the outer radius within the simulation where interaction between BHEs would begin to occur.*
\[
\frac{\partial T}{\partial t} = \alpha \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right]
\]

Where:

\[
\alpha = \frac{\lambda}{C_b}
\]

When Equation 9 is expanded explicitly in time using boundary conditions \( r = a \) when \( T = T_a \) and \( r = b \) when \( \frac{dT}{dt} = 0 \) and solved using a second order finite difference in space, this becomes:

\[
T_i^{t+\Delta t} = \left( 1 - \frac{2\alpha \Delta t}{\Delta r^2} \right) T_i^t + \alpha \Delta T \left[ \frac{T_{i-1}^t + T_{i+1}^t}{\Delta r^2} + \frac{T_{i+1}^t + T_{i-1}^t}{2r_i \Delta r} \right]
\]

Where the stable time step size for the explicit method is:

\[
\Delta t < \frac{\Delta r^2}{2\alpha}
\]

The inner boundary condition at a radius of \( r_w \) is one of specified temperature, which can be adjusted as a function of time. This allows simulation of an initial heating period, followed by cyclical operation of the heat exchanger. The simulation can also determine a heat transfer rate per unit length of BHE during a particular cycling event. This can be done by solving
Equation 13, where \( q \) represents the heat flow in W/m and is the product of the thermal conductivity, area of the borehole, \( A \) (m), and the change in temperature with distance from the borehole, divided by \( L \), which is the length of the heater.

\[
q = -\lambda A \frac{dT}{dr}
\]

5.2.1 MODEL SET UP

The numerical modeling tool requires initial inputs for borehole radius, initial temperature of the system upon start up, total length of the test, and the outer radius prior to running the simulation. The outer radius would be considered half the spacing from a single borehole to another. This is because it is inferred that this is the point where the heat from one borehole would interact with another and cause a no flow boundary due to super. Table 3 displays an example of how these inputs appear within the user interface.

From this input, the model will automatically calculate the grid spacing, thermal diffusivity, stable time step, and number of time steps necessary for the model to run smoothly. A stable time step is very important in this simulation because it is solving functions within the model explicitly. Explicit methods calculate the solution at a specified future time, \( \Delta t \), based on values at the previous time step. If the time step is not small enough, the simulation becomes unstable. This could cause the simulation to output incorrect solutions or potentially crash if the time step is too large.
Lastly, the cycling information can be input into the model. To do so, the number of cycles, specified length of each cycle, and expected temperature at the borehole are specified. Table 4 shows an example in the user interface. Once completed, the numerical simulation can be run.

![Borehole temperature data](image)

<table>
<thead>
<tr>
<th>number of cycles</th>
<th>borehole Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>end time (days)</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>210</td>
<td>270</td>
</tr>
<tr>
<td>240</td>
<td>200</td>
</tr>
<tr>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>330</td>
<td>270</td>
</tr>
<tr>
<td>360</td>
<td>200</td>
</tr>
</tbody>
</table>

*Table 4 - Cycle length and borehole temperature input*

5.3 MODELING HEAT FLOW

5.3.1 MODEL INPUTS

Typical simulations included varying time periods, spacing, and temperature cycling to determine what spacing would give the desirable flow/power output within our budget. While the BHE spacing, temperature cycling, and time periods were varied to create better outcomes, the thermal properties of the system remained constant in all tests.

A thermal conductivity for dry sand, $\lambda$, was used for this simulation due to the simplicity of the model. As the simulation cannot account for multiphase flow, it was necessary to neglect any water present within the system. But, if it were able to account for any residual water left in the pore spaces, the thermal conductivity of the system would increase because water conducts heat much better than air. Since the system must be dry in this simulation, the thermal conductivity is set to the lower value of dry sand, approximately $0.5 \text{ (W/m°C)}$. 
Additionally, the bulk volumetric heat capacity, \( C_b \), of the system needed to be determined. This was done by using Equation 6.

\[
C_b = (1 - \varphi)\rho_R C_R
\]

Constant model attributes can be seen below in Table 5.

<table>
<thead>
<tr>
<th>Model Input</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Thermal Conductivity, ( \lambda ) (W/m°C)</td>
<td>0.5</td>
</tr>
<tr>
<td>Dry Sand Heat Capacity, ( C_R ) (J/°C)</td>
<td>1000</td>
</tr>
<tr>
<td>Dry Sand Density, ( \rho_R ) (kg/m³)</td>
<td>2600</td>
</tr>
<tr>
<td>Porosity, ( \varphi )</td>
<td>0.35</td>
</tr>
<tr>
<td>Bulk Volumetric Heat Capacity, ( C_b ) (J/m³ °C)</td>
<td>1.7E6</td>
</tr>
<tr>
<td>Borehole Radius, ( r_w ) (m)</td>
<td>0.076</td>
</tr>
<tr>
<td>Initial Temperature, ( T_0 ) (°C)</td>
<td>21</td>
</tr>
<tr>
<td>Thermal Diffusivity, ( \alpha ) (m²/s)</td>
<td>2.94E-7</td>
</tr>
<tr>
<td>Radial Grid Spacing, ( \Delta r ) (m)</td>
<td>0.039</td>
</tr>
</tbody>
</table>

*Table 5 - Thermal properties used in the numerical model.*

### 5.3.2 RESULTS

Each simulation was run for a 180-day preheating period where the system began at ambient subsurface conditions, which were estimated to be roughly 21°C. During the preheating process, a 240°C fluid was circulated within the BHE. Approximately 50 days into the 180-day preheating period, the temperature near the borehole wall reached the same temperature of 240°C (Figure 7) when the spacing between BHEs was 1 meter. This was not the case for the more loosely spaced system. After the 180-day preheating period the temperature near the borehole
wall only reached approximately 236°C, meaning that the system was not yet fully heated (Figure 8).

It was important to check that the temperature was being raised at the outer radius during the heating process. This is because this would be the proposed half spacing to another BHE as shown previously in Figure 6. For the entire volume of the subsurface to store heat, the temperature at this location must be raised to combine heating from adjacent BHEs. When the outer radius becomes too distant, this effect is no longer observed. There are two methods to alleviate this issue, the first is to decrease the outer radius, while the second is to increase the length of the heating and cooling periods.

While extending the length of heating and cooling or charging and discharging cycles may be feasible for the full-scale test where the storage volume is much larger, for a small-scale field, the BHE outer radius should be decreased to increase power output from the system. However, a longer cycling period is something that should be assessed in the future if a larger spacing is necessary. The last variable to be assessed was the temperature cycling of the system. Following the initial preheating period of 180 days, the system could then be cycled to temperatures higher and lower than the initial preheating temperature of 240°C, which will add or remove thermal energy from the system.

By varying the temperature at which the system was cycled, it was determined that a larger change in temperature above or below the initial preheating temperature when cycling typically allows the power input and output to be increased. However, if too much heat is removed from the system by circulating a fluid that is too cool during a cycle, the system may not be able to reach the initial higher temperature necessary to continue to produce a consistent amount of thermal power at the start of the next cycle. By running many simulations of varying
temperature cycles and examining all the power outputs from each, it was found that a temperature cycle between 30°C and 40°C above or below the initial preheating temperature is effective. This is the case for three reasons: it provides a higher power output than cycling in a lower temperature range, it does not draw too much heat from the system which allows for continuous cycling without issues of reheating, and it is within the window of temperatures that are acceptable for the proposed heat transfer fluid of the actual system.

Based on all variable parameters described, it was found that the optimal outer radius (or half spacing) for a formation with these thermal properties should be between 0.5 meters and 1.25 meters. When the outer radius is set to 0.5 meters, or the spacing between BHEs is 1 meter, using this insulated numerical model the outer radius is heated to nearly the same temperature as the borehole wall after approximately 50 days. Therefore, it will interact with the other BHEs surrounding it and warm the subsurface between the two. In this insulated system, the conduction is so effective that a full 180-day preheating may not be necessary as the entire volume is heated as early as 50 days into the preheating process. Figure 7 displays the temperature at the borehole wall and the temperature at the outer radius during 15-day cycling events with a spacing of 1 meter. At the end of each cycle, the borehole wall temperature and outer radius can be observed as being within a few degrees of one another.

The temperature at the outer radius must be raised in order to be able to use the full storage volume for power production and a significant increase in this temperature will increase power output. The outer radius temperature in Figure 7 is highly influenced with each cycle due to the small volume of the system. While this is an advantage, the lack of storage volume in this system will also present some disadvantages.
The findings of the one-dimensional spherical analysis in Section 4.4.2 showed that the amount of heat that can be stored as well as the length of time which that heat can be stored is vastly improved by increasing the storage volume. With closer spacing of the system, if the same number of BHEs were to be used in both scenarios, the storage volume of the system with 0.5 meter spacing would be reduced. In turn, the amount of heat that could be stored and the storage time of the BTES system would decrease as well.

When the outer radius is 1.25 meters, the effects at the outer radius are delayed and a 180-day preheating period is necessary. Again, by increasing the storage volume of the system by increasing the spacing, more heat can be stored for longer amounts of time. Therefore, by increasing the outer radius from 0.5 meters to 1.25 meters increases the amount of heat that can be stored, and eventually drawn from the ground is increased.
In Figure 8, which shows the temperature near the borehole wall and at the outer radius, the outer radius is approaching a temperature of approximately 220°C after 180 days of heating the system rather than the 240°C displayed in Figure 7 with a smaller outer radius. If the outer radius were to be increased beyond 1.25 meters, there would be even less interaction between BHEs which would prevent full heating of the subsurface between BHEs. This has the potential to create a situation where power generation may be reduced in the long term and may have diminished returns after a few cycles. This would be due to a lack of thermal storage since only some, rather than all, of the anticipated storage volume would be heated.

![Figure 8 - Temperature near the borehole wall and outer radius when the outer radius is 1.25 meters.](image)

While the idea of a closely spaced system to increase temperature quickly is appealing, it also decreases the storage volume from which thermal energy can be generated. By decreasing the outer radius from 1.25 meters to 0.5 meters, the volume of subsurface in which energy can be stored is decreased sixfold. This means that the power output from the system with the smaller outer radius will require more frequent cycling to generate a power of 40 W/m. This can be seen
below when comparing Figures 9 and 10 to one another. In Figure 9, we can see that thermal power is decreasing rapidly as it is withdrawn from the subsurface where it never plateaus and at the end of the 15-day cycle is producing roughly 16 W/m. Figure 10 also shows that to keep power production above 40 W/m the system would need to be cycled weekly rather than biweekly.

