

Evaluation of Possible Solutions to Reduce Ground Source Heat Exchanger Cost

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Abstract

Ground source heat pumps (GSHPs) possess great potential to become a mainstream technology for space heating and cooling due to their long service life and low operating costs. The main barrier for wider adoption of GSHPs is the high installation costs of ground source heat exchangers (GSHEs). These high costs are primarily due to the many steps and the associated labor, material, and equipment costs involved in the installation process. While some parts of the cost are generally fixed, such as wages of drillers; others can be lowered through advances in technology. As a result, it is important to extensively explore and evaluate potential solutions for lowering the installation costs.

To reduce the installation costs, it was important to first identify the key cost drivers that have significant potential for cost reduction. A cost model originally developed at Sandia National Laboratories was updated with up to date costs and the accounting of various information associated with the installation process. A parametric study was conducted using this updated cost model to determine the effectiveness of various possible cost reduction solutions, which can then aid in identifying and targeting the key cost drivers to allow for the greatest cost reductions possible. Current technological advancements, primarily potential drilling technologies, were also researched to identify which technologies can be utilized to effectively reduce installation costs. Using this information, a guideline can then be created covering the potential solutions for reducing GSHEs cost under these conditions.

From this study, several recommendations are made for lowering the installation cost. Minimizing the number of boreholes and maximizing the borehole length is the preferred option where available land for installing GSHEs is limited, but multiple shallow boreholes drilled with low-cost drill rigs may be better where available land is plenty. Despite which option is chosen, it is best to maximize the penetration rate of drilling and minimize the borehole diameter and associated material and equipment costs.

Incorporating novel drilling methods, like the laser drill rig upon becoming economically viable, can also aid in lowering costs in places difficult to drill with conventional drill rigs.

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I. Introduction

Currently, ground source heat pumps (GSHPs) have the potential to become the leading method for heating and cooling. When compared to conventional methods of heating and cooling such as air sourced heat pumps, GSHPs are more efficient. The service lives of GSHPs are also much higher as compared to these conventional methods. Along with this, the operating cost of GSHPs are lower in comparison to the more conventional methods. The main hinderance of GSHPs which prevent them from becoming more competitive with the other means of heating and cooling are the high costs associated with installing ground source heat exchangers (GSHEs). Although the low operating costs allow GSHPs to offset the cost of installation after several years of operation, most people will be turned off by the high installation costs. Reducing these costs would allow for GSHPs to become more commonplace; however, the task of reducing the overall cost of installation is not simple. This high cost primarily arises from the many steps associated with installing the heat exchangers along with the cost of labor and materials used for installation. If this cost can be lowered, it would allow for GSHPs to become a more competitive means of heating and cooling.

There are many reports that detail the different potential means to lower the costs of different parts of the installation process, such as the heat exchanger design and the ideal drilling rig to be used; however, few reports combine this information for the purpose of creating a guideline. As such, it would be of great use to create a guideline that can advise individuals and businesses on how to best install GSHPs. By creating a guideline that covers the different areas of the installation process and how to best install the heat exchangers for a given location, it would allow for the costs of installation to be more cost effective. This would result in GSHPs becoming more widespread due to the reduction in the installation costs. In addition, the individuals involved with installing GSHPs could potentially achieve higher profits and increase in their business.

II. Literature Review

Current technology was researched to identify what can best be utilized to lower ground source heat exchanger costs. An extensive literature review was performed in the following areas: (1) drilling technologies, (2) casing, and (3) ground heat exchanger design.

II. a Drilling Technologies

II. a. i Conventional Drilling Rigs

One area of technology that was researched were the advantages and disadvantages of different drilling rigs. Ref. [1-6] contained several comparisons of these drilling rigs, including the advantages and disadvantages. Advantages of using cable tool drilling rigs include the following: they are relatively cheap, require very few individuals to operate, possess the ability to drill through hard rock and boulders, and can be used to drill to any depth with any diameter. The main disadvantage to using cable tools is the low penetration rate, causing other drilling rigs to be preferred. Unlike cable tools, rotary drillings can provide faster penetration rates. Different rotary drilling rigs, such as air and mud rotary drilling rigs, are also available that can be put into action depending on preferences and geology. Regardless of the rotary drilling rig chosen, the various rigs allow for deeper boreholes and a larger range of borehole diameters and are fairly inexpensive to use. Several disadvantages can be associated with rotary drilling rigs, however, depending on the type of rotary drilling rig used. This can be seen with mud rotaries requiring large mud pits and substantial amounts of water, while also requiring many people to help with the drilling. Down the hole (DTH) hammers can be useful when drilling in hard rock as it provides high penetration rates in those conditions while providing long bit lives and no need for mud pumps. The main disadvantages in using DTH hammers are the initial costs involved along with maintenance costs, excessive noise, and possible borehole instability, along with other issues. Auger drilling rigs can be useful in that it can provide large diameter boreholes, requires no drilling fluid, has low operating costs,

and faster penetration rates when used in the right geology. The disadvantages of using augers are that they can't be used to drill through hard rocks; they are limited in the depths which can be drilled, and they have the potential to leave large amounts of soil around the drilling site. Direct push drilling rigs can be beneficial in that they tend to be small and provide fast penetration rates, though the boreholes that are produced have small borehole diameters as compared to other drilling rigs. The depth in which the borehole can be drilled is also limited, with the drilling rig only being able to drill in suitable geologies. Sonic drilling allows for faster penetration rates when compared to other drilling rigs while also producing little waste and allows for drilling in any geology. The main concern when using the sonic drilling rig is the high vibrations that the rig produces and the amount of waste it generates. A summary of the advantages and disadvantages of these different drilling rigs can be viewed in table 1, along with the depths and diameters that these drill rigs can achieve in table 2. The penetration rate of these drilling rigs can also vary depending on the geology in which they are used to drill through. The penetration rates found in Ref [8-10, 37] covered both rotary and percussive (DTH hammer) drilling rigs, with these papers not covering the time to pull out the drill string. In these papers, it was shown that increasing modulus ratios lead to lower penetration rates for the rotary drilling rig and lead to increasing penetration rates for percussive drilling rigs; though it was also demonstrated that increasing compressive strength lead to lower penetration rates for the percussive drilling rig. The final paper then showed how the percussive drilling rig penetration rate varied with air pressure, thrust, compressive strength, and bit diameter. From these papers, several penetration rates for different geologies were chosen for both the rotary and percussive drilling rigs to be used to aid in the creation of a useful cost model, with these penetration rates being detailed in table 3. Using these penetration rates, the user of the cost model would only have to enter the percentages of geologies encountered and the type of drilling rig used while drilling. These percentages would then be used to calculate the weighted average of the different penetration rates, with this weighted average being used to determine the total time to drill a given borehole.

Table 1. Advantages & Disadvantages of Different Drilling Rigs

Drill Rig Type	Advantages	Disadvantages
Cable Tool ⁽³⁾⁽⁴⁾⁽⁶⁾	• Cheap to Purchase and Operate • Requires Few Operators • Able to Drill Through Hard Rock • Able to Drill to Any Depth with Any Diameter	• Low Penetration Rates
Rotary (Air & Mud) ⁽³⁾⁽⁴⁾⁽⁶⁾	• High Penetration Rates • Inexpensive to Operate	• Mud Rotaries Require Large Mud Pits & Considerable Amounts of Water • Requires Multiple People to Operate
DTH Hammer ⁽²⁾⁽⁶⁾	• High Penetration Rates in Hard Formations • Long Drill Bit Lives	• High Initial and Maintenance Costs • Excessive Noise • Possible Borehole Instability
Auger ⁽¹⁾⁽⁴⁾⁽⁶⁾	• Large Diameters Possible • Requires no Drilling Fluid • Low Operating Costs • Fast Penetration Rates in Suitable Conditions	• Unable to Drill Through Hard Rock • Limited in Depths Drilled • Potential to Create an Accumulation of Soil Around Drilling Site
Direct Push ⁽¹⁾⁽⁵⁾	• Small in Size • Provide Fast Penetration Rates	• Limited in Depths Drilled • Can only Produce Small Diameter Boreholes • Limited to Suitable Geologies
Sonic ⁽¹⁾⁽²⁾⁽⁵⁾	• Fast Penetration Rates • Produces Little Waste	• Produces High Vibrations

Table 2. Typical Borehole Diameters & Depths of Different Drilling Rigs

Drilling Rigs	Borehole Diameter (in)	Depth (ft)
Auger ⁽¹⁾⁽⁴⁾	< 60	< 150
Rotary ¹	< 36	< 1500
DTH Hammer ³⁶	< 16	< 2000
Direct Push ¹	< 3	< 25
Sonic ⁷	< 12	< 600

Table 3. Penetration Rates Used in Cost Model for Different Drilling Rigs

Geology	Rotary Drill Rig (ft/hr)	Percussive Drill Rig (DTH Hammer) (ft/hr)
Soil	148 ³⁷	NA
Shale	83 ³⁷	68 ¹⁰
Rock	24 ³⁷	167 ⁸

II. a. ii Novel Drilling Rigs

Flame Jet Spallation Drilling Rig

Several novel drilling rigs were also researched using Ref [11-12, 30]. [12] When using flame-jet spallation drilling rigs, stress is created in the surrounding geology due to the heat produced by the drilling rig's flame jet, leading to the formation of cracks in the geology. Flakes are then produced and then cleared away by the flame jet. This process is further illustrated by figure 1.

Flame-jet spallation drilling rigs can be useful as it requires no contact with the ground and no mechanical energy, while also being useful when drilling in hard rock. This can allow for higher penetration rates when drilling in hard rocks and no concerns regarding drill bit wear as the drilling rig does not even make contact with the ground. The main problems that make this drilling rig unattractive when used alone are the limited geologies in which it can be used and little control on the borehole is formed.

Thermo-Mechanical Drilling Rig

[12] The problems associated with flame-jet spallation drilling rigs can be rectified by using the combined thermo-mechanical drilling rig, which combines conventional drilling rigs with the flame jet spallation drilling rig. When this drilling rig is used, either the flame jet can be used as the only means of drilling or as a means of assisting the more conventional means of drilling, as demonstrated by figure 2. The use of only the flame jet can be used when the right conditions appear, while having it aid the conventional drilling rigs otherwise.

The combination of these two drilling rigs allows for a broad range of geologies to be drillable, with great control on the formation of the borehole. While these two drilling rigs can be useful, they have mainly been considered for boreholes that are several kilometers deep. Along with this, other challenges include protection from the elevated temperatures produced for the drillers along with better heat transfer when groundwater is encountered.

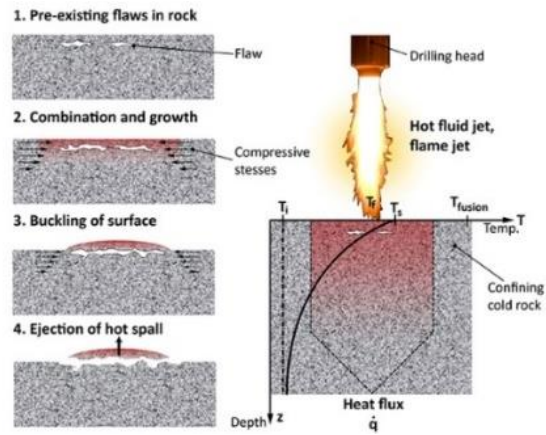


Figure 1. Thermal Spallation Drill Rig [38]

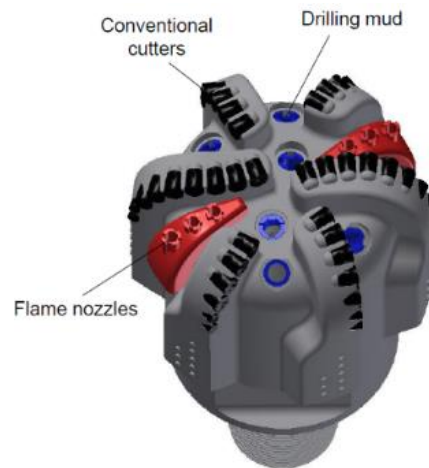


Figure 2. Thermo-Mechanical Drill Rig [12]

Coil Tubing Drilling Rig

[11] When utilizing coil tubing drilling rigs, one main benefit that arises is that, instead of using a traditional drill string, a long steel tube wound around a reel is used. When drilling commences with coil tubing drilling rigs, the reel holding the tubing rotates in the desired direction to allow for drilling with an injector providing the needed traction to allow it to be moved in and out of the borehole.

This method of drilling allows for faster tripping, with the ability to pump drilling fluid throughout the process, which can help create better boreholes and reduce the likelihood of the tubing becoming stuck. One large disadvantage of coil tubing drilling rigs is their inability to rotate, requiring downhole drilling motors, which are expensive. Once these motors become inexpensive enough to allow for better competition between drilling rigs, coil tubing drilling rigs would allow for a faster means of drilling at a more affordable cost.

Erosion Drilling Rig

[11, 30] When utilizing erosion drill rigs, high pressure jets are utilized to cut into the surrounding rock while also removing the cuttings produced during the process, as demonstrated with figure 3. During the operation of erosion drill rigs, the high pressures that are generated, which can be in the upwards of 4500 atm, cause the fluid to pass through the nozzle at high velocities. The exact velocity of the fluid can vary depending on the pressure used and the size of the nozzle, with the fluid being able to reach velocities of 200 m/s, if not higher. These high velocities allow for high penetration rates, with an increase in fluid velocity allowing for even greater penetration rates. Due to the high pressure and fluid velocity that are involved when this type of drill rig is utilized, a sizable amount of fluid is required. Even though these rigs can be utilized on their own, they are more commonly combined with more conventional drilling rigs to aid in breaking up rock. As a result, this would aid in lowering the fluid requirements of this drill rig.