When the outer radius is increased to 1.25 meters, the increased storage volume allows for increased power production for a longer period (Figure 10). At the end of the 15-day cycling event the power being withdrawn from the system is approximately 36 W/m and has begun to plateau. Therefore, while the system is slightly less than the desired 40 W/m, it is much closer and the cycling period will require being shortened by only a few days rather than halved.

By integrating the power with time, the energy into and out of each system could be estimated as well as the efficiency. During each cycling event in the system of 0.5 meter spacing, the approximate energy into the system was 73,000 kJ with an extraction of approximately 73,000 kJ resulting in an efficiency of nearly 100%. The system with an outer radius of 1.25 meters, the energy put into the system per cycle was roughly 77,000 kJ with a return of 65,000 kJ after several cycles, giving it an efficiency of approximately 85%. However, since this is a fully insulated system, this inefficiency is because the system still has not yet reached a fully heated state. Figure 10 shows that with each cycle the efficiency increases with every cycle, the power in a power out can be seen getting closer and closer to the same value.
Figure 9 – Thermal power in a system with an outer radius of 1.25 meters as a function of time.

Figure 10 - Thermal power in a system with an outer radius of 0.5 meters as a function of time.
6 LABORATORY EXPERIMENTS

6.1 LABORATORY BTES SYSTEM SET UP AND MEASUREMENTS

The borehole thermal resistance (BTR) is the thermal resistance between the fluid in the BHE and the borehole wall (Javed & Spitler, 2017). The BTR is a key performance characteristic of a BTES system and an important design parameter therefore, the main goal of the laboratory experiments was to quantify how the borehole thermal resistance is impacted by different borehole designs to deliver heat to the surrounding formation (Javed & Spitler, 2017). The most important parameters that influence the BTR are the thermal conductivity of the filling material, number of pipes, pipe position, and pipe thermal conductivity (Hellstrom, 1998). Rather than attempt to estimate them all separately, the BTR can be used to represent the sum of the resistances inside the borehole between the circulating fluid and the soil (Zhang et al, 2015). The BTR is valuable when designing the BTES system because it can have a significant effect on the system performance and should be minimized to see the best results (Gehlin, 2002).

The BTR can be determined in the field by conducting what is known as a thermal response test (TRT). A 1983 paper by Mogenson suggested that a TRT was a method by which the thermal conductivity of the ground and BTR could be obtained in situ for a specific borehole by using the entire borehole as a probe and using a U-tube with fluid circulating through it as a line source. The first practical application of the TRT was conducted in 1984 and was performed on a ground source heat pump system for a small house in Jarfalla, Stockholm by applying a constant heat extraction rate to the borehole and measuring the temperature development over time (Mogenson, 1985). Since then, other mobile TRT devices were built in Sweden at Luleå University of Technology and eventually in the USA as well. The BTR that is determined by
using the TRT method is an effective resistance between the mean fluid temperature and the borehole wall for the entire borehole (Spitler & Gehlin, 2015).

When completing laboratory experiments the BTR can be calculated by using Equation 14:

$$BTR = \frac{(T_f(t) - T_b(t))}{q_c}$$

Where the average fluid temperature of the system inlet and outlet at a specified time is represented as $T_f$ in °C, the temperature measured at the borehole wall is $T_b$ in °C, and the constant power input into the system is $q_c$ is in W/m. However, in the field a borehole wall measurement may not be able to be measured directly so the BTR may be calculated by using the line source analytical solution.

The laboratory experiments were conducted based on two typical BHE designs, U-bend and coaxial. The U-bend is a BHE that is shaped like a U with one pipe acting as the inlet and the other as the outlet. As hot thermal fluid enters the system through the inlet it begins conducting heat outward into the formation. When the fluid reaches the bottom of the BHE it passes through two elbows before exiting through the outlet.

The coaxial BHE is a radially symmetric design where a smaller pipe is seated within a larger outer pipe. A hot thermal fluid flows into the BHE through the outer shell and exits through the center of the BHE (Figure 11). All piping used was 3/4-inch, schedule 40 threaded black iron apart from the outer shell of the coaxial design which was 2-inch pipe. The major difference between this laboratory design and a typical coaxial BHE is that there is a small vacuum chamber situated between the inlet and outlet paths which was used to pull a vacuum.
The vacuum chamber serves to decrease convective and conductive heat flux across the pipe separating the inflow and outflow.

An important aspect of designing the U-bend BHE was determining the best shank spacing, or the distance between the inlet and the outlet pipes measured from the center of each pipe (Vella et al., 2020). A study conducted by Dehkordi et al. (2015), showed that the BTR and system performance were more sensitive to the pipe to borehole wall distance rather than the pipe-to-pipe separation. Therefore, it was decided that the piping of the U-bend should be as close to the borehole wall as possible to keep the BTR as small as possible. In this case, that meant that the shank spacing was approximately 4.5-inches as the borehole diameter was 6 inches across.
Each of these two designs were situated within their own 55-gallon drum within a 6-inch aluminum cylinder. Both designs were placed approximately 6-inches off the bottom of the drum and this space was filled with sand. Once properly placed, temperature-resistant thermocouples were placed vertically along the BHE, vertically at the outer radius of the borehole (3 inches), and radially halfway down the drum. The radial arrays were done in logarithmic distances which increased with distance from one another as they moved away from the BHE. Figure 12 shows the layout of a typical laboratory drum set up with the X’s indicating the location of thermocouples for temperature monitoring. Once everything was installed, the annulus and drum were filled with sand and the thermocouples were attached to a data acquisition system that would record temperatures at specified time intervals (Figure 12). Thermocouple number 6 was used for collecting borehole wall temperature measurements. A photo of the laboratory set up is displayed in Figure 13.

*Figure 12 - Schematic of thermocouple locations (X’s) in all drums in side view as well as a top view of the BHE annulus approximately halfway along the BHE.*
An additional third drum was created to analyze the effect of using a thermally enhanced grout on the BTR. For this drum, another U-bend BHE was used but rather than filling the annulus of the aluminum cylinder with sand, it was filled with a thermally enhanced calcium aluminate cement. Calcium aluminate cement (CAC) was chosen due to its ability to withstand temperatures that the system will eventually reach (200-300°C). To increase the thermal conductivity of the CAC a thermally conductive additive comprised of graphite at a ratio of approximately 6 parts CAC to 1 part graphite additive by mass was included, as advised by the maker of the additive, GeoPro, Inc.

Each drum and any piping rising above the top of the drum were insulated using 3-inch R-15 faced fiberglass insulation to minimize heat losses. On the outer boundary of the drum, the insulation is intended to reduce heat losses. In addition, foam pipe insulation was used to further reduce heat losses along the PEX tubing which connects the pump, inline heater, radiator, and flow meter to the BHEs (Figure 14).
Each one of these pieces plays an important role in the system and were specifically chosen for the task. Since the laboratory BTES system is relatively small, typical household appliances were able to be used. The pump that was chosen for our application was a Taco 007-F5 Cartridge Circulator. This is a small cast iron centrifugal pump is capable of flows of up to 23 gallons per minute. This pump uses a rotating impeller to draw in fluids. While a centrifugal pump may have issues with more viscous fluids, it was sufficient for this application as the heat transfer fluid being used is water (Figure 15).

Next, a heater that was able to keep a constant power output was used to estimate BTR properly. A stainless-steel low flow liquid circulation heater (Omega AHPF-062) was chosen for the system. The heater provided a constant power of 100 Watts to the BHE. The heater has an enclosed heating element located down the center. The heat transfer fluid flows through the annulus between the heating element and the wall of the heater where the heat is transferred from the heating element to the fluid by conduction. Once heated, it then is passed through the BHE. A photo of the 100-Watt heater is shown as Figure 16.
After the heating is completed, it is desirable to monitor the heat extraction from the system. In this case, a small radiator was used to cool the BTES system. The radiator works by passing the hot water through a series of copper pipes in contact with room temperature air. As the fluid passes through the piping, a fan blows air across the piping to help dissipate the heat into the air by convection. The cooler fluid can then pass back through the BHE and continue to extract heat from the system (Figure 17).

The BTES system used a variable area flow meter (Nxtop LZT M-15) that measured flows between 0.05 and 0.5 gallons per minute (gpm). The flow meter has a valve which allows for the adjustment of the flow rate. A variable area flow meter works by using metal float in the stream of flow. The rise of the float is proportional to the flow rate. Therefore, when water is flowing through the system the top of the float is aligned with a flow rate printed on the flow meter (Figure 18).
It was later recognized that the variable area flow meter may not have been ideal for this application. As the temperature of the water increases the viscosity decreases. The viscosity of the water is nearly halved over the temperature range exhibited during each experiment (Kestin et al., 1978). This affects the accuracy of the flow meter because as the viscosity is decreased the flow rate is likely increased. However, according to Omega, a well-known manufacturer of variable area flow meters, variable area flow meters overall are relatively insensitive to viscosity variations. However, how small or big the impact of the changing water viscosity is on the flow meter remains unknown. A diagram of the layout of the BTES system including all of these instruments is shown below in Figure 19.
Temperature of each BTES system was monitored by two kinds of devices: type T thermocouples and a datalogging thermometer. The data logging thermometer used was a Memory-Loc Ultra-Low Datalogging Traceable Thermometer. The thermometer has two probes and can log readings at both probes up to once a minute. The readings from the probes have an accuracy of 0.2°C and a resolution of 0.01°C. It can also be used in the range of -90 to 105°C where our temperature range was roughly 20-50°C.

The thermocouples used for measuring temperature within the drum were type T thermocouples (MN Measurement Instruments T-Type Thermocouple Wire). These type T thermocouples were comprised of 24-gauge copper/constantan wire with a high temperature PFA Teflon insulation. They came in a 10-yard spool, and each was cut to size using wire cutters and one end soldered using electrical solder. These thermocouples have an accuracy of 1.0°C and it was necessary to calibrate them prior to placement within the drums (Figure 20).

The thermocouples were calibrated by putting them into two known temperatures and collecting measurements for comparison. In this case the temperatures were freezing and boiling. Each thermocouple was connected to a LabJack T7-Pro data acquisition system (Figure 21). To connect the thermocouples to the LabJack the constantan wire is fastened into a ground port, while the copper wire is fastened into the associated analog input port on the LabJack. The
soldered end of the wire was then put into either boiling or freezing water while the LabJack collected readings.

The LabJack collects data by utilizing a LuaScript written specifically for our application. It can collect readings for each thermocouple as often as 1 millisecond. The script sends the collected data to a csv file after every 60 readings. By connecting the thermocouples to the LabJack we were able to collect and store data without being present in the lab. However, for the purpose of calibrating the thermocouples somebody was present to monitor the boiling water. After collecting data every 10 seconds for approximately 15 minutes, the readings for both boiling and freezing for each thermocouple could be downloaded.

The data points were averaged to determine the temperature reading from each thermocouple at each known temperature. A line could be fit between the two measured points and an equation for that line was determined. Moving forward, each time a measurement was collected by that thermocouple, it could be plugged into the equation to get the correction for that temperature. This value could then be added or subtracted from the original value to correct the difference between the thermocouple reading and the true value.

When collecting temperature measurements, aside from the thermocouples in the drums, the two thermometer probes were also placed in thermowells in the inlet and outlet. A
thermowell is a metal fitting that allows the probes to be in the fluid flow without coming in contact with it. A photo of the thermowells used in the lab are displayed as Figure 22. An additional thermowell was placed before the heater and a calibrated thermocouple was used to determine the constant power input for estimating BTR based on the temperature change before and after the water passed through the heater.

6.2 MEASUREMENTS AND CALCULATIONS

6.2.1 THERMAL CONDUCTIVITY

A transient line source thermal conductivity meter was used to determine the thermal conductivity of the sand and grout within the system. The instrument used was a transient needle probe that contains an electric heating element and temperature sensors inside a metallic sheath on the order of 5-6 mm in diameter and 100 mm in length (Spitler & Gehlin, 2015).

The electric heater element within the probe sends a constant power, $q_c$ in W/m, outward and used the built-in temperature sensors to measure the temperature of the formation surrounding it. The recorded average temperature rise will be higher for soils with lower thermal conductivity because the soil does not conduct the heat away from the probe as quickly as soil with higher thermal conductivity (Zhang et al., 2014). Once the constant power test was completed and the temperatures were recorded, the reported temperatures were plotted against the natural log of time. The slope of the line was calculated and used in Equation 15 to determine the thermal conductivity of the materials used to construct each design. Figure 23 displays
images of the conductivity measurements taking place in different grouting materials as well as the sand used within each drum.

\[ \lambda = \frac{q_c}{4\pi(slope)} \]

6.2.2 MEASURING BOREHOLE THERMAL RESISTANCE

To determine the BTR of each design, a heating test was conducted on each drum separately. By measuring the temperature difference at the inlet and outlet of each drum, the thermal power, \( q_c \), entering the dry sand could be calculated by using Equation 16; where power (W/m) is the result of the mass rate, \( \dot{m} \) (kg/s), specific heat capacity, \( C \) (J/kg°C), and change in temperature, \( \Delta T \) (°C) of the transfer fluid all divided by the length of the BHE (m):

\[ q_c = \frac{(\dot{m}C\Delta T)}{L_{BHE}} \]

The mass rate is the result of multiplying the density of the heat transfer fluid, water, by the flow rate. As previously discussed, because of the variable area flow meter, the flow rate may
be different than measured due to the decreased viscosity of the water at higher temperatures. A thermocouple on the outside of the aluminum cylinder was used to collect the temperature measurement at the borehole wall needed to quantify the BTR of each design by using Equation 16. Once all the temperature measurement equipment was properly placed, water of a known flow rate could be circulated through the system. To be able to measure the temperature drop between the inlet and outlet, this flow rate needed to be reduced to approximately 0.1 gallons per minute (6.31E-6 m³ per second).

After an ambient fluid and drum temperature were established the 100-Watt inline heater was turned on and allowed to heat the water in the system until the temperature at the borehole wall was no longer increasing. At this point, the heater was turned off and the water bypassed the heater and was passed through a radiator to cool the system. By taking measurements throughout the heating and cooling process at increments of either 30 seconds or one minute, the temperature difference between the inlet and outlet could be used in accordance with Equation 17 to calculate the thermal power (W) entering or leaving the BTES system.

\[ Q = \dot{m}c\Delta T \]

6.3 BTR DERIVATION USING A LINE SOURCE ANALYTICAL SOLUTION

The typical procedure for determining BTR in the field is by conducting a TRT. This requires a controlled heat source where water can be pumped through the BHE and exchange heat with the formation, while the inlet and outlet fluid temperatures are measured. The average of the two instantaneous temperature measurements is taken to represent the average fluid...
temperature, $T_r(t)$, in the BTES system at any given time (Zhang et al., 2014). The data could then be analyzed by using the solution for the thermal line source.

The analytical solution for a line source of heat, in Equation 18 from Pahud et al. (2001), was used as an alternative method to estimate the BTR and thermal conductivity of each system. When compared to laboratory BTR values, using this method always resulted in a higher BTR value than what was directly measured. Prior to using this method, the thermal conductivity for the subsurface material must be calculated by using Equation 15 described previously in Section 6.2.1:

$$T = T_0 + \frac{q_c}{4\pi \lambda} \int_{r^2/4\alpha t}^{\infty} \frac{e^{-y}}{y} dy$$

Equation 18

This can be written as:

$$= T_0 + \frac{q_c}{4\pi \lambda} E_1(u)$$

Equation 19

where $E_1(u)$ is the exponential integral:

$$u = \frac{r^2}{4\alpha t}$$

Equation 20

When $t$ is large:
For “small” $u$ values, the Cooper-Jacob Approximation can be used for this equation, so:

$$E_1(u) \cong -\ln(u) - \gamma + \frac{u^2}{4} + \frac{u^3}{18} \ldots$$

This is valid so long as:

$$u < \frac{1}{20}$$

So, at large time values and small radii:

$$T = T_0 + \frac{q_c}{4\pi \lambda} \left[ \ln \left( \frac{1}{u} \right) - \gamma \right]$$

The temperature at the borehole wall, $T_b$, at the radius of the borehole wall, $r_b$, is then:

$$T_b = T_0 + \frac{q_c}{4\pi \lambda} \left[ \ln \left( \frac{4\alpha t}{r_b^2} \right) - \gamma \right]$$

Borehole thermal resistance, BTR, is defined:

$$q_c = \frac{(T_f(t) - T_b)}{BTR}$$
Which becomes:

\[ T_f(t) = q_c BTR + T_b \]

So:

\[ T_f - T_0 = \frac{q_c}{4\pi\lambda} \left[ \ln \left( \frac{4\alpha t}{r_b^2} \right) - \beta \right] + q_c \times BTR \]

\[ = \frac{q_c}{4\pi\lambda} \ln(t) + q_c \left[ BTR + \frac{1}{4\pi\lambda} \left( \ln \left( \frac{4\alpha}{r_b^2} \right) - \beta \right) \right] \]

The borehole resistance, BTR, can be computed:

\[ BTR = \frac{T_f(t) - T_0}{q_c} - \frac{1}{4\pi\lambda} \left[ \ln \left( \frac{4\alpha t}{r_b^2} \right) - 0.5772 \right] \]

6.4 EXPERIMENT RESULTS

6.4.1 THERMAL CONDUCTIVITY

Using the transient line source thermal conductivity meter, the heat injection rate, \( q_c \), that the needle probe was able to conduct into the surrounding material was approximately 4.06 W/m, provided by the device. The temperature results of the two materials are plotted as a function of the natural log of time where time was measured in milliseconds in Figure 24 where the black arrows are indicating where the slope was taken for the calculation described in Equation 15.
Based on the results of the TRT, the slope of the data points for the heating process can be calculated from Figure 24. Once completed, the thermal conductivity of each material is calculated by using Equation 15. The thermal conductivity of the dry sand and thermally enhanced grout were calculated to be 0.35 and 2.60 (W/m°C), respectively.

The thermal conductivity probe showed that the thermal conductivity of the thermally enhanced grout was approximately 7.5 times greater than that of the dry sand. Therefore, it is expected to conduct heat into the surrounding formation more quickly than that of the sand. We anticipate that this would equate to a lower BTR.

6.4.2 BOREHOLE THERMAL RESISTANCE

After testing of each individual drum was completed, the data was analyzed by first determining the power input, $q_c$, into the system for each test by using Equation 16 from Section 6.3.2. Next, the temperature data collected at the inlet and outlet was averaged to determine the
fluid temperature at each recorded data point. These values, along with the measured borehole wall temperature, were used in Equation 14 to determine the data driven BTR. While average values are shown in Table 6 for brevity, the BTR varies with time. The inlet, outlet, and borehole wall temperature measurements that were used to complete the BTR calculation are found in Figures 25-27 while plots of how the BTR varies with time are shown in Figures 28-30.

The theoretical line source solution (Equation 29) was used to estimate the borehole wall temperature and predict the BTR for comparison purposes. The thermal conductivities used for this calculation were those found in section 6.4.1 by using the thermal conductivity meter. The values of the power input and two average BTR values for each test can be seen below in Table 6.

<table>
<thead>
<tr>
<th>Drum Description</th>
<th>U-bend in sand</th>
<th>U-bend in grout</th>
<th>Coaxial</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_c$ (W/m)</td>
<td>84</td>
<td>36</td>
<td>76</td>
</tr>
<tr>
<td>$BTR_{DATA}$ (m°C/W)</td>
<td>0.13</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>$BTR_{CALC}$ (m°C/W)</td>
<td>0.21</td>
<td>0.19</td>
<td>0.21</td>
</tr>
</tbody>
</table>

*Table 6 - BTR results for TRT at each drum.*

Based on the results of the heating test, the BTR of the coaxial design is the lowest of the two designs in direct contact with the dry sand when the measured borehole wall temperature data is used. The U-bend with a grout annulus yielded a significantly better BTR value in comparison to the others. Numerical simulations were created to compare the effects of different BTRs on the heating and cooling of the subsurface, as described in Section 7.
Figure 25 - Measured temperatures at the inlet, outlet, and borehole wall of the U-bend BHE with a sand annulus.

Figure 26 - Measured temperatures at the inlet, outlet, and borehole wall of the coaxial BHE with a sand annulus.
Figure 27 - Measured temperatures at the inlet, outlet, and borehole wall of the U-bend BHE with a grout annulus.

Figure 28 – Borehole thermal resistance as a function of time measured in the U-bend BHE with a sand annulus.
Figure 29 - Borehole thermal resistance as a function of time measured in the coaxial BHE with a sand annulus.