As stated previously, in order to obtain the high penetration rates that these rigs can achieve, the fluid requirements are also large in order to maintain a constant pressure and fluid velocity. Either way, erosion drill rigs can aid in achieving high rates of penetration in a wide variety of formations, which would have

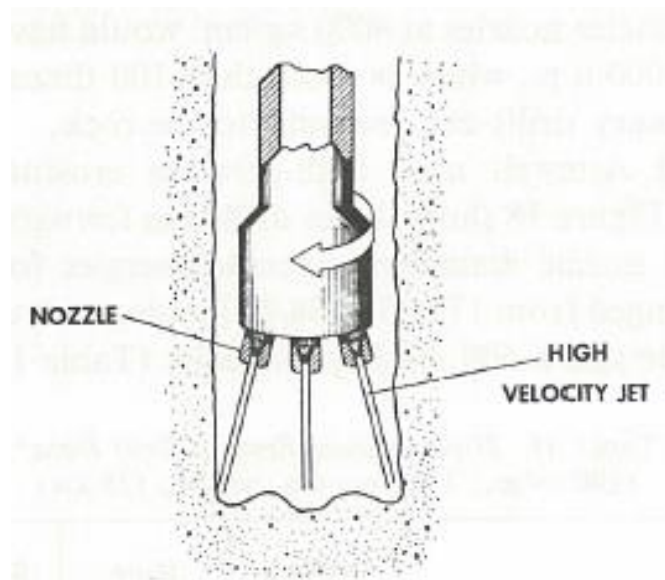


Figure 3. Erosion Drill Rig [30]

the potential of lowering costs as long as the fluid requirements can be minimized. Alongside the issue with the fluid requirements of the drill rig, other disadvantages of erosion drill rigs that can negatively impact their popularity are the potentially high operating and development costs when these rigs are used, which can potentially be offset when combined with more conventional drill rigs.

Microwave Drilling Rigs

[30] Microwave drilling rigs operate by heating the rock both at and below the surface. This is accomplished through the combined use of two magnetrons. The microwaves that are produced cause spalling at the surface while creating fractures below the surface. The time it takes for this to occur, though, varies depending on the geology and rock size. For sandstone, for instance, pieces of sandstone begin to flake off after about two minutes and can begin fracturing on the upwards of about ten minutes, depending on the size of the sandstone. The fractures created do not always cause the rock to break up and do occasionally require mechanical work to break. To improve the efficiency of microwave drill rigs, the initial use of more conventional drill rigs before switching to the microwave drill rig has been shown to be beneficial. More dense formations also allow for more efficient drilling as it prevents less microwaves to pass through the formation. Though microwave drill rigs can aid in increasing penetration rate by decreasing the strength of the surrounding rock, there are several problems with these rigs. One such problem is the efficiency of these rigs, with the magnetrons only reaching a maximum efficiency of 60%. This means that the efficiency of microwave drill rigs is low. Some rocks are also resistant to spalling, making microwave drill rigs ineffective in these rocks. Along with this, power transmission is a problem when drilling deep boreholes, with the power also being limited to the magnetrons due to the size of the boreholes. Another disadvantage of using microwave drill rigs is that they are limited to dry boreholes as water can absorb the microwaves emitted. Overall, there are multiple problems to overcome before microwave drill rigs like that shown in figure 4 can become a viable means of drilling on its own.

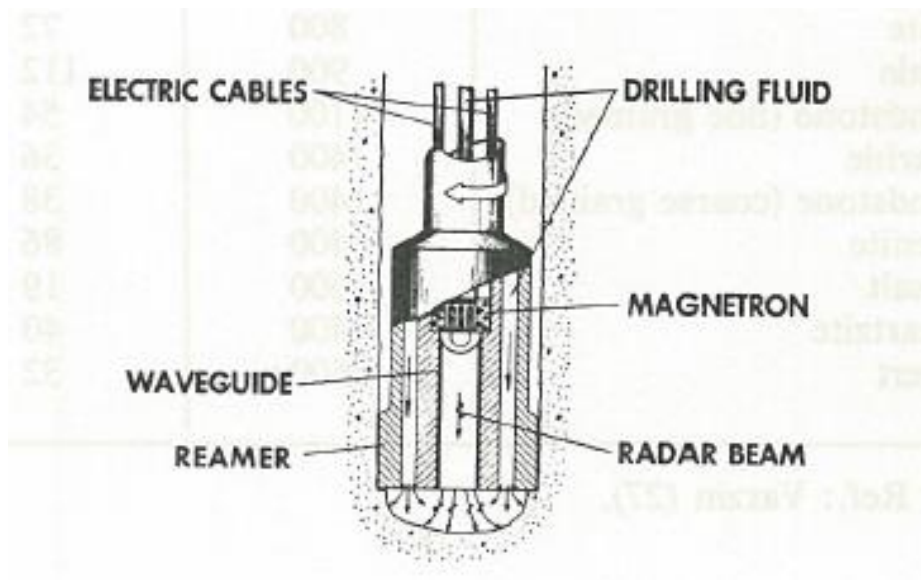


Figure 4. Microwave Drill Rig [30]

Spark Drilling Rig

[30] When using a spark drilling rig like that shown in figure 5, high voltage sparks are utilized in a given water filled borehole to create pressure pulses that have the capability to break up the surrounding rock. These sparks are created by the brief formation of hot plasma inside the water filled borehole. Due to this, high pressures are created in the surrounding water, allowing for rock inside the borehole to break. If air is used in place of water, the large pressures needed for breaking rock is not produced as the sparks produced in the air are not as effective as they would be in water. The pressures created by this rig can reach values on the upwards of 10^6 atm with the sparks lasting, at most, 50 microseconds. These short spark durations allow for fast spark rates, with as many as 330 sparks every minute.

This method of drilling allows for great penetration rates and the ability to drill through hard rock like marble, though it does require a means in which to transmit the needed energy to operate the rig at any given depth. When desired, spark drilling rigs can also be combined with other drilling rigs, such as the spark percussion drill shown in figure 6, with one of the main differences of this rig being longer spark durations. Though spark drill rigs can be beneficial, they do have some downsides, such as higher power requirements when compared to conventional drill rigs. As stated earlier, spark drill rigs also require the borehole to be filled with water to effectively through the surrounding rock.

Explosive Drilling Rig

[30] Explosive drilling operates by using explosives to drill the borehole. This is accomplished by dropping up to 12 explosive capsules a minute to the bottom of the borehole. To have consistent explosions in the borehole, the two liquids that are to be combined to produce the needed mixture for the explosion are initially separated via a membrane. As these capsules pass through the constriction near the bottom of the drill pipe, this membrane is broken, allowing for the creation of the explosive mixture. Upon exiting the drill pipe, the fins that are attached to the capsules spread apart, allowing for the percussion pin to be freed. This pin then causes a detonator inside the capsule to fire as the capsule

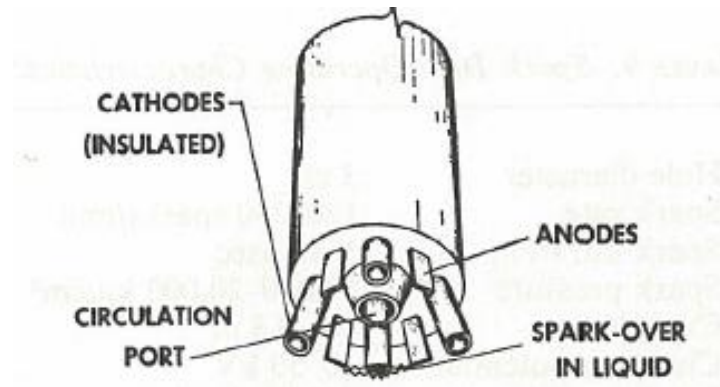


Figure 5. Spark Drill Rig [30]

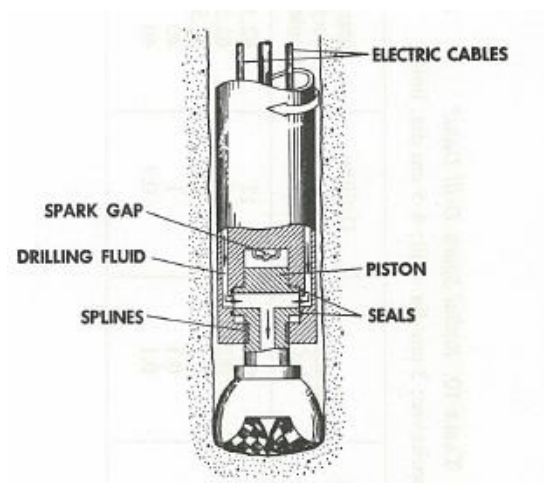


Figure 6. Spark Percussion Drill Rig [30]

impacts the surrounding formation. The process in which explosive drill rigs operate can be further illustrated by figure 7.

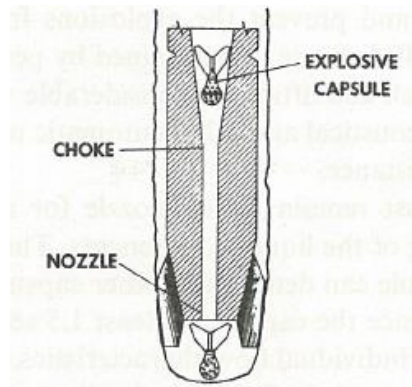


Figure 7. Explosive Drill Rig [30]

Though this method of drilling has an increased penetration rate that is maintained with depth as compared to conventional methods, the key problems arise from the safe and reliable ignition from the explosives, along with properly distributing and counting the explosives in the borehole. In order to be sure that the fluids properly mix inside the capsule, the capsule needs to stay in the nozzle of the drill pipe for at least 1.5 seconds. The capsules also must be spaced 1.5 seconds from each other when dropped to prevent the shockwave from an exploding capsule detonating another capsule inside the nozzle. One benefit of using this means of drilling is that rock strength has negligible impact on the drilling rate. This allows for higher penetration rates in harder rock when compared to conventional drill rigs.

Rock Melters

[30] Encompassing several different methods of drilling, rock melters supply substantial amounts of energy to the surrounding rock to aid in overcoming the rock fusion temperatures, which can be in the upwards of 2000°C, causing the rock to melt. The cause for the multiple rock melter methods is due to the different means in which the energy produced by the drills can be transmitted to the rock, with each method having certain requirements of their own. Four such rock melter methods that have been

researched include electric heaters, plasma torches, electron beams, and lasers, which are shown in figure 8. In order to transmit the required energy to the rock for the first method, electric heaters conduct electricity through a resistance wire, which is enclosed in an electrical insulator, causing the wire to heat up to 1600°C. To remove the newly molten rock, the downward progression of the electric heater causes the rock to flow up through a central pipe, which is then cooled with helium gas upon exiting the pipe. As the high temperatures resulting from the molten rock can potentially be a hinderance during the removal process, water is circulated around the central pipe to keep the piping cool.

When a plasma drill rig is utilized, electricity is passed through a high velocity gas, causing the gas to ionize. This newly formed ionized flame can then be in the upwards of 20,000°C, which allow for holes to form in a desired rock. To prevent the electrodes from melting as a result of the high temperature flames, water is required to aid in cooling, which can require up to 40% of the required input power to do so. Though gas type possesses different usages depending on what is preferred, two of the more popular gases used when plasma drill rigs are used are helium and argon. The purpose of using these gases are that they allow for the electrodes to be used longer as compared to their lifespan when other gases are used.

Electron beam drills operate by accelerating beams of electrons towards the rock. To be sure that these electron beams properly strike the rock, the electrons are focused onto the rock by using lenses and a bias grid, with higher voltage beams being easier to focus as compared to low voltage beams. As high power concentrations can be harmful when drilling due to the potential of the vaporization of rock, the electron beam would benefit from covering a large enough area of rock with the beam of electrons, causing the rock to spall. By tightening the focus of the electron beam, the rock can be made to melt if spallation is not possible or desired.

Since rock melters do not need to rotate, it allows for the use of coil tubing drilling rigs. Along with this, rock melters do not need mud pumps or mud cleaning equipment for most cases as the melted rock has