Figure 30 - Borehole thermal resistance as a function of time measured in the U-bend BHE with a grout annulus.
7 THREE DIMENSIONAL NUMERICAL SIMULATIONS

7.1 TOUGH MULTIPHASE FLOW CODE

Several field scale simulations were performed using the Lawrence Berkeley National Laboratory TOUGH code (Pruess et al., 1999). The TOUGH multiphase flow code can be used to create a realistic simulation of the BTES system as the subsurface is heated and cooled because it can account for heat conduction and convection with boiling, vapor flow, and condensation. Additionally, it allows for water and gas phases to be fully mobile with capillary and relative permeability effects. These are important to the BTES system because it will be necessary to boil off any residual water left in the pore spaces during an initial heating period. Therefore, having a simulation that can model these phase changes is necessary.

7.1.1 DESCRIPTION OF TOUGH METHODOLOGY

The TOUGH code gives us the ability to create three-dimensional simulations of field conditions by considering multiphase flow within the system. When attempting to achieve temperatures greater than 100°C, the phase change effects become very important and could have significant effects on the system. This is because any residual water trapped within the pores must be boiled off prior to continuing to heat the BTES system beyond 100°C. Therefore, if not enough heat is being conducted into the formation, the system has the potential to be stuck at 100°C for an extended period as water boils.

For these simulations, TOUGH 2 v2.1 with EOS3 was used. TOUGH uses the integral finite difference method (IDFM; Pruess et al., 2012). The use of IDFM allows the grid to have regular or irregular discretization by avoiding the reference of a global system of coordinates, however, this method is still equivalent to conventional finite different methods for conventional
grids (Pruess et al., 2012). For this system, the Equation of State 3 module (EOS3) was used, EOS3 which is designed for applications involving water, air, and heat. TOUGH2 EOS3 considers single phase (gas or liquid) and two-phase conditions with full relative permeability and capillary pressure effects. TOUGH2 was run using the RockWare PetraSim user interface (www.rockware.com).

Typically, when injecting heat into the subsurface the user will create an injection well by inputting a rate and enthalpy for injecting water/steam or air. Another method commonly used is to create extra cells for each well and specify a heat rate into the subsurface. Rather than using these methods, we developed a method that allows for the simulation of each BHE using a specified BTR and an analytical approximation for conductive heat transfer from the BHE into the numerical elements which contain the BHE. This method can be implemented by using the add well feature in PetraSim to set up the length of the BHE as is commonly done. After polygonal discretization and refinement of the system, “named/printed cells” are automatically generated by PetraSim. At this point, the user creates “extra cells” for each BHE intended to be used. After doing so, the set up for each BHE can begin. The approach is to manually attach the BHE cells to the appropriate grid blocks.

This method allows for the internal piping to be represented by the BHE cell porosity. The injected fluid then mixes in the cell and is produced at the same mass rate while the BHE loses or gains heat by conduction to the cells that it is attached to. Special BHE material must be created in the material set up section where the other geologic information is input in TOUGH. To simulate a BHE, this material must have an extremely low intrinsic permeability in the X and Y directions to prevent any leakage of the fluid to the formation. While the permeability is extremely low in two directions, the Z direction has a permeability value that is relatively high.
which allows the user to create something we call a “pipe cell.” The pipe cell will allow for the fluid to flow across the cell boundaries in the Z direction which will allow for multiple BHEs to be connected in series.

To use this method, the injection of the hot fluid into the closed “pipe” requires a specified mass rate and enthalpy. An example of a BHE that is represented by an "extra cell" is shown in Figure 31. The attachment of the BHE to surrounding grid blocks is displayed as Figure 32. Since the system is using water, which will boil when exposed to temperatures greater than 100°C at atmospheric pressure, the water must be pressurized to 10 MPa, a pressure that will allow water to stay a liquid at temperatures up to 300°C.

Finally, the fluid can exit the system by setting a specified backpressure and resistance and then attaching it to a pipe cell, or DELV well condition. The DELV well conditions use a specified productivity index and pressure to determine when it will allow the well to begin production. In this case, the productivity index is specified as the permeability of the pipe in the Z direction and the pressure is set to be the same as the desired pressure of the fluid in the system of 10 MPa. Therefore, when connected to a BHE in the Z direction, the mixed fluid will exit into the specified grid block against the specified backpressure and resistance.

![Diagram showing BHE cell with instructions for injection and exit conditions](image-url)

*Figure 31 – Example of a BHE that is represented by an "extra cell" prior to being attached to adjacent grid blocks.*
To set up the system using the direct BTR values determined by the laboratory experiments, several calculations must be done to complete the BHE to cell connection in two parts: from the BHE to the interface (BHE radius) and from the interface to the effective cell radius. To solve the distance between the BHE and the interface, the inner conductance can be determined based on the area of the connection and thermal conductivity. The area for each BHE connection and volume of the entire BHE can be found by using Equations 30 and 31, respectively.

\[ A = 2\pi r_b \Delta z \]  
\[ V = \pi r_b^2 L \]

Once completed, the distance from the BHE to the BHE radius, \( d_1 \), from the integral finite difference method (IDFM) needs to be calculated. To do so, Equations 32 and 33 for heat flow and the inner conductance can be set equal to one another to produce Equation 34. In these
equations the BTR from Equation 17, \( r_b \) is the borehole radius (m), \( L \) is the length of the BHE (m), \( \Delta z \) is the change in the Z direction between the “named/printed cells” (m).

\[
\text{Heat Flow} = \text{COND}_{BHE} (T_f - T_b)
\]

Where:

\[
\text{COND}_{BHE} = \frac{\lambda_{\text{grout}} A}{d_1} = \frac{\Delta z}{BTR}
\]

\[
\text{Heat Flow} = \frac{\Delta z (T_f - T_b)}{BTR} = \frac{\lambda A}{d_1} (T_f - T_b)
\]

By rearranging the equation, the connection from BHE to BHE radius, \( d_1 \), becomes:

\[
d_1 = \frac{\lambda A (BTR)}{\Delta z}
\]

To determine the distance from the interface to the effective cell radius a derivation analogous to the Thiem solution from Anderson and Woessner (1992), commonly implemented to evaluate steady-state radial flow to a pumping well during an aquifer pumping test, can be used. The effective cell radius, \( r_e \), will need to be determined prior to this which can be calculated by solving the differential equation for steady-state radial heat conduction (Equation 36).
\[ \frac{d}{dr} \left( r \frac{dT}{dr} \right) = 0 \]

Where the boundary conditions are:

**BC1:** \( r = r_1 \quad q = 2\pi r_1 \lambda \left. \frac{dT}{dr} \right|_{r_1} \)

**BC2:** \( r = r_2 \quad T = T_2 \)

The solution is:

\[ T = T_2 - \frac{q}{2\pi \lambda} \ln \left( \frac{r_2}{r} \right) \]

Considering a traditional i, j cartesian grid, if radial flow is assumed then at each grid block, we have:

\[ r = r_e \text{ when } T = T_{i,j} \]

Where \( T_{i,j} \) is the temperature in the element attached to the BHE element and \( T_{i+1,j} \) is an adjacent element.
\[ r_2 = \Delta x \text{ when } T_2 = T_{i+1,j} \]

Finally, \( r_e \) can be solved by looking at the heat flows across the grid block. A visual representation of this is displayed below as Figure 33.

Rearranging Equation 39 to solve for \( q \):

\[
q = 2\pi \lambda \frac{(T_{i+1,j} - T_{i,j})}{\ln \left( \frac{\Delta x}{r_e} \right)}
\]

From Fourier’s Law, \( q \) is:

\[
q = 4\lambda \Delta x \frac{(T_{i+1,j} - T_{i,j})}{\Delta x}
\]
The two q values can then be equated to one another to become:

\[ 2\pi\lambda \left( \frac{T_{i+1,j} - T_{i,j}}{\ln \left( \frac{\Delta x}{r_e} \right)} \right) = 4\lambda (T_{i+1,j} - T_{i,j}) \]

When like components are cancelled out, the equation leaves behind:

\[ \ln \left( \frac{\Delta x}{r_e} \right) = \frac{\pi}{2} \quad \text{or} \quad \frac{\Delta x}{r_e} = e^{\frac{\pi}{2}} \]

Which, when simplified, equates to:

\[ r_e = \frac{\Delta x}{\frac{\pi}{2}} = 0.208\Delta x \]

For an irregular grid this may be approximated by:

\[ r_e = 0.208\sqrt{A_{TOP}} \]

Where \( A_{TOP} \) is the top area of the element.

Once the effective cell radius, \( r_e \), value is found, the distance, \( d_2 \), for the IDFM connection can be determined. By using the analytical solution from Equation 42 to the outer thermal conductance becomes:
\[ \text{COND}_{\text{THEIM}} = \frac{2\pi \lambda \Delta z}{\ln \left( \frac{r_c}{r_b} \right)} = \frac{\lambda A}{d_2} \]

Where the first term represents radial heat flow and the second the IDFM term. However, it is important to note that the effective cell radius must be larger than the borehole radius for this method to work properly. When Equation 48 is rearranged, \( d_2 \) becomes:

\[ d_2 = \frac{\ln \left( \frac{r_c}{r_b} \right) A}{2\pi \Delta z} \]

These calculations can then be incorporated in the TOUGH simulation under the connected cells information within the “extra cells.” In PetraSim the ‘To’ Cell column represents the “named/printed cells” which are representative of the BHE. The orientation column can be specified as a value of 1, 2, or 3 which tells the program which permeability values to use, where 1 and 2 are extremely low in the X and Y directions and will not allow fluid leakage to the formation while 3 is the Z direction which has a much higher permeability. Next, the Dist ‘This’ column is where the calculated \( d_1 \) value from Equation 35 would be entered while the Dist ‘To’ column is where the calculated \( d_2 \) value from Equation 49 would be entered. Finally, the next column is the area, which was calculated in Equation 30.

Lastly, the method of delivering the heated fluid to the subsurface needs to be input into the “extra cell” that has been created for each BHE. In PetraSim, under the source/sinks tab of the “extra cells” data input screen, the injection of water/steam should be checked. Within this, the option for constant injection or a table of specified injection rates is available. Since the
system will undergo cycling events where the temperature will differ at specified times, a table was used to provide this data.