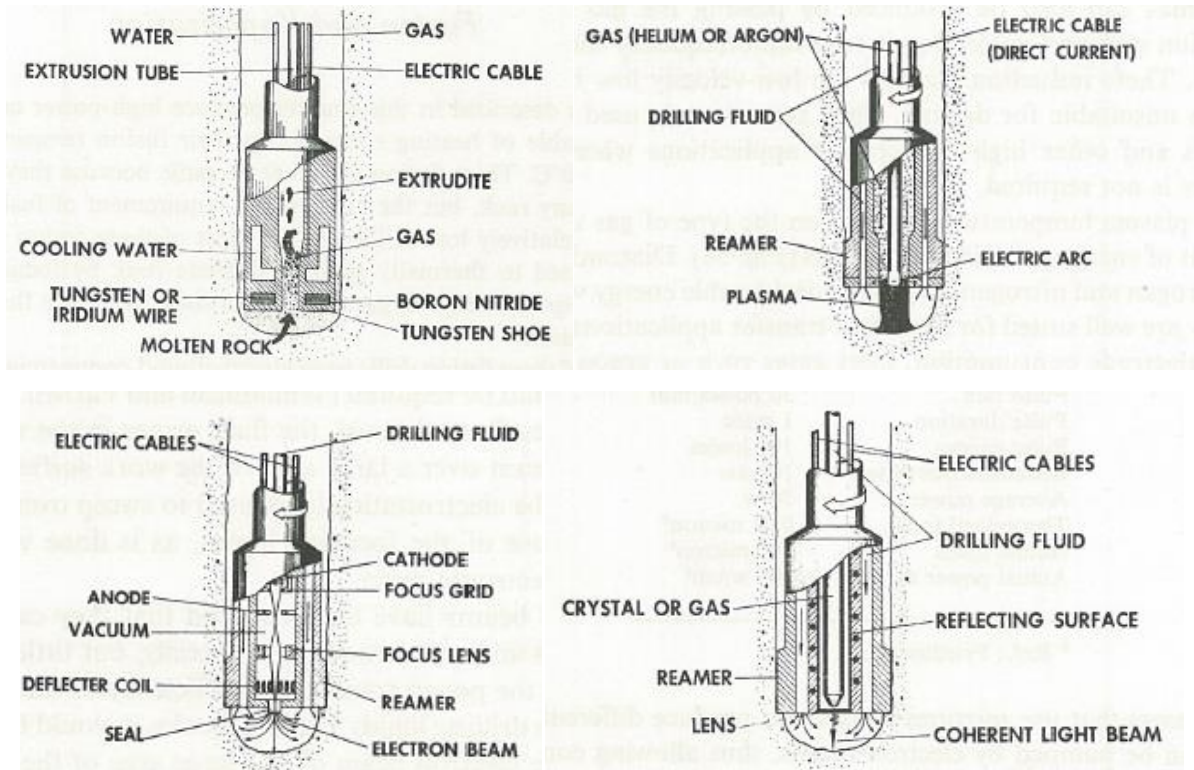


Figure 8. Rock Melters (Top Left – Electric Heater, Top Right – Plasma Torch, Bottom Left – Electron Beam, Bottom Right – Laser) [30]

the potential to create a glassy lining on the borehole; it is important to mention, however, that not all rocks create this glassy lining when the rock melters are used. Similar to a few of the previously mentioned drilling rigs, one problem with the rock melters is that the power needs to be conducted to the bottom of the borehole. Another problem is the difficulty of removing the melted rock at the bottom of the borehole. Rock melters also tend to be slow when compared to other types of drill rigs. Along with these more general problems, each type of rock melter has its own specific issues. Electric heaters, for example, loses half of its energy to water cooling. This also happens to the plasma drills, where up to 40% of the inputted power is used to water cooling. Along with this, the lifespan of the electrodes used for plasma drilling tends to be short, so the gases used must carefully be chosen to maximize the lifespan of these electrodes. As stated in ref [30], plasma drilling is best suited for high heat transfer situations, so the use of plasma drilling in situations other than this would not be desirable. One of the issues with electron beam drills is that they require vacuums in order to properly operate as to prevent scattering. This can be overcome, though, by using a dynamic seal. To prevent scattering upon leaving this seal, focusing lenses can be used to aid in covering the rock face.

Pulsed Laser Water Jet

[11] When using the pulsed laser water jet, two lasers are used to break up the rock: one laser to determine the natural frequency of the rock and the other laser to cause breakage in the rock at these frequencies. These lasers are to travel through a stream of water as it was determined that this breakage can be improved upon with water.

Though this means of drilling is still relatively new, it does have the potential to become an effective means of drilling as it takes advantage of the natural frequencies of the rock.

II. a. iii Casing

Casing is important as it aids in the drilling process by stabilizing the borehole when drilling in unstable geologies, or at the very least, aids in making a given borehole more stable than it would have been otherwise. The way in which casing is typically implemented is that, after a certain depth is reached when drilling, the drill string is pulled out, so the casing can be inserted into the borehole, with the casing being sealed to the wall of the borehole after being installed, with grout being one means to seal the casing. Two materials typically used in making the borehole casing are steel and PVC, with the use of either material being dependent on factors like geology type and if water is present. To help reduce the amount of time drilling, ways to improve casing of the boreholes were researched, as it is one means of reducing the amount of time for drilling while also reducing the cost of casing. As demonstrated in Ref [13], it takes about 3% of the total time of drilling the borehole to case the borehole. It also takes time to remove the drilling rig from the borehole to case the borehole. One such means of reducing the time can be seen in Ref [14] with the implementation of a casing drilling rig. As mentioned in the paper, casing is incorporated in the drilling process by replacing the drill string with the casing. Along with saving time, it can also solve problems associated with the drill string, such as borehole stability. The main problem with the casing drilling rig is that it has not been implemented to install heat exchangers yet, with their main purpose being to drill deep boreholes. Overall, this would help reduce the drilling time while also solving a few problems associated with drilling in the process once it can be used for the installation of ground source heat exchangers.

II. b Ground Heat Exchanger Design

Several ground source heat exchanger designs were also researched to see which of them could better aid in the installation process. Heat baskets, as detailed in Ref [15], could help with the installation process. As mentioned in the report, the heat baskets were installed 3 meters into the ground. This could be useful when hard rock is encountered when installing the heat exchangers. As hard rock can be difficult to drill

through, heat baskets can be a potential solution. One downside of using heat baskets are their diameter, which, as mentioned in the paper, have a maximum diameter of 1.3 m. Since typical heat exchangers have much smaller diameters, this increase in diameter does have the potential to affect the installation cost. It is important to mention, however, that 100 m worth of pipe were used for the heat basket, making it more comparable to a vertical heat exchanger that is 50 m deep, with the maximum COP for heat basket being up to 25% higher than that of the vertical heat exchanger. As such, it is important to determine if the tradeoff, in depth and diameter, is important regarding the installation costs.

In Ref [16], Geothex details a co-axial ground source heat exchanger design that allows for greater efficiency. This was accomplished through a coaxial-like design, with the main difference being that there are helical vanes on the outside of the inner pipe, causing the fluid to follow a helical path through the vanes. As this design can allow for greater efficiency, it can potentially allow for smaller boreholes, helping reduce the cost of installation. As mentioned in the paper, this heat exchanger design can be used for depths of 30 to 400 m. One of the main problems of this design is the problems with the pressure loss of the fluid inside the heat exchanger. As mentioned in the paper, this heat exchanger was barely able to contend with the typical U-tube in terms of pressure loss. If this is improved upon, this would allow for the Geothex heat exchanger to become more efficient.

Ref [17] provides a ground source heat exchanger that can help reduce the size of the borehole, known as a twister ground source heat exchanger. This heat exchanger is designed so that eight 3/4" inch HDPE pipes are wrapped around a 2" pipe, with these eight pipes being used to create four loops. This design can aid in reducing the borehole length by up to 41% due to the increased efficiencies. Another added benefit of this heat exchanger is that it is designed to be very similar to the conventional heat exchanger designs in terms of installation. This arises from the twister heat exchanger being placed into the borehole by either reels or coils and having the U-bend fittings being factory prepared. Overall, using the twister heat exchanger design can allow for greatly reduced borehole length without sacrificing performance. As

there are multiple advantages and disadvantages of using this and the previously mentioned heat exchanger designs, table 4 was created to allow for an easier comparison of these designs.

Table 4. Advantages and Disadvantages of Different Heat Exchanger Designs

GSHE Design	Advantages	Disadvantages
Heat Baskets ¹⁵	• Heat basket length is 3 m • Heat basket has a maximum COP of 3.25	• The maximum diameter of the heat basket 1.3 m
Geothex Heat Exchanger ¹⁶	• Thermal resistance is very low • Can improve performance by up to 30% • Allows for a reduced borehole diameter • Applicable to a wide range of depths	• Pressure losses can be improved upon • Difficulty achieving steady state heat transfer
Twister Heat Exchanger ¹⁷	• Potential to reduce borehole length by 40% • Savings of up to 31%	• Thermal properties of the borehole can affect the benefits of the Twister heat exchanger • The exact costs of the conventional pipes and twisted pipes can potentially vary depending on the manufacturer

II. c Sandia National Laboratory Cost Model

In Ref [35], Sandia National Laboratory (SNL) performed a study where they visited several drilling sites to investigate the installation methods performed at each site, with the intention to identify which parts of the installation process can be improved upon with better technology, allowing for a meaningful reduction in GSHE installation costs. In total, SNL collected data from eight separate sites, collecting information

such as the type and costs of materials used to the times to perform certain tasks of the installation process. Using this information, SNL created a cost model that can aid in calculating the cost associated with installing GSHEs. Though this cost model can be a useful aid in calculating the cost of installation, there are a few issues with the model, with one of the main issues being that the cost model is about twenty years old. As a result, various costs that were used for materials, labor, etc. are no longer accurate as these costs have either been lowered or raised over the years due to factors like inflation and recent technology. This can potentially have reasonable effect on the installation costs. Another issue with this cost model are the assumptions made when creating the cost model, such as a linear ROP with increasing depth. As this cost model can be a useful aid in determining the costs associated with installing GSHEs, these issues will be tackled in a later section to create a more accurate cost model that will aid in the determination of the key areas of improvement in the installation of GSHEs.

III. Methodology

When determining how to best lower the GSHE installation costs, the first task that was undertaken was a literature review to determine current and emerging technologies associated with the installation process, with an emphasis on drilling technology. As there are multiple areas associated with installing GSHEs that can be improved upon to reduce installation costs, especially with drilling, a collection of these different technologies can aid in determining how to best lower these costs. Using an updated cost model based on the cost model provided by Sandia National Laboratory, it can be better identified how to effectively use these different technologies to best lower the cost of installation. By considering the many different areas of the installation process, such as borehole design, drilling rig used, materials used, etc., this cost model can show what the ideal technology combination would be, whether it be for few and long boreholes, short and many boreholes, or fast or slow penetration rates. By determining how to effectively reduce costs for each situation and the technologies that would be best suited for the different situations, a guideline can then be created. This guideline can aid in future installations as how to install GSHE as effectively as possible so that the installation costs would be at a minimum. To further aid in lowering the installation costs of GSHEs, potential means of reducing costs were researched. As drilling is the largest contributor to costs, possible methods of drilling were focused upon, whether it be conventional or emerging drilling rigs. A cost analysis was then performed on the newer drilling technologies to gain an understanding on their current effectiveness on reducing the cost of installation. By conducting this cost analysis on these emerging technologies, it would provide a better idea on what can be incorporated in the drilling process, even though these technologies would require further optimization before becoming a realistic means of aiding in the installation process.

IV. Potential Drilling Technology

Currently, there are drilling technologies that have been shown to be of use in the oil and gas industry. This is due to these drilling technologies showing their ability to produce higher penetration rates in some or all formations as compared to more conventional drill rigs. As can be inferred from this, these means of drilling can reduce times required for drilling, and thus reduce the costs associated with drilling. Reasons for these technologies not being more commonplace can vary depending on the drilling method, whether it being from these methods still being fairly new, requiring more effort to make them more efficient, or the capital cost of these drilling methods. If these drilling methods can be optimized for the purpose of drilling boreholes for ground source heat exchangers, it would have the potential to greatly reduce the installation costs. Using information that is currently available, an analysis of a few of these methods will be provided below to demonstrate their potential in installing ground source heat exchangers.

IV. a Laser Drilling

When first introduced as a possible means of drilling in the 60's, the use of lasers was deemed to be too inefficient to properly drill boreholes, with individuals initially thinking that they would be, at most, only useful when combined with other means of drilling. As the technology advanced, lasers began to show their potential as a standalone drilling method, with the literature showing their usefulness in more recent years. While they can drill through melting rock as mentioned in the previous section, other means in which lasers can drill through rock are through thermal spallation and vaporization, with studies showing that lasers are the most efficient when used right before the rock melts. Even though thermal spallation is the most efficient means of drilling when lasers are utilized, this efficiency can vary depending on the lasers used and the laser operating conditions. As these items can impact the usefulness of the lasers used, a description of how lasers operate and which lasers and laser parameters are the most efficient will be provided below [24-25].

IV. a. i Laser Drilling Description

[22-23] In order for a laser to properly run, three key components are required: a medium to provide a means of transmission for the laser, reflective mirrors to be placed on either side of the medium, and an energy source to pump energy through the medium. The medium that is placed in the middle of these mirrors can be made of a variety of materials and can be either a solid, liquid, or gas. The main purpose of the medium is to amplify the light oscillating between the two mirrors, with the medium of choice also contributing to the wavelength of light. This amplification process is a result of one case of atom energy emission called stimulated emission. Starting with the simplest case of an atom with only two energy levels, when energy is transmitted to the atom, the electron that is in the ground level is excited into the higher energy level. Shortly after the electron is excited into this higher energy level, the electron returns to the ground level, releasing a photon that possesses the energy equal to the difference in the two energy levels. The most common means in which this photon is released is when the electron spontaneously returns to the ground level, which is also known as spontaneous emission. To achieve the aforementioned stimulated emission case, a photon with an energy equal to the difference in energy levels needs to hit the atom before the electron spontaneously lowers to the ground level. This causes the emitted photons to have the same frequency and phase as the initial photon, a wave of photons is created, which causes the amplitude of the photons to greatly increase. After the light is sufficiently amplified, the light is then passed through one of the mirrors, which this mirror being partially reflective. In order to provide the needed energy for this process of light amplification, an energy source is utilized, which is also known as a pump. The means in which this energy is pumped into this system can vary depending on what is needed or preferred, with several pump examples being optical, electrical discharge, electrical current, and electron bombardment. When operating a laser, there are two ways in which they can be used: Through the creation of a continuous wave or pulses of energy. Continuous wave lasers operate through the continuous output of a constant power level. Pulsed lasers, on the other hand, produce quick pulses of energy. These pulses have very high peak powers with average powers similar to that of continuous wave levels. Depending on how the laser is operated, the energy pulses created by the pulsed lasers can have

their pulse durations and the time between pulses (The repetition rate) varied. The energy per pulse can also be varied for both types of lasers, with the limitation being the maximum power that these lasers can produce. Though every laser has its own advantages and disadvantages, Nd:YAG lasers will be the main focus for reasons that will be discussed further below.

IV. a. ii Laser Drilling Performance

Though a wide variety of lasers are available for use, one laser was commonly seen in the literature when used to drill through rock, with this laser being a pulsed Nd:YAG laser. Though other lasers were also used to drill through rock, such as a CO₂ laser, pulsed Nd:YAG lasers had several advantages that make them attractive for use in drilling, which are as follows: the use of fiber optic cables which enables long distance power transmission, boosted rock removal due to thermal stresses induced by laser, ability to focus on small surface areas, and the ability to produce high peak and low average power outputs [26-27]. In addition to this, various experiments have shown that pulsed Nd:YAGs can provide penetration rates in the upwards of 100x that of more conventional drill rigs [24]. One of the main issues that needs to be tackled when using lasers in drilling is scaling the holes created to become large enough to install ground source heat exchangers, as the lasers used in these experiments tend to create small diameter boreholes (about 0.5 in) [24]. As such, there are several possible means in which this obstacle can be overcome to allow for lasers to become an effective means of drilling, which will be covered in the upcoming sections.