When injecting heat into the subsurface, the enthalpy can remain constant. However, when the system is ready for production, the temperatures must be specified more frequently to eliminate an unrealistic power spike. This power spike will occur if the fluid temperature changes too rapidly so the enthalpy was specified every 0.1 days. To do so, Equation 50 was used to calculate the temperature every 0.1 days for the duration of the cycling event. Equation 50 estimates the temperature of the borehole wall at every specified time, for a desired heat flow q.

\[
T_b = T_0 - \frac{q_c}{4\pi\lambda} \left[ \ln \left( \frac{4\alpha \Delta t}{r_b^2} \right) - 0.5772 \right]
\]

Once the temperature for each specified time is calculated, a program in Visual Basic was used to convert the temperatures into the corresponding enthalpies using the subroutine from TOUGH. An example of a table with specified times (years), mass rates (kg/s), and enthalpies of the thermal fluid (J/kg) used for each BHE is shown Figure 34.
An additional parameter that needed to be specified within the model was the BHE element porosity. The porosity of the BHE is determined by using the ratio of the U-bend area to the area of the borehole. This calculation is shown below as Equation 51.

\[
\varphi_{BHE} = \frac{A_{ubend}}{A_{borehole}}
\]

7.2 COLORADO SCHOOL OF MINES FIELD HEATING EXPERIMENT

Between June and September 2014, Tugce Baser et al. (2015) performed a heat injection test on a low-temperature BTES system located at the Colorado School of Mines (Mines) in Golden, Colorado. Five, 9-meter BHEs were used during this experiment with a single BHE located at the center while the other four comprised four corners surrounding the central BHE. The system had a radial spacing of 2.5 meters between BHEs. The BTES system utilized U-
bends made up of PEX tubing as their BHEs with a sand-bentonite grout in the annulus of the borehole. The heat transfer fluid used in this experiment was a mixture of 20% propylene glycol and 80% water. Figure 35 depicts the layout of the five BHEs (BH-1 through BH-5) as well as five monitoring locations labeled T-A through T-E.

![Figure 35 - Birds eye view of the BHE and monitoring well locations of the field site.](image)

During the Mines experiment, the heat transfer fluid was heated and circulated at a rate of 500 mL/s into the center BHE. After passing through the central BHE, the heat transfer fluid was split into four streams and passed through the remaining four BHEs before returning to the heater and restarting the process. The heating event lasted 75 days, however, at approximately 49 days the flow rate into the central BHE had decreased to 300 mL/s. After 75 days of heating, the BTES system was allowed to rest. Measurements continued to be collected for an additional 90 as the subsurface adjusted back to ambient conditions. A schematic of the movement of the heat transfer fluid within the BTES system is shown in Figure 36.
Subsurface conditions of the field site were as follows from top to bottom: approximately 0.8 meters of topsoil and organic material followed by 0.1 meters of 60 mil high-density polyethylene (HDPE) hydraulic barrier, an additional 0.1 meters of site soil, approximately 7 meters of colluvial sandy gravel, 1 meter of sand, and finally a clay layer to the final depth. Groundwater was encountered and coincided with the top of the sand layer at approximately 7 meters below the ground surface. Only one of the 2500-Watt heaters was used for heating the BTES system. A cross-section of the subsurface is shown in Figure 36.

7.3 NUMERICAL SIMULATION COMPARISON TO MINES EXPERIMENTAL DATA

7.3.1 MINES MODEL INPUTS

To confirm that this new method for simulating heat injection into the subsurface was effective, it was compared to the Mines experimental data. Fortunately, many of the parameters necessary for creating a realistic model were supplied within the 2015 paper and only a few...
needed to be inferred. In the model, the grid uses a polygonal refinement around the BHEs to provide more resolution around areas of interest.

A thin layer at the top of the model was created to represent the atmosphere, while a thin layer at the base of the model is used to give a specified hydrostatic pressure to generate water table conditions. Both layers are set to a fixed state and when the simulation is run for a long period of time (50 years) with the BHEs disabled, the simulation can properly calculate the location of the water table at steady state. It can be used to establish gravity-capillary equilibrium in the vadose zone which is used as the initial conditions for the final simulation.

For this simulation, the lateral boundaries were selected to be far enough away that they would not be influenced by the BHEs. Model boundaries for this simulation are listed in Table 7 while the layout of the model is displayed in Figure 37:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-15</td>
<td>15</td>
</tr>
<tr>
<td>Y</td>
<td>-15</td>
<td>15</td>
</tr>
<tr>
<td>Z</td>
<td>-15</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 7 - Model boundaries for the numerical simulation of the Mines BTES system.*
Prior to the creation of the main simulation, an initial conditions simulation is made. The simulation requires a hydrostatic pressure to be applied in order to create water table conditions at approximately 8 meters below ground surface (bgs). The initial temperature of the subsurface was 12°C which was reported as the ambient temperature for the subsurface on the Mines campus by Tugce Baser et al. (2015). Additionally, the top layer of the model was comprised of a thin atmosphere layer with a surface pressure of $1.01 \times 10^5$ Pa while hydrostatic pressure at a thin, clay bottom layer was set to $1.70 \times 10^5$ Pa. When at hydrostatic equilibrium, the water table will be present at approximately 7 meters from the bottom.

In addition to the thin atmospheric and clay layers at the bottom and top of the model, there were four layers that coincided with the geology as described by Tugce Baser et al. (2015). They included insulation, colluvium, sand, and additional clay layers (Table 8). Each of these layers also had its own set of thermal properties associated with it.

![Figure 37 - Layout of the BHEs and monitoring points used in the TOUGH simulation.](image)
<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Number of Layers</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Insulation</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>Colluvium</td>
<td>6</td>
<td>6.0</td>
</tr>
<tr>
<td>Sand</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Clay</td>
<td>8</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 8 – Vertical discretization of the Mines numerical model.

Since none of the properties of the soils were supplied, estimates were made based on known earth material properties. The thermal conductivities were estimated to be slightly higher than the laboratory thermal conductivity measurements for dry, uncompacted sand. The saturated thermal conductivity is known to be higher than dry thermal conductivity for all soil types (Jorand et al., 2011). Therefore, when selecting a wet thermal conductivity, a higher value was selected. The specific heat of each type of soil were also estimated based on the average values for different sediment types from Hamdhan and Clark (2010). The rock grain density of each heavily reflects the rock grain density of quartz in most cases with the exception of the insulation which was provided in Tugce Baser et al. (2015). All materials used in the simulation were assumed to be isotropic and homogenous. Therefore, only one intrinsic permeability value must be calculated but can be used for horizontal and vertical values. Both of which were calculated using Equation 52:

\[
k = K \frac{\mu}{\rho g}
\]

Where \( k \) is the intrinsic permeability in \( m^2 \), \( K \) is the estimated hydraulic conductivity of the soil (m/s), \( \mu \) is the dynamic viscosity of water (Pa s), \( \rho \) is the density of water (kg/m\(^3\)), and \( g \) is...
represents the acceleration due to gravity (m²/s). The hydraulic conductivity values for each soil type were provided by Coduto (1999). Complete soil properties used in the simulation are listed in Table 9.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Specific Heat (J/kg°C)</th>
<th>Rock Grain Density (kg/m³)</th>
<th>Horizontal Permeability (m²)</th>
<th>Vertical Permeability (m²)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>2.0 (wet), 0.5 (dry)</td>
<td>1200</td>
<td>2600</td>
<td>$1 \times 10^{-12}$</td>
<td>$1 \times 10^{-12}$</td>
<td>0.35</td>
</tr>
<tr>
<td>Colluvium</td>
<td>2.0 (wet), 0.5 (dry)</td>
<td>1200</td>
<td>2500</td>
<td>$1 \times 10^{-12}$</td>
<td>$1 \times 10^{-12}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Clay</td>
<td>2.0 (wet), 0.5 (dry)</td>
<td>1200</td>
<td>2500</td>
<td>$1 \times 10^{-14}$</td>
<td>$1 \times 10^{-14}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.03</td>
<td>900</td>
<td>1005</td>
<td>$1 \times 10^{-16}$</td>
<td>$1 \times 10^{-16}$</td>
<td>0.1</td>
</tr>
<tr>
<td>BHE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9 – Material properties for the Mines numerical model.

Additional material properties that needed to be specified included the capillary pressure and relative permeability functions. The capillary pressure function that was chosen for this
application was the van Genuchten function. These capillary pressure curves show that at low liquid saturation the capillary pressure is large but rapidly becomes small as the liquid saturation increases (Pruess et al., 1999). Another van Genuchten function was chosen for relative permeability as well. Values used in this simulation for relative permeability and capillary pressure curves are provided as Table 10.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Permeability</th>
<th>Capillary Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td></td>
<td>( S_{gr} )</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td></td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( 1/P ) (1/Pa)</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( P_{max} ) (Pa)</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td>Colluvium</td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{gr} )</td>
<td>0.5 0.0 1E-3 1E7</td>
</tr>
<tr>
<td></td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( 1/P ) (1/Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( P_{max} ) (Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td>Clay</td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{gr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( 1/P ) (1/Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( P_{max} ) (Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td>Insulation</td>
<td>( \lambda ) (W/m°C)</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td></td>
<td>( S_{gr} )</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td>BHE</td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{gr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( \lambda ) (W/m°C)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{lr} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( 1/P ) (1/Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( P_{max} ) (Pa)</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
<tr>
<td></td>
<td>( S_{ls} )</td>
<td>0.5 0.0 1E-4 1E7</td>
</tr>
</tbody>
</table>

Table 10 – Relative permeability and capillary pressure properties for the Mines numerical model.

In addition to all the material conditions that needed to be considered, the method by which the BHEs were connected was also important. Since the BHEs were all connected in series to BHE1, this was also implemented within the numerical simulation by using DELV well conditions as described in Section 7.1.1. Additionally, the \( d_i \) value that must be implemented into
the system required a BTR that was not provided. Therefore, a value of 0.1 W/m was selected for use in the simulation since it was roughly the average of the BTR values determined in the laboratory experiments previously described. The connected cells area was found to be 0.48 m², while the \( d_1 \) value was 0.024 m and the \( d_2 \) value was 0.048 m.