Foro Energy Hybrid Laser Mechanical Drill Rig

Fairly recently, Foro Energy created a hybrid laser mechanical drill rig for the purposes of drilling through very hard rocks that would otherwise be difficult to drill through with more conventional drill rigs. Though this hybrid drilling rig is designed to drill oil and gas boreholes, it does have the potential to aid in installing ground source heat exchangers. This hybrid drilling method was achieved by combining a rotating drill bit with a 20 kW laser, which can be viewed in figure 9. To provide the needed power to the

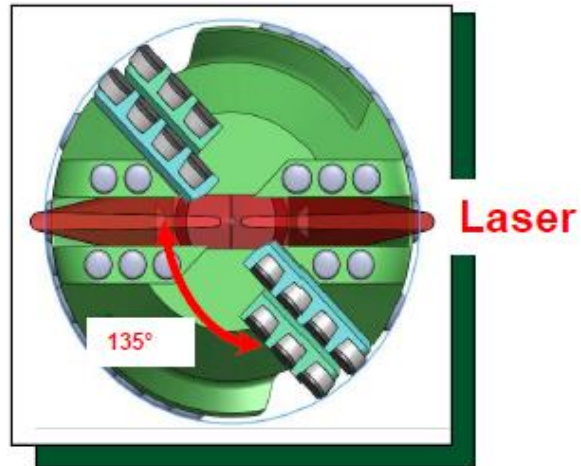


Figure 9. Laser Mechanical Drill Bit [28]

laser in the drill bit, fiber optic cables pass the required energy from the laser system that is near the drill rig, through the drill rig stem, and to the laser in the drill bit. As long cables are needed to adequately provide the needed power to the laser, long strands of fiber optic cable are housed on a spool, which is then unwound as the drill bit is lowered into the borehole. One of the key issues that had to be overcome with the fiber optic cable is the problem with power transmission between the non-rotating cable and the cable inside the rotating drill stem. To overcome this issue, Foro Energy utilized an optical slip ring that allows for the power transmission across the rotary joint of the drill stem, allowing for the two fiber optic cables to be connected. The process in which the power is transmitted from the laser system outside the borehole to the rock at the bottom of the borehole, along with the transmission equipment used for this rig, is provided by figure 10. In order to provide a means of removing the cuttings produced by this drilling rig, a supply of nitrogen gas is used to remove these cuttings as demonstrated in figure 11, with this gas also providing the added benefit of keeping the lasers cool during the drilling process. This figure also provides the multiple items required to allow for the use of the combined laser mechanical drill rig.

In order to understand just how cost effective using this laser mechanical drill rig can be, an updated version of the Sandia National Laboratory, which will be discussed in upcoming sections, was used to receive a rough cost estimate of using this drill rig. When performing this cost estimate, it was assumed that 50 boreholes with a diameter of 5 inches and a depth of 200 feet are to be drilled. As there are no immediately available costs of the laser mechanical drilling rig used by Foro Energy to the author's knowledge, it is assumed that the cost of the rig is the combined cost of a new rotary drill rig and the 20 kW laser used by Foro Energy. As the cost of lasers are about \$50/Watt, the 20 kW laser used for this drill rig would cost about \$1,000,000, with a new rotary drill rig costing about \$500,000. Combining the cost of both the laser and the rotary drill rig results in a cost of about \$1,500,000. Though Foro Energy does not provide much in terms of the penetration rate of their laser mechanical drill rig, they do mention that it can provide a penetration rate of about 10 ft/hr in very hard rocks [29]. This is much higher than what rotary drill rigs can manage, which only manage about 3 ft/hr in these hard rocks [29 – 30]. The



Figure 10. Laser Power Transmission Process [28]

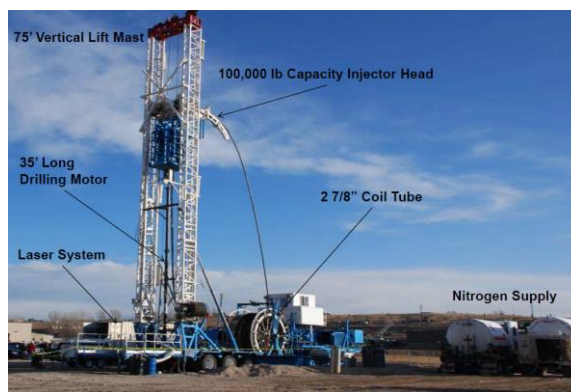
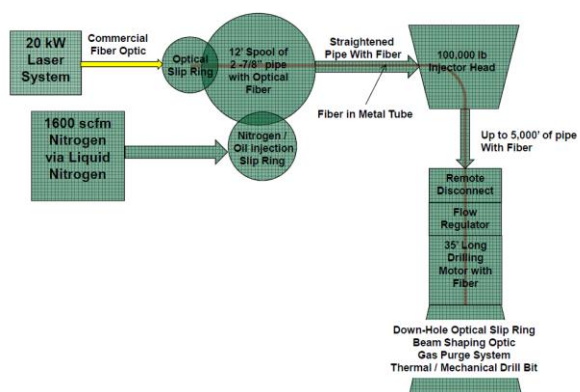


Figure 11. Foro Energy Laser Mechanical Drill Rig Schematic [28]

nitrogen and fiber optic cable costs used during the drilling process was also accounted for, with the current cost of liquid nitrogen being about \$0.5/gallon [31]. It was then assumed that the liquid nitrogen immediately turns into gaseous nitrogen upon entering the borehole, with the flow rate provided in the above schematic being used to determine how much gaseous nitrogen is used. For the fiber optic cable cost, it was assumed that it would cost about \$5/foot. Using this information, the initial cost estimate of using a rotary drill rig to install ground source heat exchangers in hard rock is about \$1,460,000. When using the laser mechanical drill rig, the installation costs are reduced to \$1,960,000, which is a 35% increase in costs. If the number of boreholes is to be reduced to 25 boreholes while the borehole depth is simultaneously increased to 400 feet, the difference in costs is even greater. The cost of using rotary drilling to install ground source heat exchangers in this situation is about \$1,360,000, with the use of the laser mechanical drill rig maintaining a 35% increase in costs of \$1,840,000. Realistically, the cost of the laser mechanical drill rig would be higher than that stated above due to it still being a fairly new means of drilling. If the drill rig costs were increased to \$2,000,000 to better simulate the costs of the laser mechanical drill rig, the laser mechanical drill rig maintains much higher costs when compared to the rotary drill rig than before. Implementing this new cost into the cost model, it results in a new cost of about \$2,160,000 for the first case of 50 boreholes, each with a depth of 200 feet, and a cost of \$2,010,000 for the second case. This equates to a cost increase of about 48% for both cases when compared to the use of a rotary drill rig. Though there are some issues when trying to compare the installation costs when both the rotary and laser mechanical drill rigs are used, which will be discussed further in a later section, these rough cost estimates demonstrate that, currently, laser mechanical drill rigs are not ready to be used to install ground source heat exchangers. Though this drill rig possesses potential when drilling through hard rock to install ground source heat exchangers, the main hinderance are the cost of the rig itself and the substantial amounts of nitrogen used when drilling. As stated earlier, the laser mechanical drill rig would realistically be expensive, up to three times that of rotary drill rigs, if not higher. This results in the equipment costs to be much higher than what it would be otherwise, causing a greater increase in installation costs. This is further compounded by the high flow rates used by this drill

rig, which results in a large amount of nitrogen used while drilling. Even though the cost of liquid nitrogen is fairly low, the high flow rates cause the overall cost of nitrogen to become one of the dominating factor in the increased costs. To make this means of drilling more feasible for ground source heat exchanger installation, these issues can possibly overcome through the implementation of several potential solutions. The first of these solutions is to greatly increase the lifespan of the drill rig as compared to more conventional drill rigs. If this can be accomplished, it would allow for the equipment costs to be reduced, which would then aid in the reduction in installation costs. Another option is to purchase the laser mechanical drill rig after the drill rig has been on the market for several years, which would allow for these drill rigs to reach a more competitive cost. In addition to this, it is also important to target the nitrogen usage. To minimize the amount of nitrogen used while drilling, it is important to minimize the flow rate of the nitrogen as it plays a key role in the amount of nitrogen used while drilling. In addition to this, it would also be beneficial to maximize the penetration rate of the laser mechanical drill rig as higher penetration rates would result in the use of less nitrogen. Though it is not as flexible, it would also be beneficial to minimize the cost of nitrogen, which can aid in reducing the overall cost of nitrogen. If these different solutions can be implemented, it would allow for laser mechanical drill rigs to become more competitive.

Laser Drilling Rig

Though lasers can be combined with more conventional drill rigs, they do have the ability to drill boreholes without the need to be used with other means of drilling. As stated earlier, though, the main challenge is scaling the size of the lasers, as the holes created by the lasers in the literature read typically had diameters of about half an inch. Several pieces of literature, however, do provide a potential solution to this which would allow for the possibility of the scaling of these lasers. Ref [24] provides a method in which would allow scaling, whereby one of the recommendations that was made was to utilize multiple overlapping lasers, like that shown in figure 12. To properly use the several lasers required by this setup, it was recommended that these lasers are to fire sequentially or in groups to allow for relaxation time,

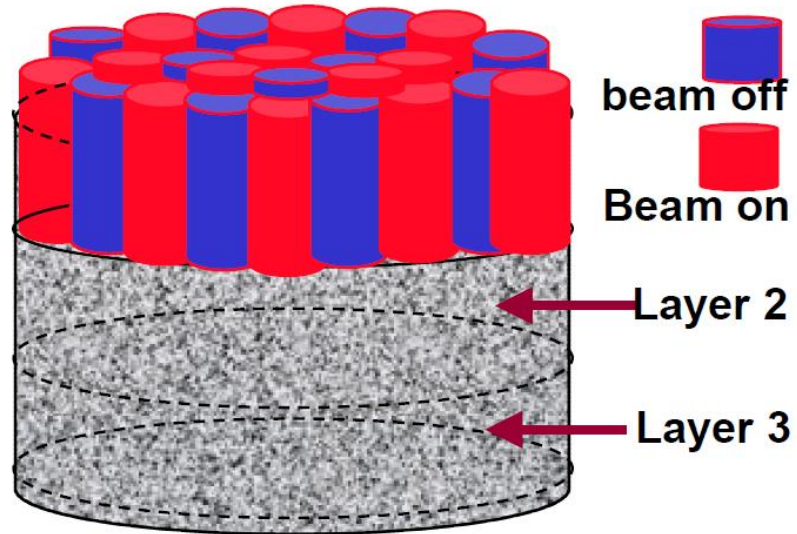


Figure 12. Laser Drilling Schematic [24]

which would in turn prevent the melting of the rock. To prevent the newly formed rock fragments caused by these lasers from hindering their performance, a purging system would be used to clean the borehole, similar to the nitrogen gas used in most of the laser drilling experiments conducted in the researched literature.

From the experiments that were conducted with a single Nd:YAG laser, penetration rates of up to 950 ft/hr were able to be produced in shale [24]. Though the report does not directly provide this penetration rate, it can be calculated by using the provided information in the report and equation 1.

$$ROP = \frac{SP}{SE} \quad \text{Eqn. 1}$$

This is greatly higher than the penetration rates that rotary drill rigs can produce, with experiments in ref [37] finding penetration rates of about 85 ft/hr for rotary drill rigs. If these high penetration rates can be maintained after scaling, it could potentially allow for great cost savings. One of the key issue, though, lies with the cost of the laser themselves. Though no actual testing was conducting with the above laser drilling schematic, if it is assumed that the same number of 24 1.6 kW Nd:YAG lasers were to be used to drill with an average cost per watt of \$50/W, it would equate to a cost of about \$2,000,000. This is 4x greater than a new rotary drill rig as stated in ref [32]. When considering the nitrogen consumption of this laser drill rig, it was assumed that the flow rate used by a single laser was scaled up to match the increase in size. As mentioned in the literature, the flow rate that was most commonly used for these lasers was 400 ft³/hr [24]. Assuming that the diameter of this laser configuration is seven times greater than the diameter of a single laser, the new flow rate comes out to be 19,600 ft³/hr, which is nearly 50x greater than the initial flow rate. To compare the costs needed to install ground source heat exchangers for both rotary and laser drilling techniques, a modified version of the Sandia National Laboratory cost model was utilized to get a rough cost estimate, similar to that of the laser mechanical drill rig. When using this

model, it was assumed that 50 boreholes with depths of 200 feet and a diameter of 5 inches are to be drilled, with the costs of a new rotary drill rig and the lasers used also being implemented in the model. As no actual costs are provided when using multiple lasers to drill boreholes, it was assumed that the costs of the laser drill rig would be close to the \$2,000,000 laser cost estimate. Assuming that the drill rigs primarily drill through shale, the cost of installing ground source heat exchangers would be about \$273,000 when using a rotary drill rig. Using the laser drill rig, though, leads to a cost of \$354,000, a 30% increase in costs. These higher costs were due to the steep costs of the lasers used when drilling combined with the high nitrogen flow rates. Even though the penetration rates provided by the lasers are greater than that of rotary drill rigs, it was not enough to overcome the high laser costs and flow rates. There are potential solutions to this, however, the first of which is to use these lasers to drill very deep holes. If 25 boreholes with depths of 400 feet were to be used instead, lasers would only cost about 17% more than the \$179,000 needed to install ground source heat exchangers with rotary drill rigs. This suggests that if the boreholes were to be deep enough, this laser setup would become the more efficient means of drilling. The area in which lasers would be the most beneficial, though, would be in very hard rocks. Even then, though, the laser cost overshadows the overall cost savings that would be gained from this. From ref [30], the penetration rate can be as low as 3 ft/hr when using rotary drill rigs in hard rocks. While not much has been found in regards to the penetration rate of lasers in very hard rock, ref [26] does provide the laser penetration rate in granite, which was found to be about 7 ft/hr. As stated in this piece of literature, this penetration rate was achieved using the minimum power required to penetrate the granite. As such, the penetration rate in granite would realistically be much higher. When assuming 25 boreholes and a depth of 400 feet, the costs of using a laser drill rig was about \$1,680,000, which was a 23% higher than when the rotary drill rig was utilized. As stated previously, the main issue that keeps arising when using laser drilling rigs to drill these boreholes were the cost of the lasers combined with the flow rate of the nitrogen. The main contributor to the large cost increase is the high nitrogen flow rate, as the low penetration rates combined with the deep boreholes means that much more nitrogen is required when

compared to the previous cases. This can potentially be rectified, however. Ref [33] proposes an arrangement that would utilize fewer lasers than the initial estimate above.

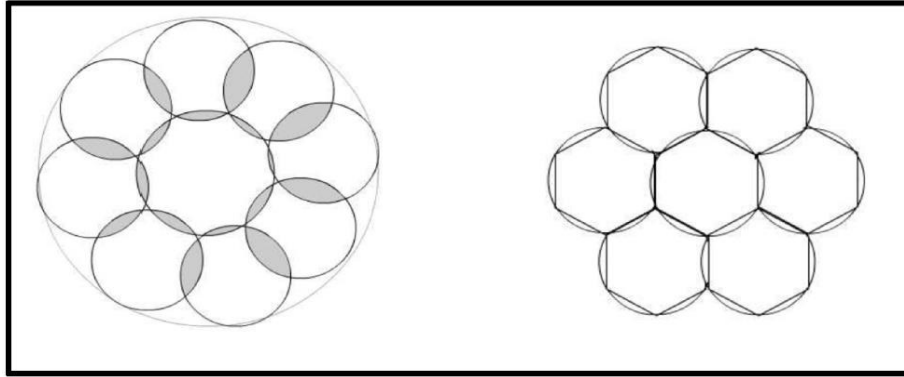


Figure 13. Possible Laser Arrangements [33]

Assuming that the smallest configuration of lasers from figure 13 is used, being the use of seven lasers, and the same assumption of the use of Nd:YAG lasers and a cost of \$50/Watt, the new cost of the lasers would then be about \$600,000. Along with this, the nitrogen consumption was also updated to reflect the new laser configuration. The diameter of this configuration was assumed to be three times greater when compared to a single laser, meaning that the new nitrogen flow rate is about 3,600 ft³/hr. Using this new laser cost and flow rate, the cost of installation is then greatly reduced to \$241,000 for the case of 50 boreholes and a depth of 200 feet per borehole, which is about 12% less than the cost of installation when rotary drill rigs are used. For the second case of 25 boreholes, each with a depth of 400 feet, the difference in costs is even greater, with a cost of installation of \$149,000, which is 17% less for when the rotary drill rig. Unlike the previous scenario where a configuration of 24 lasers was utilized, there is even a cost reduction when this new configuration was used to drill 25 boreholes with depths of 400 ft each in hard rock. When using this laser configuration to drill through the hard rock, the cost of installation came out to be about \$719,000, which was a 47% cost reduction. As the penetration rate provided for granite is

on the low side due to the means in which it was determined, the cost savings would realistically be much higher than that provided above.

As demonstrated above, laser drilling possesses the ability to efficiently drill through rock, though testing still needs to be conducting to prove the standalone capability of using multiple lasers to drill through rock. The cost of these lasers combined with the nitrogen flow rate also need to be minimized to make laser drilling more cost efficient. To the author's knowledge, only one piece of literature detailed experiments conducted to test the capability of multiple lasers to drill, but even then, only one laser was used. To simulate multiple lasers, this single laser was moved in between firings, with it taking about half a second for the laser to fire and half a second to move. Though the specific energy found in this paper was found to be higher than those found in other literature, with the specific energy needing to be as low as possible to maximize the penetration rate, it could be due to the limitations of the equipment and purging system used, as stated in ref [34]. The main obstacle to overcome when testing the applications of using multiple lasers to drill is the cost of the lasers themselves. As such, testing is still needed to prove the concept of using a multi laser design to drill through hard rocks.

Laser Drilling Cost Estimate Limitations and Comments

When the costs associated with installing ground source heat exchangers were calculated for both the laser and laser mechanical drill rigs, several limitations prevent the installation costs presented from being as accurate as they would have been otherwise. This cost model also does not consider the reduced tripping time and drill bit wear resulting from the use of the lasers, which would have the potential to further reduce installation costs. Along with this, as there were no provided costs on the expenses of these laser drill rigs. Knowing the actual expense of these laser drill rigs would go a long way in providing more accurate cost estimates. As there was no full scale experiments conducted testing the potential of using multiple small lasers to drill through rock, the cost estimates were also limited in the fact that the penetration rates used had to be assumed to be the same for multiple small lasers as a single small laser. Along with this, the borehole diameter was assumed to be constant while doing the cost

analysis of laser drilling, where it would realistically vary depending on the configuration utilized. As mentioned in the literature, each laser can drill a hole 0.5 inches in diameter, with more optimistic diameters reaching 0.79 [24] [33]. Due to this, the range of diameters possible using the seven laser configuration is between 1.5 and 2.4 inches. For the larger configuration of 24 lasers, a much larger borehole can be created, ranging from 3.5 to 5.5 inches. Due to the expense of the lasers, it is preferable to minimize the diameter of the boreholes such that the number of lasers used can be reduced.

Overall, lasers possess a great potential in reducing the costs of installation. If these limitations can be overcome, a more accurate cost model can provide a more detailed cost estimate on how much money laser drilling rigs can save. As it currently stands, though, the cost estimates that were calculated for these laser drill rigs show that it would be most effective in when drilling deep boreholes, which was expected. Along with this, if multiple lasers are used instead of combining the lasers with a more conventional drill rig, the costs estimates show that the highest cost savings come from the laser configuration that used the fewest number of lasers. This suggests that if the borehole diameter can be minimized, fewer lasers would be required, allowing for even greater cost savings. As effective as laser drill rigs may be, however, the technology still needs to be perfected to become a viable means of drilling, with Foro Energy being one of the few companies that are doing just this. If the technology can be perfected and designed for the purposes of installing ground source heat exchangers, it can become a great resource in reducing the costs of installation.

Laser Drilling Experiments

As lasers possess a great potential to reduce costs associated with the installation of GSHEs, further experiments can aid in demonstrating their potential in regard to drilling while simultaneously providing information on what needs to be further improved upon. Due to this, an experiment was conducted to provide better insights on the potential of laser drilling. For this experiment, a Continuum Powerlite DLS 8020 laser was utilized. This laser was then used to produce multiple holes in a 2" diameter, 2" long sample of crab orchard sandstone.

Table 5. Laser Specifications

Wavelength (nm)	Energy per Pulse (mJ)	Repition Rate (Hz)
532	500	20

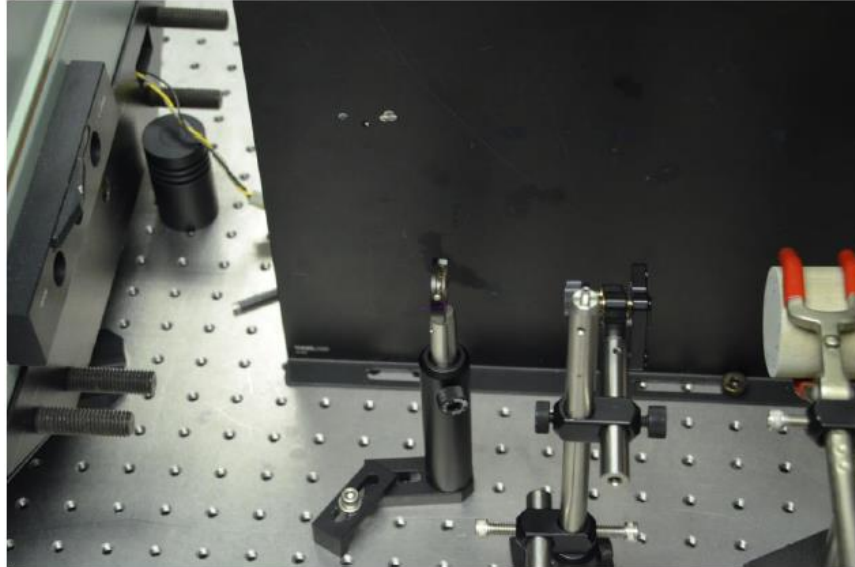


Figure 14. Experiment Setup

Though the laser was not as powerful as the ones in the literature, with the laser specifications in table 5 and the experiment setup in figure 14 shown above, it was still capable of creating holes in the sandstone. Using two different lens sizes (50 & 100 mm), the laser was able to produce nine different holes of varying diameters, as shown with figure 15. After measuring these holes, with the results of these measurements being provided in figure 16, it demonstrated that focusing the laser upon the sample for longer periods of times allowed for larger diameter holes. It was also shown that using smaller lenses allows for quicker formation of larger diameter holes when compared to larger lenses. This was caused by the energy being more tightly focused upon the sample. Due to the limitations of the laser, however, the

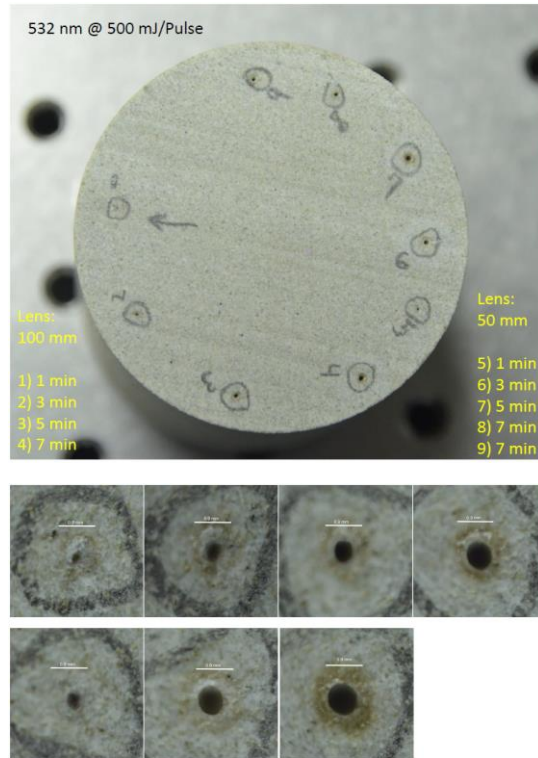


Figure 15. Shallow Holes Drilled Using Varying Exposure Times and Lens Diameters

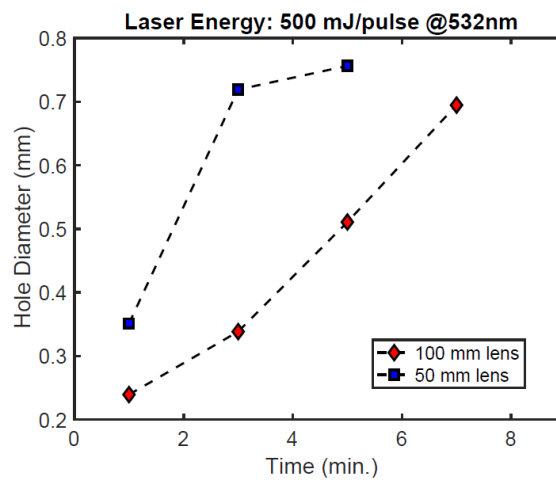


Figure 16. Laser Drilling Results

holes created were produced are smaller than those created by lasers utilized in the literature. The time needed to drill these holes would also realistically be lower when comparing these lasers due to the differences in power output. Given the high unconfined compressive strength of the tested sandstone, the results from this experiment are still positive as more conventional drill rigs, like rotary drill rigs, would provide slow penetration rates in similar rock. If more research can be conducted into optimizing lasers for drilling in rocks similar to that used in this experiment, it would greatly aid in reducing the time required for drilling.

V. Cost Model

V. a Ground Source Heat Exchanger Survey

V. a. i Survey Contents

To understand what current industry practices are in regard to GSHE installation, a survey was conducted in conjunction with Oak Ridge National Laboratory among individuals who work for businesses that actively install GSHEs. The questions asked in this survey covered the multiple areas of the GSHE installation process, ranging from the ground loops that were installed to how the boreholes were drilled and grouted. The individuals participating in the survey were also asked to provide information regarding their place of work so that a better understanding of these businesses can be achieved. When the survey was designed, the questions were organized into specific sections to best cover the different areas of the installation process and business information, with an overview of the questions asked being discussed in the sections to follow.

Company Information

To gain a better understanding on who is participating in the survey, the participants were asked on how long they have been involved in the field along with their title inside the business. Information regarding the businesses that the participants serve was also inquired, with the questions mainly revolving around the description of the businesses and how many heat exchangers the business has installed within the past two years. The number of states these businesses serve were also asked, as answers for later questions can vary per state, such as labor.

Ground Loop

As ground loops can be designed multiple ways depending on the desired performance and costs of the heat exchanger, several questions were asked to see if there was any trend in the information provided by the different businesses. The first set of questions asked in regards to the ground loop were how often certain ground loop types were installed, how often these loops were made of a given material, and the

cost of installing these loops per ton. To go along with these questions, the average cost per foot of installing different diameter ground loops were also asked. Another set of questions were also asked concerning the boreholes that are created for these loops, with the average depth and diameter being asked, along with the average penetration rate of drilling these boreholes. Similar to the ground loops, the cost per foot of drilling a given borehole was also asked. Along with asking about the ground loops and boreholes, other questions asked were the cost per foot of different diameter horizontal header piping, how many feet of trenches are dug in a working day on average, and the average cost per foot of digging these trenches.