7.2.2 SIMULATION AND RESULTS

According to Tugce Baser et al. (2015), a single 2500-W heater was used to heat the thermal transfer fluid used at the Mines field site but, it is unknown if the temperature of the fluid or the power was held constant during the experiment. For the simulation, 45°C water was circulated within the BTES system at the flow rates specified by Tugce Baser et al. (2015) over the first 75 days as shown in Table 11. After 75 days, fluid circulation was discontinued, and the system was allowed to return to ambient subsurface conditions while the temperatures were monitored. A snapshot of temperatures after 75 days of heating at the four monitoring locations (shown in Figure 36 in Section 7.2) was taken from the numerical model for comparison. The results are shown below in Figure 38.

<table>
<thead>
<tr>
<th>BHE Location</th>
<th>Flow Rate (0-49 days) (mL/s)</th>
<th>Flow Rate (49-75 days) (mL/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>83</td>
</tr>
</tbody>
</table>

*Table 11 – Fluid flow rates at each BHE at different times in the numerical simulation.*
The comparison of the experimental and numerical data indicated that the method that was developed for simulating the BTES system using heater to cell connections returns results that are similar when the thermal properties of the system are able to be estimated. Therefore, this method could be utilized to determine what effects a higher or lower BTR may have on the system as well as give the ability to estimate the amount of power that could be produced from a high-temperature BTES system. Time series plots at all four monitoring locations are shown as Figure 39 and 40 and allow us to compare the differences between the way the experimental data and numerical simulation heat the subsurface. The numerical model, in all four cases, initially heats the subsurface more rapidly before the heating begins to slow.
Figure 39 – Time series plot of the temperature of experimental and numerical values as a function of time at monitoring locations T-A and T-C.

Figure 40 – Time series plot of the temperature of experimental and numerical values as a function of time at monitoring locations T-B and T-D.
The power into the BTES system was calculated by using Equation 17 from Section 6.2.2 by using the difference between the inlet and outlet temperatures from the numerical simulation and the rates specified in Table 11. When calculated, the average power being delivered to this system was approximately 36 W/m, which is almost twice as much as the 20 W/m that were measured by Tugce Baser et al. (2015).

7.3 SMALL-SCALE HIGH TEMPERATURE BTES SYSTEM SIMULATION

A small-scale BTES system is the next step after laboratory testing is completed. Therefore, based on the information gathered from laboratory experiments about the BTR from different system designs, several small-scale simulations of a proposed field site were completed. In addition to testing different BTR values to see how they affect the power output, the spacing was varied between the minimum and nearly maximum values determined in Section 4.

From the insulated radial model numerical simulation, it was noted that a BHE spacing of between 1 meter and 2.5 meters would be most effective for heating the subsurface in dry sand. However, for storage purposes, the BHE configuration in which the volume is greatest would allow for thermal power to be stored longest, if it can achieve appropriate temperatures. The goal of these models is to assess the feasibility of meeting a goal of heating the subsurface to a temperature great enough to produce 40 W/m.

7.3.1 CONCEPTUAL MODEL AND MODEL INPUTS OF A SMALL-SCALE BTES SYSTEM SIMULATION

The small-scale BTES system is planned to be located close to the university in Clemson, South Carolina. This location is in the Piedmont region of the southeastern United States. The geology is typically categorized by a thin layer of organic rich topsoil followed by saprolite that
is underlain by bedrock. According to the USGS, bedrock is typically granite and begins at depths ranging from approximately 50 to 100 feet bgs (https://pubs.usgs.gov).

The field site selected for study is near the top of a hill which will likely allow for the 6-meter long BHEs to remain above the water table. Therefore, at the start of the investigation, the soil should only be partially saturated with a residual water content, expected to be between 50 and 50 percent. During an initial preheating period, this residual water will be boiled away and remain dry as the study progresses. An insulating layer will be applied from the surface to approximately 1-meter bgs to prevent rainwater infiltration as well as to help minimize heat losses.

Many of the parameters used were based on known properties of soils of similar types from Hamdhan and Clark (2010) and Coduto (1999). The model is a polygonal grid with refinement around the BHEs to provide more accuracy around the areas of interest. A thin layer at the top of the model is made to represent the atmosphere while a thin layer at the base of the model is used to give a specified hydrostatic pressure. Both layers are set to a fixed state and when the simulation is run for a long period of time (50 years) with the BHEs disabled, the simulation can calculate the location of the water table at steady state. This is then used as the initial conditions for the final simulation.

For all small-scale simulations, the BHEs were 6 meters long and were placed in the simulation as starting at 3 meters and extending to 9 meters bgs. The boundaries were selected to be far enough away that they would not be influenced by the BHEs. Model boundaries for this simulation are listed in Table 12 while the layout of the model is displayed in Figure 41.
Once again, an initial conditions simulation was created prior to the final simulations in the same way it was done in Section 7.3.1. Initial subsurface temperature of the system was estimated to be approximately 21°C. The top layer of the model was comprised of a thin atmosphere layer with a surface pressure of $1.01 \times 10^5$ Pa while hydrostatic pressure at a thin, saprolite bottom layer was set to $1.31 \times 10^5$ Pa. When at hydrostatic equilibrium, the water table will be present approximately 3 meters from the bottom of the model. Insulation and additional saprolite layers were included in the simulation and layers and thicknesses are shown in Table 13.
<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Number of Layers</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Insulation</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>Saprolite</td>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

*Table 13 – Vertical discretization of the numerical model.*

Each of the materials listed in Table 13 has its own set of soil properties. Since the materials were not able to be directly measured, estimates, using methods described in Section 7.3.1, were made based on known earth material properties. Complete soil properties used in the simulation are listed in Table 14.

**Saprolite**
- Thermal Conductivity (W/m°C): 2.0 (wet), 0.50 (dry)
- Specific Heat (J/kg°C): 1000
- Rock Density (kg/m³): 2600
- Horizontal Permeability (m²): \(1 \times 10^{-12}\)
- Vertical Permeability (m²): \(1 \times 10^{-12}\)
- Porosity: 0.35

**Insulation**
- Thermal Conductivity (W/m°C): 0.15
- Specific Heat (J/kg°C): 1000
- Rock Density (kg/m³): 2600
- Horizontal Permeability (m²): \(1 \times 10^{-16}\)
- Vertical Permeability (m²): \(1 \times 10^{-16}\)
- Porosity: 0.1

**BHE**
- Thermal Conductivity (W/m°C): 2.0
- Specific Heat (J/kg°C): 1000
- Rock Density (kg/m³): 2500
- Horizontal Permeability (m²): \(1 \times 10^{-23}\)
- Vertical Permeability (m²): \(1 \times 10^{-10}\)
- Porosity: 0.056

*Table 14 – Material properties for numerical model.*

The flow rate for fluid being circulated at each BHE was 1 gallon per minute, or a mass rate of 0.067 kg/s. Each numerical simulation had a 180-day preheating period prior to the
commencement of cycling of the temperature. The temperature at the BHE was then cycled for 6-day periods of either heating or cooling. During the heating process, the fluid temperature entering the system was 270°C, whereas the temperature during the cooling process was allowed to drop as low as necessary to continually produce thermal power during the 7-day period. The BHEs were connected in parallel.

The $d_1$ values for the connection between the BTR elements and the grid elements of the system require a BTR value to calculate so three different BTRs were explored in these simulations. The BTR values that were used as well as the $d_1$ and $d_2$ values input into the connected cells table are listed below in Table 15.

<table>
<thead>
<tr>
<th>BTR (m°C/W)</th>
<th>0.03</th>
<th>0.13</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$ (m)</td>
<td>0.007</td>
<td>0.031</td>
<td>0.048</td>
</tr>
<tr>
<td>$d_2$ (m)</td>
<td>0.022</td>
<td>0.022</td>
<td>0.022</td>
</tr>
</tbody>
</table>

*Table 15 – Connected cells model input for the numerical simulation.*

Additional material properties that needed to be specified included the capillary pressure and relative permeability functions. In both cases, a van Genuchten function was chosen for the simulation. Values used in this simulation for relative permeability and capillary pressure curves are provided as Table 16.
### Table 16 – Relative permeability and capillary pressure properties for the small-scale numerical model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Permeability</th>
<th>Capillary Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saprolite</td>
<td>$\lambda$ (W/m°C)</td>
<td>$1/P_0$ (1/Pa)</td>
</tr>
<tr>
<td></td>
<td>$S_{lr}$</td>
<td>$P_{\text{max}}$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>$S_{ls}$</td>
<td>$S_{ls}$</td>
</tr>
<tr>
<td></td>
<td>$S_{gr}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insulation</th>
<th>$\lambda$ (W/m°C)</th>
<th>$1/P_0$ (1/Pa)</th>
<th>No Capillary Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{lr}$</td>
<td>$S_{ls}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.1</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BHE</th>
<th>$\lambda$ (W/m°C)</th>
<th>$1/P_0$ (1/Pa)</th>
<th>No Capillary Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{lr}$</td>
<td>$S_{ls}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>5E-4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 7.3.2 SIMULATION AND RESULTS

It is difficult to estimate the impact of the BTR on a BTES system from a simple calculation. We know that an increased BTR typically results in less conduction of heat into the formation and in turn will reduce the amount of power into and out of the BTES system. With numerical simulations, it is possible to quantify the effects of having a higher or lower BTR on the power output. Also, a clearer representation of the effects of different spacing of the BHEs was evaluated by using a spacing method at the low and high end of the range of possible configurations from the 1-D axis-symmetric numerical simulation from Section 5. Figures 42 and 43 show the circulating BHE fluid temperature compared to the temperature of the ground measured halfway (either 0.5 or 1.2 meters) between the center BHE and an outer BHE.
Figure 42 - Measured temperature of the circulating fluid compared to the subsurface temperature at 0.5 meters from the central BHE. BTR for this simulation was set at 0.13 m°C/W and BHE spacing was 1 meter.

Figure 43 - Temperature of the circulating fluid compared to the subsurface temperature at 1.2 meters from the central BHE. BTR for this simulation was set at 0.13 m°C/W and BHE spacing was 2.4 meters.
The results of the subsurface temperature at the monitoring well in each simulation demonstrated that, while using a larger spacing may be beneficial in terms of storage volume, it may not be feasible when using only a few BHEs. Therefore, the larger spacing may need to be reserved for the pilot scale project that will allow for longer preheating times and cycling periods. Figures 42 and 43 also show that there is a large discrepancy between the expected temperatures at the monitoring locations compared to the results of the dry insulated models in Section 5.3.2.