Drilling & Grouting

When a borehole is being drilled, a given company may use different drilling rigs depending on circumstances like the local geology and cost of the drilling rig. As such, the first question that was asked was the drilling rigs that these companies used and the frequency in which they are used. Along with these drilling rigs, the type, size, cost, and life of the drill bits used by these drilling rigs were also inquired. Additional questions concerning the drilling rigs used were asked to glean more information about the rigs, such as the cost to move the drilling rigs, the amount of people needed to operate the drilling rigs, the cost of fuel and labor, and the cost per hour of using the drilling rigs, whether owned or rented. Though the average cost per foot of drilling a given borehole was asked in the previous section, this cost can vary depending on the geology in which the borehole is created in. Due to this, the participants were asked if they charged varying rates for different geologies, and if they do, what the cost per foot for drilling a given borehole is for a certain geology. Along with this, the most common type of geologies encountered while drilling were also questioned. Similar to the question regarding the cost per hour of using the drilling rigs, the cost per hour of using other equipment, such as a water truck or air compressor, were also asked. After asking about the drilling rig and other equipment, information about the grout and mud used were questioned. The inquired grout and mud information were the cost of the materials per borehole and the type of grout and mud used on average.

Other Cost Information

Even though information regarding the ground loops, drilling, and grouting were inquired, there were still several miscellaneous items that were asked about. The several items in which were inquired about were the costs associated with designing the ground loop, conducting a site survey, flushing and purging, ground loop leakage detection, site restoration, and other associated administrative costs. A few other items that were questioned were the percentage of fitting cost to total horizontal piping cost, warranty offered by the company, and average total ground loop cost per cooling ton, which this cost including both direct and indirect costs.

V. a. ii Survey Results

Out of the multiple individuals and businesses to whom the survey was sent, only eight were returned. All eight of these individuals and businesses indicated that they were involved with installing heat exchangers for over ten years with the majority having installed hundreds or even thousands of GSHEs. When asked about the loop used for the heat exchanger, the most common material used for the loop was HDPE with only a few occasionally using other materials, such as copper and PEX. It was also indicated that single U-tubes were the most common type of loop used, with other less frequent loops used being double U-tubes and direct heat exchangers, with the cost of installing these loops averaging up to \$0.69 per foot for a 1 ½ inch loop. The cost of installing these loops per ton was also provided, with the loops averaging about \$2400 per ton. When installing these heat exchangers, these businesses favored using both mud and air rotary drilling rigs along with the downhole hammer, with cable tools being used only occasionally. These businesses were then asked to detail the average penetration rate of these drilling rigs, with the overall average of these businesses resulting in a penetration rate of $100 \frac{ft}{hr}$, with the drill bit life of these drilling rigs averaging around 3000 ft. To determine what drilling fluids were utilized to aid in drilling, the participating businesses were then asked what drilling fluid was used on average, with the two most common responses being Quick Gel and Bentonite. After inquiring about the average borehole produced

by these drilling rigs, the average borehole depth and diameter as provided by these businesses were 350 ft. and 5 in., respectively. When prompted about the grout used for the borehole, there was no commonality between responses. Each of these businesses used a separate grout on average for their boreholes, whether it be Geo-Thermal Pro or BoroTherm Gold. The cost per foot to drill any given borehole was also provided, with the boreholes costing an average of about \$8.36 per foot to drill. It is important to mention though, that this cost varies depending on the geology. The two prominent geologies for which the costs were provided were limestone and shale, with these geologies having an average cost per foot of \$8.17 and \$5.75. To better organize the results that were gathered from conducting this survey, tables 6-8 were created.

V. b Drill Rig Survey

Currently, drilling is one of the leading causes for the high costs associated with installing ground source heat exchangers. As such, an additional survey was conducted to collect further information regarding the drill rigs currently used in the industry. The aim of this survey was to find a correlation between the various drill rig parameters (such as horsepower, cost, ROP, etc.), along with the performance of these drill rigs in different formations. This information can then aid in guiding individuals on which drill rigs would be best suited for a given situation. To provide what was asked of the individuals who undertook taking the survey, the survey contents will be provided below along with the results of the survey as well.

V. b. i Drill Rig Survey Contents

Similar to before, the individuals participating in the survey were asked how many years they have been installing ground source heat exchangers, with the purpose of understanding how much experience the respondents have in the field. Since drill rig usage can vary depending on location and preferences, the percentage of several types of drill rig used was again asked. Other information regarding the drill rigs

Table 6. Ground Loop Survey Results

Ground Loops Installed	Company Percentage
Single U-Tube	87.50%
Double U-Tube	37.50%
Direct Heat Exchanger	12.50%
Ground Loop Materials	Company Percentage
HDPE	100%
PEX	12.50%
Copper	12.50%
Ground Loop Diameter	Average Cost per Foot
3/4"	\$0.30
1"	\$0.35
1 1/4"	\$0.53
1 1/2"	\$0.69
Average Ground Loop Cost per Ton	
\$2,400	

Table 7. Drill Rig Survey Results

Drill Rig	Company Percentage
Mud Rotary	87.50%
Air Rotary	37.50%
Downhole Hammer	12.50%
Average Penetration Rate (ft/hr)	
100	
Average Drill Bit Life (ft)	
3000	
Drilling Fluid	
Quick Gel, Bentonite	

Table 8. Borehole Survey Results

Borehole Specifications	
Borehole Depth (ft)	Borehole Diameter (in)
350	5.00
Cost per Foot	
Average Borehole	\$8.36
Shale	\$5.75
Limestone	\$8.17

used were then asked, such as the manufacturer, model, age, and cost of these rigs, along with the average penetration rate and borehole depth of these rigs. As the actual penetration rate can vary in different formations, the penetration rate in different formations were also asked in addition to the average penetration rate for each drill rig used. The final set of questions that were asked in regards to the drill rigs used by these individuals had to do with the drill bits used when drilling, similar to the previous survey. Just like before, the drill bit type, cost, and diameter were asked for each drill rig owned by the respondents. At the end of the survey, respondents were asked to leave any comments that they had that can potentially aid in the drilling process.

V. b. ii Drill Rig Survey Results

Out of the multiple surveys that were sent out, only ten were submitted. Out of these ten individuals, nine marked that they have worked in the industry for over ten years, with only one mentioning they have been in the industry between 6 to 10 years. One of the first questions that were asked of these respondents in regards to the drill rigs that they owned were the type of rigs they most commonly used. From this, the most commonly used drill rigs that were used were mud and air rotary drill rigs, with each of these rigs having five individuals using them between 75-100% of the time. Along with these two drill rigs, DTH hammers were also popular, with 3 of the respondents indicating that these rigs were used between 75-100% of the time. Even though some of these respondents may rely on one of these rigs, a majority of them indicated that they do use other rigs occasionally, with how commonly these respondents used each type of rig being provide in figure 17. The least popular drill rig that was indicated was the cable tool drill rig, with only one respondent indicating that it was used. Even then, this single individual indicated that this rig was used below 10% of the time. As air and mud rotary and DTH hammer drill rigs were the predominate rigs in which information was provided for, these three drill rigs will be the only rigs that will be discussed in the remainder of this section. Following this, the manufacturer, model number, and

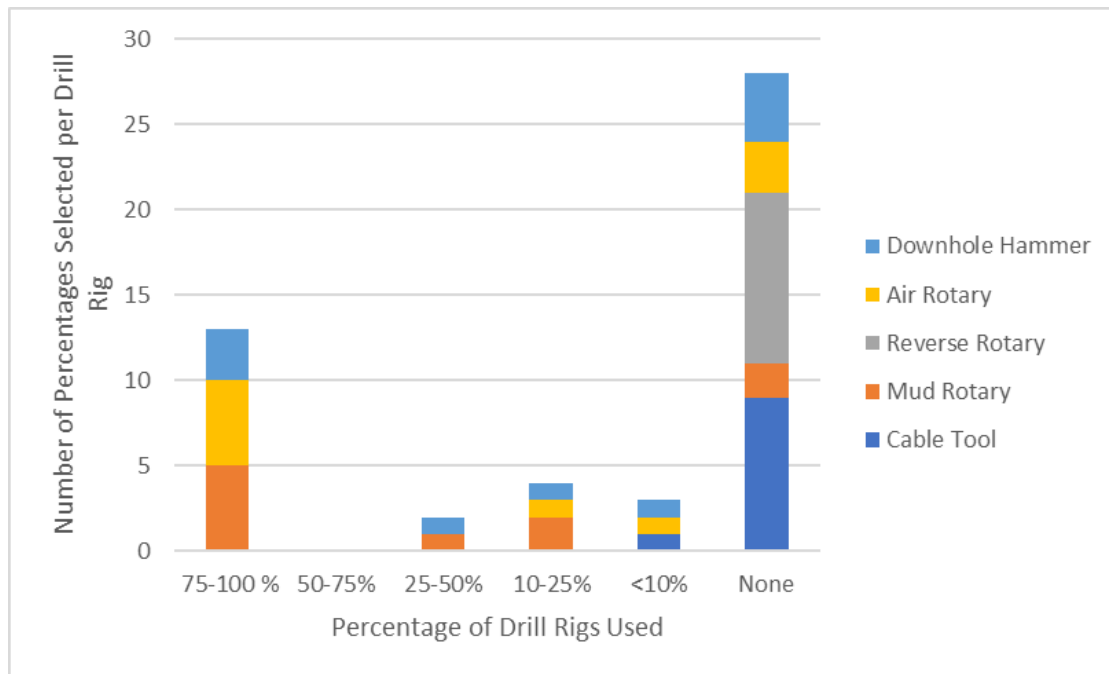


Figure 17. Percentage of Drill Rigs Used per Respondent

age of these drill rigs were asked, with the manufacturer and model number responses being provided in appendix III. For all three drill rigs, the age varied quite significantly, ranging from fairly new to 45 years old, which can be viewed in figure 18. On average, the newest drill rigs were that of mud rotary drill rigs, with the average age of these rigs being about 12 years. The oldest of these rigs were air rotary drill rigs, which had the average age of 20.5 years. Having an average age between the other two drill rigs, the average age of DTH hammers came in at an age of 15.5 years.

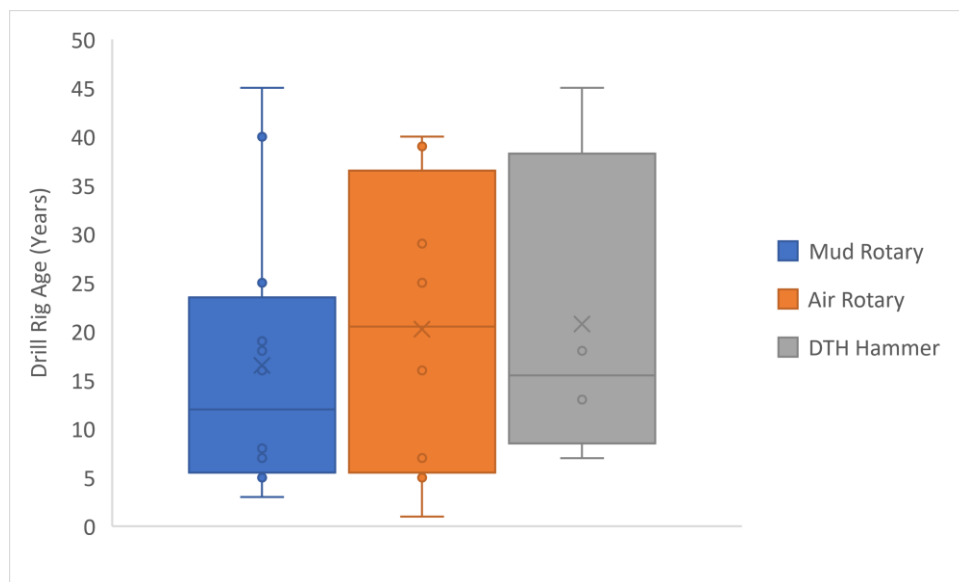


Figure 18. Average Drill Rig Age Results

Respondents were then asked the average costs of the drill rigs that were used alongside the average borehole depth drilled and penetration rate of these rigs. When providing the average cost of these rigs, some respondents provided the average actual costs, while others provided the cost per foot. Due to this, results from both will be mentioned, with the results from both being visible in figure 19 and 20. When considering the average actual costs, the cheapest drill rig was the mud rotary, which had an average cost