After 180-days of heating the systems with 240°C BHE fluid, the expected temperatures in the insulated model are approximately 240°C and 220°C at 0.5 meters and 1.25 meters, respectively. Figure 38 shows the heating process of each system after the 180-day preheating and at the end of one cooling and one heating cycle. In the TOUGH simulations those temperatures reach only 148°C and 108°C at 0.5 meters and 1.2 meters from the central BHE after 180 days. This is partially because the system is not insulated like the 1-D radially symmetric numerical model and because the TOUGH simulation considers thermodynamic impacts of any residual water in the system.

This can be seen in both Figures 41 and 42 where the monitoring location temperatures plateau for an extended amount of time at 100°C as the water trapped inside the pores is boiled off. In the more closely spaced model, this period lasts roughly 25 days but when more loosely spaced this boiling period lasts over 100 days. The thermal power into the system was calculated by using Equation 17. From this information, the energy necessary to boil off the residual water in the BTES system can be calculated by integrating the power with time. When the energy for the boiling period in each BTES system is summed, it will give the value for the energy required to boil away the water at that half-spacing location. This means that the area from the central
BHE to the outer BHE is dry. When this is calculated, the BTES system with larger spacing is nearly 50 times greater than that of the smaller system (61 Gigajoules to 1.25 Gigajoules).

Once the pores are completely dry and the system reaches superheated conditions, the temperature begins to rise again once again. As the temperatures increase, the smaller spaced system rises much more quickly and once again expends less energy to do so. At the end of the initial 180-day preheating period, the smaller BTES system used only 1800 kWh and arrived at a final temperature of 148°C. While the larger BTES system reaches a final temperature of 108°C with almost 25,000 kWh of energy being used to do so. The small-scale field site will require more closely spaced BHEs to have a chance at power production due to a lack of interaction between the BHEs in the larger spaced system.

The production of thermal power serves as the main purpose of the BTES systems. Therefore, it was necessary to estimate whether this BTES system would be able to generate upwards of 40 W/m using either of these preliminary designs. Because the temperature of the subsurface between the more largely spaced BHEs did not reach significant temperatures above boiling, the production of power from them for more than a few hours was not feasible. So, only the results of the simulations using 1-meter spacing are displayed in Table 17 which shows the power production at the end of 6-day cycling events as well as efficiency of each system. The efficiency value was calculated by integrating the power with time and using the final cycling events ratio of energy produced to energy input. Figure 44 shows the 3D simulation for the two differently spaced models after the preheating period as well as at the end of a heating and cooling cycle.
As expected, the BTES system with the lowest BTR was able to generate the most thermal power over the weekly cycling events with a value of 22.0 W/m after 6 days of extraction. It was also able to keep the power production above 40 W/m for over 3.9 days. When compared to the simulation with the highest BTR, the power extraction rate at the end of the 6-day period was approximately 8 W/m greater than that with the lowest and has an efficiency almost 5% higher. The simulation with the lower BTR value was also able to produce power at a rate of 40 W/m for almost an entire day longer. This shows that even at the small scale, the BTR can have quite an impact on the productivity of the BTES system, which will likely only become
more apparent as the system is enlarged due to the addition of more BHEs where the effects of the BTR will be compounded.

7.4 PILOT SCALE TOUGH NUMERICAL SIMULATION

After the Clemson field-scale BTES system is completed, a final pilot-scale BTES system is to be completed near Columbus, Georgia. The proposed location for the pilot-scale system is Ft. Moore so a numerical simulation for this site was also completed. It was determined that, although it did not necessarily work in the small-scale simulations, it is likely that a larger-scale model would benefit from a more distantly spaced grid. Therefore, the spacing of these simulations was set to 2.4 meters. This is also important because it will be necessary to have a greater storage volume to produce more thermal energy.

A larger volume increases the area to volume ratio, which will help with the efficiency of the system. Based on the volume of the BTES system when using this spacing, the spherical heat loss model estimates that at steady state the system will be losing approximately 23.5 kW in a finite system with the constant temperature boundary set to 5 meters. This value can be later compared to what is found from the 3D numerical simulation to determine whether the system more closely matches a finite or infinite boundary scenario in the spherical model and on the proposed design from Falta et al., 2021.

The layout of the BHEs was chosen based on a literature review. One of the most well-known BTES systems is the Drake Landing Solar Community (DLSC) located in Alberta, Canada. The system, while not used for high temperatures, was successful in providing 90% of the heating requirements to 52 houses (Sibbit et al., 2012). Their system contains 144 BHEs arranged in a hexagonal pattern which is a conventional design for many BTES systems.
Therefore, this is the design that was adopted for the pilot scale project. The anticipated number of BHEs in this pilot system is 37 rather than 144.

An issue that was noted during literature review was the possibility of heat pipe effect around the outside of the system. According to Smits et al. (2013), as the water around the heat exchanger array is heated, it vaporizes and then moves upward due to buoyancy. As it approaches colder regions away from the heat source, it will release latent energy while it cools. The water will then condense and flow downward due to gravity and back toward the dry soil and around the heat source via capillarity.

To counteract this issue, ten vents were installed in the simulations around the outside of the BTES system. The vents were simulated by taking advantage of the DELV well condition that uses a specified productivity index and pressure to determine when it will allow the well to begin production. In this case the vents were set up like a vacuum by setting the pressure as lower than atmospheric pressure. The productivity index of each vent was calculated by using Equation 53 (Coats, 1977):

\[
P_I = \frac{2\pi(k\Delta z_l)}{\ln\frac{r_e}{r_w}}
\]

Where \( \Delta z_l \) (m) represents the layer thickness, k is the permeability, \( r_e \) is the effective grid block radius for flow, and \( r_w \) is the well radius. The vent locations are shown as Figure 45, located around the outside of the BTES system.
7.4.1 CONCEPTUAL MODEL AND MODEL INPUTS OF THE PILOT-SCALE BTES SYSTEM SIMULATION

The potential pilot site is located in a different regional geology called the Coastal Plain. The coastal plain is characterized by unconsolidated sediment that alternates between marine and land sediments as the ocean transgressed and regressed through time (Veatch and Stephenson, 1911). This geologic region tends to have a much deeper bedrock buried beneath many layers of sediment. At the time of this simulation, the depth to the water table at the site is unknown and therefore was inferred based on the topography and hydrology of the area. The proposed pilot site is also in an elevated area with a nearby river, and the depth to the water table was estimated to be about 18 meters based on digital elevation maps (https://apps.nationalmap.gov/).

For all pilot-scale simulations, the BHEs were 9 meters long and were placed in the simulation as starting at 3 meters and extending to 12 meters bgs. The boundaries were selected...
to be far enough away that they would not be influenced by the BHEs. Model boundaries for this simulation are listed in Table 18 while the layout of the model is displayed in Figure 46 below:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-36</td>
<td>36</td>
</tr>
<tr>
<td>Y</td>
<td>-36</td>
<td>36</td>
</tr>
<tr>
<td>Z</td>
<td>-50</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 18 - Model boundaries for the numerical simulation of the pilot-scale BTES system.*

An initial conditions simulation was created prior to the final simulations in the same way it was done in Section 7.3.1. The ambient subsurface temperature is expected to be similar to that
of the small-scale model, 21°C. A thin layer at the top of the model was created to set the surface pressure to $1.01 \times 10^5$ Pa. The hydrostatic pressure was created by using a thin layer of unconsolidated sediment at the bottom of the model where the pressure was $2.8 \times 10^5$ Pa. When at hydrostatic equilibrium, the water table will be present approximately 18 meters from the bottom of the model. Insulation and additional unconsolidated sediment layers were included in the simulation and layers and thicknesses are shown in Table 19.

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Number of Layers</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Insulation</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>Unconsolidated Sediment</td>
<td>24</td>
<td>48</td>
</tr>
</tbody>
</table>

*Table 19 – Vertical discretization of the numerical model.*

Each of the materials listed in Table 19 has its own set of soil properties. Since the materials were not able to be directly measured, estimates, using methods described in Section 7.3.1, were made based on earth material properties. Complete soil properties used in the simulation are listed in Table 20.

<table>
<thead>
<tr>
<th>Unconsolidated Sediment</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Specific Heat (J/kg°C)</th>
<th>Rock Density (kg/m³)</th>
<th>Horizontal Permeability (m²)</th>
<th>Vertical Permeability (m²)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.0 (wet), 0.50 (dry)</td>
<td>1000</td>
<td>2600</td>
<td>$1 \times 10^{-12}$</td>
<td>$1 \times 10^{-12}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Specific Heat (J/kg°C)</th>
<th>Rock Density (kg/m³)</th>
<th>Horizontal Permeability (m²)</th>
<th>Vertical Permeability (m²)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.15</td>
<td>1000</td>
<td>2600</td>
<td>$1 \times 10^{-16}$</td>
<td>$1 \times 10^{-16}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

| BHE                     |                              |                        |                      |                            |                            |          |
The flow rate in each BHE was the same as the previous models at 1 gallon per minute, or 0.067 kg/s, at each BHE. Each simulation was given a one-year initial preheating period where a 240°C fluid was circulated through the BTES system prior to the commencement of temperature cycling. Once completed, 30-day cycling events were assessed. During each cycling event the system would be heated using 270°C fluid in the BHEs for 30 days followed by a 30-day cooling cycle where the temperature was allowed to drop as low as necessary to continually produce thermal power for the entire period. The goal is to try to extract power at a rate of 40 W/m for a two-week time period, as set forth in the proposal. The BHEs in these simulations were connected in parallel rather than series.

The BTR element to grid element, $d_1$, values of the system require a BTR value to be calculated, so three different BTRs were explored in these simulations. The BTR values that were used as well as the $d_1$ and $d_2$ values input into the connected cells table are listed below in Table 21.