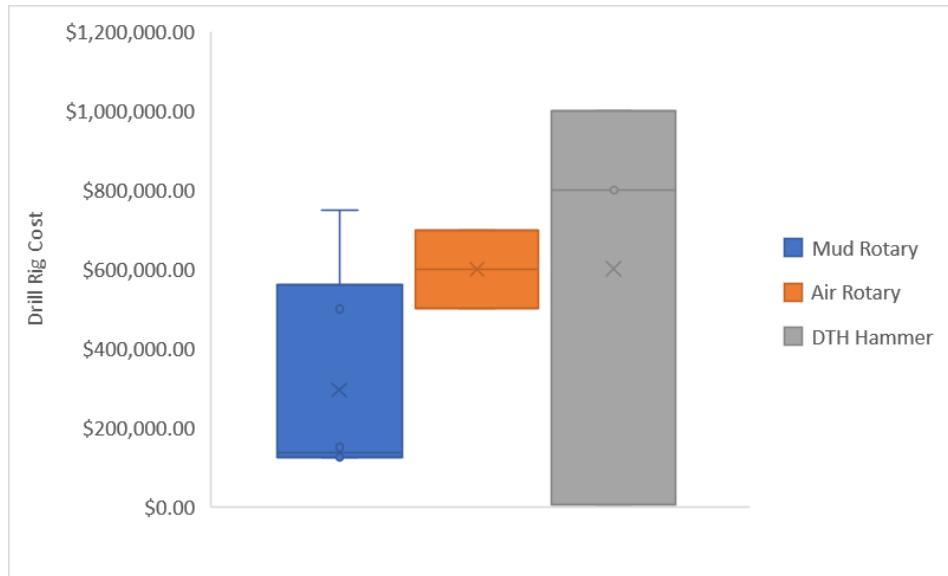


Figure 19. Drill Rig Cost Results

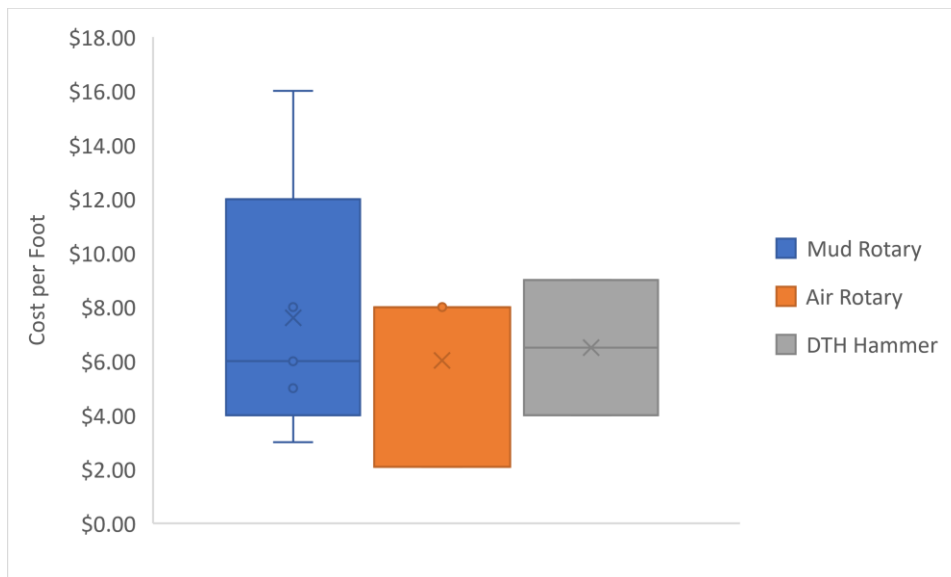


Figure 20. Drill Rig Cost per Foot Results

of \$137,000. The most expensive rig was the DTH hammer, coming in at a cost of \$800,000. For the air rotary drill rig, the average cost provided for this rig was about \$600,000. When using the cost per foot data, the results showed that the highest cost per foot belonged to the mud rotary drill rig, which turned out to be about \$7.60 per foot. The air rotary resulted in the lowest average cost per foot at about \$6.03 per foot, with DTH hammer having a cost per foot of about \$6.50 per foot. Using the average borehole depths provided by the respondents, which can also be viewed in figure 21, mud rotary was shown to have the deepest boreholes, with an average depth of 747 feet. Air rotary had the next deepest of 410 feet, with the smallest average boreholes belonging to the DTH hammer, which had an average depth of 363 feet. Using the penetration rates provided by the respondents, the drill rig that had the highest penetration rate belonged to the air rotary as demonstrated by figure 22, having an average penetration rate of 120 ft/hr, followed by the mud rotary, which had an average penetration rate of about 109 ft/hr. Following this, the DTH hammer had the lowest penetration rate of about 85.3 ft/hr. In addition to the overall penetration rate, the average penetration rate for several different formations were also asked for. These formations ranged from softer formations, like soil and clay, to harder formations, like marble and clay. The results of these questions will be provided in figures 23, with the average penetration rate per formation being provided in table 9. As can be seen from these figures, the penetration rates provided varied greatly in all formations for each drill rig, given that enough information was provided for a given formation. Aside from the small sample size of people asked in regards to this, other factors possible contributing to this could be due to the horsepower and age of the rigs used while drilling in these formations. Overall, this survey provides a rough overview of current industry practices, with a summary of the survey being provided in table 10. Though this survey had more respondents when compared to the previous survey, it still suffers from the lack of individuals participating in the survey. Due to this, a more extensive survey would allow for a more comprehensive overview of current industry practices than that provided in this paper. This would allow for the cost analysis of ground source heat exchangers to become more cost effective, which will be discussed further in a later section. A more extensive survey would also aid in targeting parts of the installation process that can greatly impact the

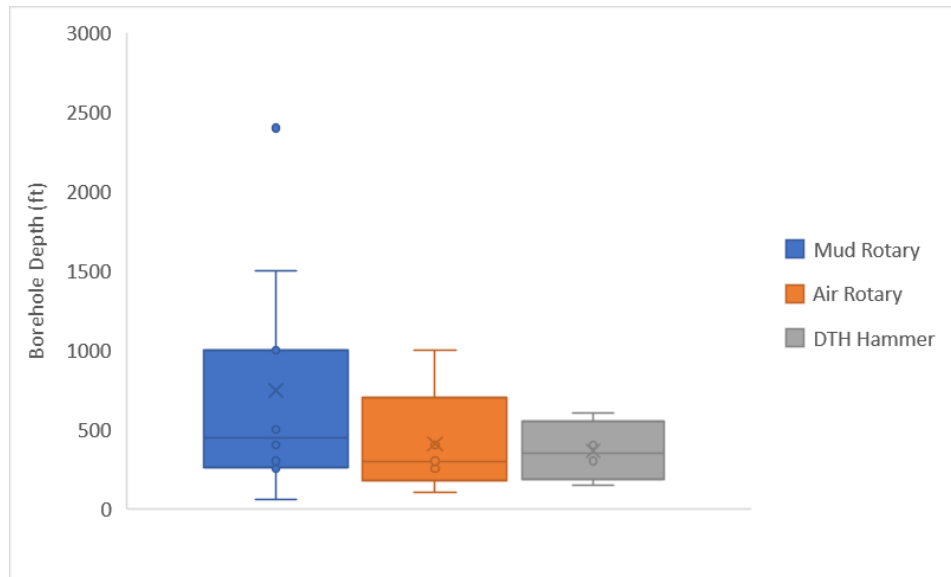


Figure 21. Borehole Depth per Drill Rig

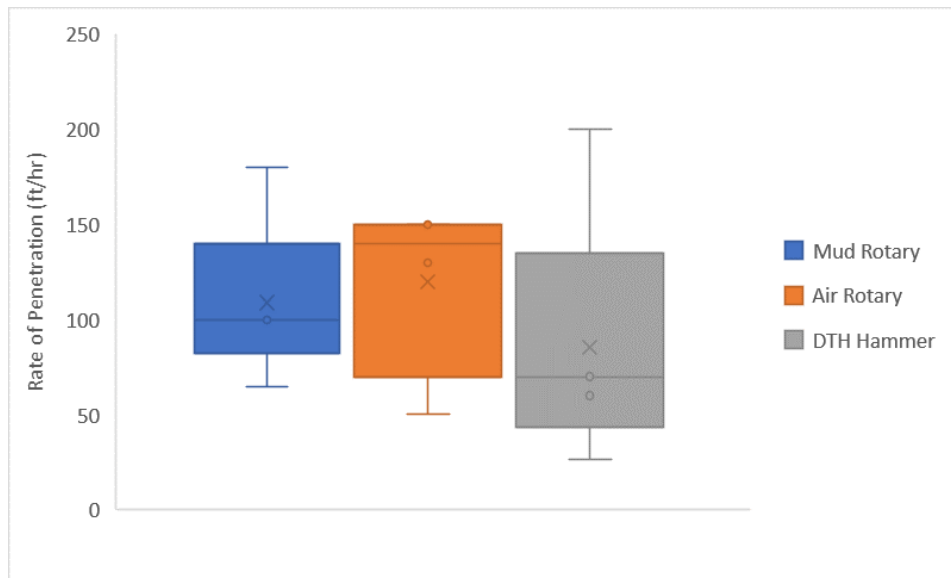


Figure 22. Rate of Penetration per Drill Rig

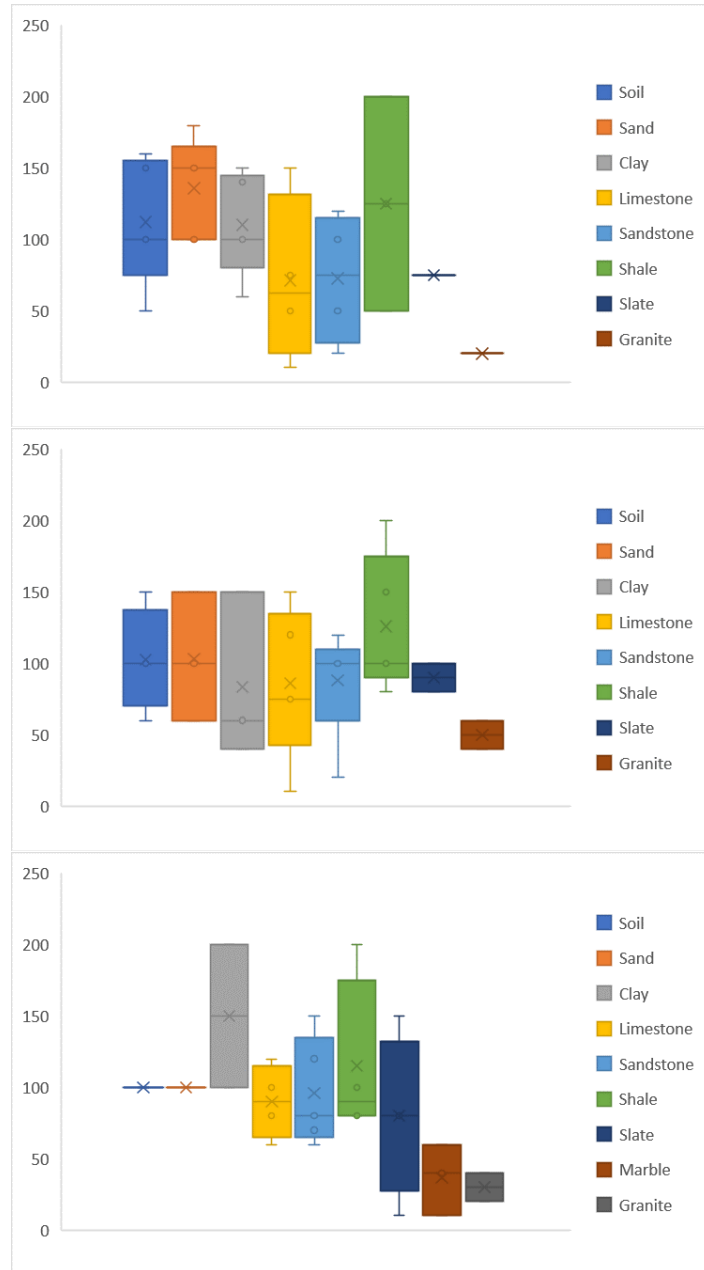


Figure 23. Penetration Rate per Formation (Mud Rotary – Top, Air Rotary - Middle, DTH Hammer – Bottom)

Table 9. Average Drill Rig Penetration Rate per Formation

Formation	Mud Rotary	Air Rotary	DTH Hammer
Average	109	120	85
Soil	112	103	100
Sand	136	103	100
Clay	110	83	150
Limestone	71	86	90
Sandstone	73	88	96
Shale	125	126	115
Slate	75	90	80
Marble	-	-	37
Granite	20	50	30

Table 10. Drill Rig Survey Overview

Drill Rig Specifications	Mud Rotary	Air Rotary	DTH Hammer	Cable Tool
Drill Rig Usage	80%	70%	60%	10%
Average Age (Years)	16.5	20.25	20.75	-
Average Depth (ft)	747	410	363	-
Average Drill Bit Diameter (in)	6	6.875	5.6	-
Average Drill Bit Cost	\$1,380.00	\$1,570.00	\$950.00	-
Average Cost	\$296,000.00	\$600,000.00	\$602,000.00	-
Average Cost per Foot	\$7.60	\$6.03	\$6.50	-

cost of installation. Though a more extensive survey would be desirable, information received from performing these two surveys can still aid in performing an analysis on the cost of installation, which will be further discussed in the upcoming sections.

V. c Updated Cost Model

As discussed previously, ref [35] developed a cost model for GSHE installation based on information collected from eight site visits. Figure 24 shows the structure of the cost model. Based on a few inputs of the GSHE design, geological condition of the job site, and the drilling rigs to be used, this model calculates both the cost for installing an individual GSHE and distributed costs for implementation of the entire bore field. This model can output detailed breakdown of labor, material, and equipment cost of installing an individual GSHE and the overall cost for implementing the entire bore field. As discussed in ref [32], changes were made to this cost model, which will be further expounded upon in the following sections.