<table>
<thead>
<tr>
<th>BTR $(\text{m}^2\text{C/W})$</th>
<th>0.03</th>
<th>0.13</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$ $(\text{m})$</td>
<td>0.007</td>
<td>0.031</td>
<td>0.048</td>
</tr>
<tr>
<td>$d_2$ $(\text{m})$</td>
<td>0.022</td>
<td>0.022</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 21 – Connected cells model input for the numerical simulation.
Additional material properties that needed to be specified included the capillary pressure and relative permeability functions. In both cases, a van Genuchten function was chosen for the simulation. Values used in this simulation for relative permeability and capillary pressure curves are provided as Table 22.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Permeability</th>
<th>Capillary Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconsolidated Sediment</td>
<td>$\lambda$ (W/m°C)</td>
<td>0.5 0.1 1.0 0.1</td>
</tr>
<tr>
<td>$S_{lr}$</td>
<td>$S_{ls}$</td>
<td>1.0 0.1</td>
</tr>
<tr>
<td>$S_{gr}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>$\lambda$ (W/m°C)</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td>$S_{lr}$</td>
<td>$S_{ls}$</td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td>$S_{gr}$</td>
<td></td>
<td>No Capillary Pressure</td>
</tr>
<tr>
<td>BHE</td>
<td>$\lambda$ (W/m°C)</td>
<td>0.5 0.15 1.0 0.1</td>
</tr>
<tr>
<td>$S_{lr}$</td>
<td>$S_{ls}$</td>
<td>$1/P_0$ (1/Pa)</td>
</tr>
<tr>
<td>$S_{gr}$</td>
<td></td>
<td>$P_{max}$ (Pa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S_{ls}$</td>
</tr>
</tbody>
</table>

Table 22 – Relative permeability and capillary pressure properties for the small-scale numerical model.
Previously, it was observed that the lower the BTR value, the better power production the BTES system was able to have, with an approximate 8 W/m difference in power production at each BHE between the locations with the lowest and highest BTR values. It was expected that this trend would continue as the simulation was expanded. By creating pilot-scale simulations using the same BTR values, the effect of the BTR value on the system was quantified. Table 23 displays the power output at the end of a 30-day cycling event for each simulation of varying BTR values.

<table>
<thead>
<tr>
<th>BTR (m°C/W)</th>
<th>Power production after 30 days (W/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>57.7</td>
</tr>
<tr>
<td>0.13</td>
<td>47.1</td>
</tr>
<tr>
<td>0.2</td>
<td>37.9</td>
</tr>
</tbody>
</table>

*Table 23 - A comparison of the different power extraction rates depending on the BTR value.*

As with the small-scale model, the BTES system with the lowest BTR value was able to generate the most thermal power throughout the cycling event. The power production remained at roughly 58 W/m at the end of the 30-day extraction period. When compared to the simulation with the lowest BTR, the power production was approximately 20 W/m higher. However, even with this large difference between the two values, it is important to note that even with a BTR value of 0.13 m°C/W, the estimated power production is above 40 W/m at the end of the 30-day period. Therefore, while a lower BTR value is preferred and certainly helpful for what is being attempted, the goal of reaching 40 W/m in power production is possible even when the BTR is
relatively high. A graph of the power production throughout several cycling events is displayed below as Figure 47.

![Graph showing power production over time](image)

*Figure 43 - A plot showing power as a function of time for the BTES system with a BTR of 0.13 m°C/W.*

For the first 365 days, the power is steadily decreasing with time as the system tries to reach the preheating temperature of 240°C. The plateau it reaches toward the end of the preheating period is indicative of the constant power being lost out of the system, in this case roughly 23 kW. After the initial 365-day heating period, the system begins 30 day cycling events where the temperature is varied above and below that initial 240°C. When the temperature decreases, the system is producing power and displays a negative power value in Figure 47 because it is being removed from the subsurface. When the system is heating the power values are positive because heat is being put into the subsurface. As the cycling continues, the efficiency of the system should also improve.

Figure 48 shows a 3-D display of the numerical model with a BTR of 0.13 m°C/W through the initial preheating cycle and then at the end of a heating and cooling cycle. The
simulation is shown at three stages of the preheating process: beginning, middle, and end. A cycling event was shown to demonstrate that while removing power over thirty days, the temperature decline is not so great that it cannot rebound during the following heating cycle. This model shows that it is feasible to achieve 40 W/m of power production, which is a system that is hot enough to generate power and have enough volume that the temperature within the BTES system does not drop substantially between BHEs during the extraction process. Therefore, the system can be properly restored to the hotter temperature during the following heating cycle and the system can be cycled indefinitely without issue.

![3D model images with temperature annotations](image)

*Figure 44 – A 3-D display of the numerical model with a BTR of 0.13 m°C/W through the first 455 days of operation.*

A monitoring location was simulated 1.2 meters from the central BHE or halfway between two BHEs (Figure 49). By doing so, we were able to observe how the system is heating and drying out over time. Figure 50 displays a graph of temperature as a function of time while Figure 51 shows a graph of water saturation as a function of time at the monitoring location.
Figure 45 - Monitoring location at 1.2 meters from the central BHE and 1.2 meters from the next BHE.

Figure 46 - Fluid temperature and monitoring location temperature as a function of time in the BTES system with a BTR of 0.13 m°C/W.
Figures 50 and 51 show that there is water in the pores at the time of start up in the system. As the system heats and the temperature plateaus at 100 °C in Figure 50 as the water is boiled away. By comparing this behavior to Figure 51 at the same time, we can confirm that this is in fact what is taking place within the system. Figure 51 shows a decrease in liquid during this time and eventually drops to zero, meaning that the system is dry. As the system’s water saturation goes to zero, we can see that this is also when the temperature begins to increase above 100 °C in Figure 50.

These three simulations were able to show the different efficiencies of each system based on the BTR values used in the simulations. By integrating the power over time of each system, the efficiencies of each BTES system could be determined. Efficiencies for all systems were relatively low, ranging from approximately 18-23%. Efficiency increases primarily with volume. A table of the efficiencies based on BTR value is displayed below in Table 24.
Lastly, the spherical heat loss model can be compared to the results of the pilot scale simulation to help determine the relevancy of that simple model. Figure 47 shows the power curve of the BTES system with a BTR of 0.13 m°C/W. The steady state power loss can be observed when the curve flattens out during the initial preheating period. In this case, the value is 23 kW with similar values in the two other models with higher and lower BTR values.

When comparing these values to the heat loss for a spherical model of this volume, it provides information about where the constant temperature boundary should be located to get a similar result. To get values around 23 kW, it is necessary to have the constant temperature boundary located approximately 5 meters beyond the storage radius. This shows that the simple spherical model can provide a useful order-of-magnitude estimation for heat losses if the storage volume is reasonably close to a sphere.

<table>
<thead>
<tr>
<th>BTR \ m°C/W</th>
<th>Energy Efficiency \ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>23.2</td>
</tr>
<tr>
<td>0.13</td>
<td>21.1</td>
</tr>
<tr>
<td>0.2</td>
<td>18.0</td>
</tr>
</tbody>
</table>

*Table 24 - Efficiency of each pilot-scale simulation based on BTR value used.*
8 SUMMARY

This work examines the concept of using the subsurface as a thermal battery by creating a high temperature borehole thermal energy system that will reach temperatures in the 200 to 300°C range. This could act as an alternative to conventional energy storage methods and could have an added level of resiliency.

Major results from the analytical and numerical simulations as well as laboratory experiments are summarized below:

1. Based on the one-dimensional axi-symmetric numerical simulation, the upper and lower boundaries for the effective spacing of a BTES system in dry sand were identified. It was determined that the smallest spacing between BHEs that would produce thermal power for an extended period was approximately 1 meter, while the maximum spacing was 2.5 meters. 2.5 meters was the maximum spacing that could be used without potentially depleting the heat within the storage volume to an extent where the BTES system would be unable to rebound from the cyclical extraction process.

2. The one-dimensional spherical analysis of different storage volumes and formations showed that while granite is a great conductor, it may not be effective in storing heat at the smaller scale volumes. In general, the amount of heat stored in the formation and the length of time which that heat can be stored is vastly improved by increasing the volume of the system. For a smaller demonstration, it is probably best to use an unconsolidated, dry storage medium and to maximize the volume of the BTES system.
while keeping the spacing tight enough that the BHEs and surrounding formation can store and extract thermal power.

3. By completing several thermal response tests in the laboratory, the borehole thermal resistance of all three BHE configurations was able to be calculated. This gave an indication of which design may work best for conducting heat into the formation for the field scale application. It was found that the U-bend and coaxial designs in direct contact with the unconsolidated sediment had similar BTR values ranging from 0.1 to 0.13 m°C/W. Meanwhile, the grouted U-bend had a BTR of 0.03 m°C/W. Therefore, the use of a thermally enhanced grout in the borehole annulus will be most effective at keeping the BTR low.

4. The pilot scale TOUGH numerical simulations, power production at the end of a 30-day extraction period remained approximately at or above the goal of 40 W/m that was proposed. Therefore, the model showed that the intended BTES system can likely meet the goals set forth at the beginning of this project.
9 CONCLUSION

Methods to reliably store the energy produced when supply exceeds demand have always been a topic of interest. A variety of approaches have been used over the years; however, most tend to be landscape dependent, and each has its own set of drawbacks (www.energy.gov/eere/renewable-energy). The use of the subsurface for storing thermal energy has become more recognized as a potential viable alternative to conventional methods.

Through the work completed, it was determined that the pilot scale BTES system has the potential to produce power at or above 40 W/m for at least thirty days when BTR is reduced. If the pilot scale project proves successful, it has the advantage of being able to be expanded. By expanding the size of the BTES system, the storage volume is increased, bringing performance benefits. Based on the spherical storage volume analysis, a larger storage volume offers greater power production.

In addition to being able to scale the system up pending a successful pilot scale demonstration, the use of the subsurface makes the system more resilient to any disruptions that could potentially occur. Since the storage of surplus energy for later consumption is not always available, it is common that consumers may experience interruptions to their power service during times of high energy demand (i.e., busy times of day, heat waves, etc.). By having a surplus of energy stored in the subsurface, these issues can be circumvented thus making this a more reliable system than currently available.

BTES systems are also quite flexible if energy demands are low. For example, if it is not necessary to use the stored energy after a heating cycle, the system can continue to be heated as it has a constant heat loss across the surface area of the system. The system does not necessarily
have to produce the full amount of thermal power discussed in Section 8. It has the potential to produce over 40 W/m for at least thirty days. However, if there is a lesser amount of energy needed, less power can be extracted by dropping the temperature of the circulating fluid more gradually than was done in the simulations.

Finally, when the pilot scale project is completed, the next step is to connect the BTES system to a renewable energy source which could heat thermal fluid (solar, waste energy, etc.). By connecting the BTES system to a renewable energy source, the system becomes more resilient and will not be open to the kind of disruptions that are common in conventional energy production. Additionally, it helps dismiss many of the typical concerns that people have surrounding the viability of renewable energy sources.


Coats, K.H. Geothermal Reservoir Modeling, paper SPE-6892, presented at the 52nd Annual Fall Technical Conference and Exhibition of the SPE, Denver, Colorado, October 1977.