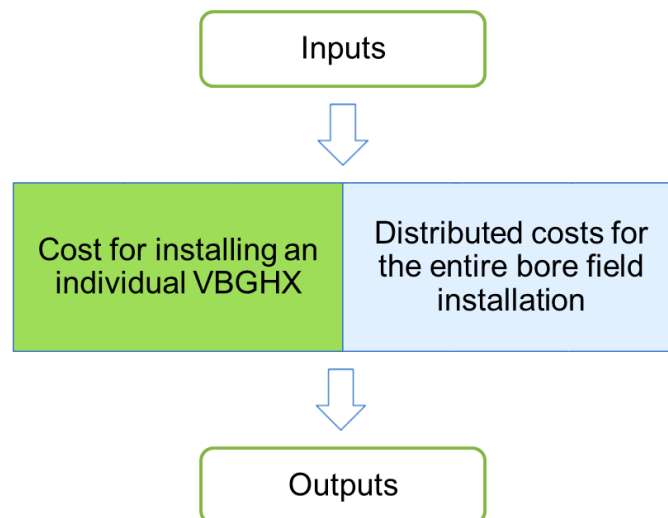


Figure 24. Cost model structure for vertical bore ground heat exchangers [32]

V. c. i Cost Model Changes and Assumptions

This model is updated in this project with up-to-date information collected from the above survey and other resources. In addition, the model is improved by accounting for:

- impacts of geological conditions (i.e., soil/rock type at different layer of subsurface of the ground) on the ROP
- cost of casing
- alternative BHE designs, including loop configurations and materials of pipe, grout, and heat transfer fluids.
- regional difference in labor cost (which can be retrieved from Ref [17])
- impacts of drilling rigs on the equipment cost and ROP
- cost of design, profit and overhead

The cost of casing is calculated with a normalized casing cost (\$ per foot) and the depth of casing, both of which are user inputs. User can select from existing options of different GSHE types, pipe materials, grout materials, and heat transfer fluid. The selection of GSHE type will affect the needed amount of materials of pipe, grout, and heat transfer fluid. Based on user selections, unit prices of the selected materials will be picked up from a built-in cost data library and used in the cost model. The penetration rate of rotary and percussive drill rigs in various ground formation (as discussed previously) is implemented in the model to calculate the ROP for a given drill rig at a given ground formation (i.e., the layers of different ground formations encountered during drilling). Along with this, the selection of either the rotary or percussive drilling rig is also implemented into the model. This would allow for calculating a weighted average of the ROP for various ground formations encountered during drilling. The cost of bore field design is accounted for as a percentage of the barebone cost of the installation. In addition, the profit and overhead of the bore field installation was calculated on top of the barebone installation cost and the

bore field design cost. Once the total project costs were computed, a calculation was added to determine the cost per foot of the project. To account for the impacts of the number of boreholes on the distributed costs, the horizontal looping cost was calculated as a function of the number of boreholes as this cost is associated with individual boreholes. A user-friendly interface is developed to allow a user to enter all the needed inputs and displays all the results. Inputs of the updated model are listed below.

- Borehole depth
- Borehole diameter
- GSHE type (single u-tube, double u-tube, coaxial, or “Twister”)
- Materials of grout, pipe, and heat transfer fluid
- Casing information (normalized casing cost, depth of casing, time)
- Drilling rig to be used (rotary, percussive, sonic, or auger)
- Ground formation (thickness and type of various soils/rocks layers along the depth of a borehole)
- Total number of boreholes

V. c. ii Description of Cost Model Sections

The updated model calculates the costs of labor, material, and equipment associated with each step of a typical VBGHX installation, as listed in Table 11. The method and data used to calculate each item listed in Table 11 is presented in the following sub-sections.

Labor Cost

Labor cost is calculated based on the hourly rate of a driller and helpers (usually two) and the estimated time for them to perform specific tasks. The hourly rate is calculated based on the average wage of

Table 11. Items for calculating the installation cost of individual vertical bore ground heat exchanger [32]

Borehole Installation Steps	Labor cost	Material cost	Equipment cost
Prepare heat exchanger loop (e.g., single u-tube)	Based on fixed time (0.5 hr) and hourly rate	Based on calculated loop length and pipe cost	NA ^(a)
Reposition drill rig	Based on fixed time (0.15 hr) and hourly rate	NA	Based on fixed time and hourly rate
Set cellar box and mix mud	Based on fixed time (0.25 hr) and hourly rate	Based on fixed amount of bentonite and cost	Based on fixed time and hourly rate
Drill bore hole	Based on bore depth, geological condition, drilling rig, and hourly rate	Based on bore depth and cost for water and drill bit	Based on calculated time and hourly rate
Casing borehole ^(a)	Based on design and hourly rate	Based on user inputs and material cost	Based on calculated time and hourly cost
Circulate and POOH ^(b)	Based on fixed time (0.1 hr)	NA	Based on fixed time and hourly rate
Install loop	Based on fixed time (0.1 hr)	Based on water cost and calculated volume to fill the loop	Based on fixed time and hourly rate
Pull weight bar	Based on fixed time (0.1 hr)	NA	Based on fixed time and hourly rate
Anchor top of heat exchanger loop	Based on fixed time (0.1 hr)	Based on fixed amount and re-bar cost	Based on fixed time and hourly rate
Put grout in place	Based on fixed time (0.4 hr)	Based on grout material cost and calculated amount of grout	Based on fixed time and hourly rate
Charge heat transfer fluid	Based on fixed time (0.1 hr)	Based on fluid cost and calculated volume to fill the loop	Based on fixed time and hourly rate
Pump excess mud into tank/vacuum truck	Based on fixed time (0.15 hr)	NA	Based on fixed time and hourly rate
Clean and pick up cellar box	Based on fixed time (0.1 hr)	NA	Based on fixed time and hourly rate

Note:

- a) NA stands for “Not Applicable”
- b) Casing is needed in certain areas where the overburden (soil) is soft. In this case, a vertical bore is cased with steel pipe from the ground surface until reaching the bedrock.
- c) POOH is the abbreviation for “pull out of the hole” (i.e., removing the drill strings from the bore hole)

drillers and helpers and the rates of other indirect costs paid by their employer (e.g., medical insurance, social security, and Medicare). Table 12 lists the average wage range of drillers and helpers, as well as the rate of other indirect costs. The average wages of drillers and helpers are obtained from Ref [18] and the rates of indirect costs are estimated based on available information of similar jobs. Workmen's compensation is the amount given to the worker if that worker is injured while working, which is determined as a percentage of the hourly wage. Medical insurance is the amount of money set aside to pay for medical insurance for the workers, with the insurance costing \$250/month per person. SUTA is the rate charged for state unemployment tax as charged as a percentage of the first \$7000 given to the worker. FICA is a tax taken out of the worker's wages to help pay for items such as social security and Medicare, which is determined as a percentage of the worker's wages. Holiday and vacation represent time paid to employees as part of their benefit compensation.

Table 12. Wages and rates of other costs of a driller and a helper

Wages	
Driller	\$25/hr
Helper	\$20/hr
Rates	
Workmen's comp	18%
Medical insurance	\$250/month per person
FUTA/SUTA	3.40% on the first \$7k
Social security	6.10%
Medicare	1.45%
Holidays	6%
Vacation	5%

As shown in Table 11, the time for performing all of the tasks is fixed (i.e., user input), except for drilling and casing a bore hole. The time needed to drill a given borehole is dependent on borehole depth and the penetration rate of the drill rig utilized in a given formation, as shown in equation 2. Using Ref [10], the

time needed for casing a borehole was determined to be a percentage of time needed for drilling the borehole.

$$t = \frac{L}{ROP} \quad \text{Eqn. 2}$$

Material Cost

Material cost is calculated based on the amount of needed materials and the current market price of each material. As indicated in table 11, the needed amounts of materials are fixed in a couple of steps (e.g., mix mud), and they are variable and calculated based on the GSHE design in other steps. Since the original Sandia National Laboratory cost model was created twenty years ago, these material costs were outdated, with the original costs being detailed in table 13 with the exception of the drilling fluid costs as it was not included in the original cost model. Table 14 lists the current unit price of various materials used in the installation, which were retrieved from Ref [19] and from the above survey. This category was comprised of different inputs associated with the materials used, including pipe, heat transfer fluid, grout, etc. Based on the unit cost of each material and the specified borehole design (i.e., borehole depth and diameter, the number of boreholes), cost of each material is calculated.

Equipment Cost

Equipment cost is calculated based on the hourly rate for utilizing equipment (e.g., drill rig, auxiliary equipment, and air compressor) and estimated time to perform specific tasks. The hourly rate of equipment accounts for both the costs for purchasing the equipment and for maintaining the equipment. The purchase price of an equipment, interest rate of the loan, depreciate period, and effective working time of this equipment are used to calculate a portion of the hourly rate that is needed to pay back the loan. When determining the drilling rig purchase price, figure 25 can be used to determine the average cost of several drilling rigs per year in which they were manufactured, along with the overall purchase price of these drilling rigs, with these costs being retrieved from Ref [20].

Table 13. Original Unit Price of Various Materials

Material	Price	Unit
Bentonite	\$0.10	per lb
Water	\$0.05	per gallon
Pipe (HDPE)	\$0.75	per ft (double run)
1/2" re-bar	\$0.20	per ft
Grout	\$0.50	per gallon
Header	\$5.00	per hole
Drill bit	\$300	Each

Table 14. Current unit price of various materials

Material	Price	Unit
Bentonite	\$0.41	per lb
Water	\$0.00	per gallon
Pipe (HDPE)	\$0.52	per ft (double run)
1/2" re-bar	\$0.44	per ft
Grout	\$0.33	per gallon
Header	\$8.40	per hole
Drill bit	\$350	Each
Heat transfer fluid	\$2.30	per gallon (Ethyl alcohol)

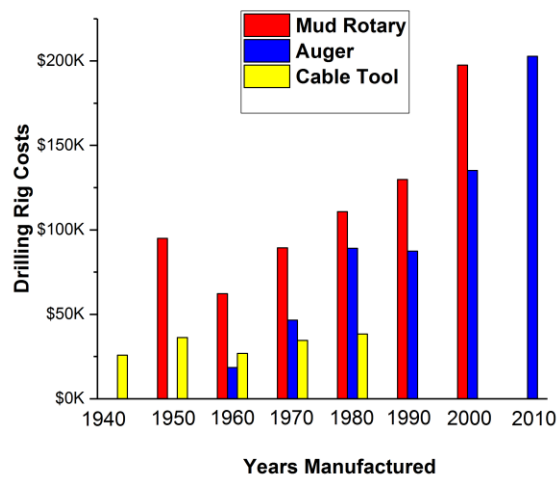


Figure 25. Cost of Different Drilling Rigs by Year

The other portion of the hourly rate is to recover the maintenance cost. The cost and frequency of maintenance/replacement of the major components of a mud rotary drill rig (engine, mud pumps, tires, and rotary system) were estimated by ref [35] and they are used to calculate the hourly maintenance cost of the drill rig. The hourly maintenance cost of a drill pipe is calculated based on life of the drill bit (i.e., the total length of drilling) used in the drill pipe and the ROP of the drill rig. When comparing the maintenance costs to the overall equipment costs, the cost of maintenance is minimal, with the costs for each item being under a dollar an hour and contributing less than 1% per item. The main exception to this is the cost of the drill pipe. As the frequency of the drill pipe maintenance is dependent on the penetration of the drilling rig, higher penetration rates lead to more frequent maintenance. If very low penetration rates are to be used, the cost of maintenance for the drill pipe will be on the same order of magnitude as the other maintenance costs. If high penetration rates are to be used, as with typical drilling rigs, the drill pipe maintenance cost would become the leading cost in terms of maintenance. The annual maintenance cost of other equipment was assumed to be 5% of their purchase price. The hourly fuel cost, which is calculated based on the hourly fuel usage for operating the equipment and the current fuel prices, is also accounted for in the hourly rate of equipment.

Distributed Costs

Distributed costs include the cost for designing borehole field, moving rigs to job site, locating underground utilities, horizontal piping to connect heat exchangers in each individual bore, site restoration, as well as overhead and profit (including contingency cost). Some of these costs are directly from user inputs (e.g., locating utilities, and moving the rig to location costs), but other costs (e.g., horizontal piping) are calculated based on the size of the bore field (i.e., the number of bores).

Mapping Between Inputs and Costs

To help understand how information from the previous categories affected both sections, table 15 was created to help detail how the inputs and parameters from previous categories were related to the calculations in this category, along with stating the assumptions made with the cost model.

Table 15. Mapping between Component Costs and Various Inputs and Parameters [32]

Borehole Installation Steps	Labor (Helper)	Total Labor	Hole Depth	Hole Diameter	Number of Boreholes	Rate of Penetration	Drilling Fluid Cost	Water Cost	Loop Mat'l Cost	1/2" Re-bar Cost	Grout Cost	Grout Interval	Header Cost	Bit Cost	Bit Life
Trench (1 man, 20' of trench/hole)	x				X	X			X						
Install headers and lay lines in trenches		x			X	X			X				x		
Back-fill trenches and restore site		x			X	X									
Make up loop	x		x						X						
Reposition rig		x				X									
Set cellar boxes and mix mud		x				X	x								
Drill hole		x	x	x		X		x							
Circulate and POOH		x				X									
Install loop		x	x			X		x						x	x
Pull weight bar OOH		x				X									
Anchor top of loop		x				X				x					
Grout loop in place		x	x	x		X					X	X			
Pump excess mud into tank/vacuum truck		x				X									
Clean and pick up cellar box		x				X									
Total borehole costs					X										

Assumptions

- Assume penetration rate does not change with bore depth
- Cost of co-axial loop is just a rough guess (no actual quote for co-axial loop is available)
- Assume all the trenching related costs are multiplied by the number of boreholes
- Uncertainties in the estimated bore field design cost and the profit margin/contingency cost

VI. Potential Solutions for Cost Reduction

Using the cost model that was provided before the multiple changes were implemented, barring the distributed costs being made a function of the number of boreholes, a parametric study was conducted to determine how the project costs react to changes in several parameters. The main parameters that were varied were related to the borehole, which are as follows: the borehole diameter and depth, the number of boreholes, and the penetration rate. As one parameter was varied, the others remained at a constant value, as shown in table 16, with the exception being the number of boreholes and the borehole length. As either the number of boreholes or borehole length was varied, equation 3 was used to be sure that the cooling load was kept constant, with the conversion factor, used in the equation below, maintained at $200 \frac{ft}{ton}$.

Table 16. Key Parameters and Parameter Values

Parameters	Baseline Value
Cooling Load (tons)	50
Number of Boreholes	50
Borehole Length (ft)	200
Borehole Diameter (in)	4.25
Rate of Penetration (ft/hr)	100

$$L = \frac{L_o C}{NoB} \quad \text{Eqn. 3}$$

VI. a Cost Reduction Baseline

When beginning the study, a baseline was created, as shown in figure 26. This allowed for the observation of how the project costs and the cost per foot vary with the different parameters, and to witness how

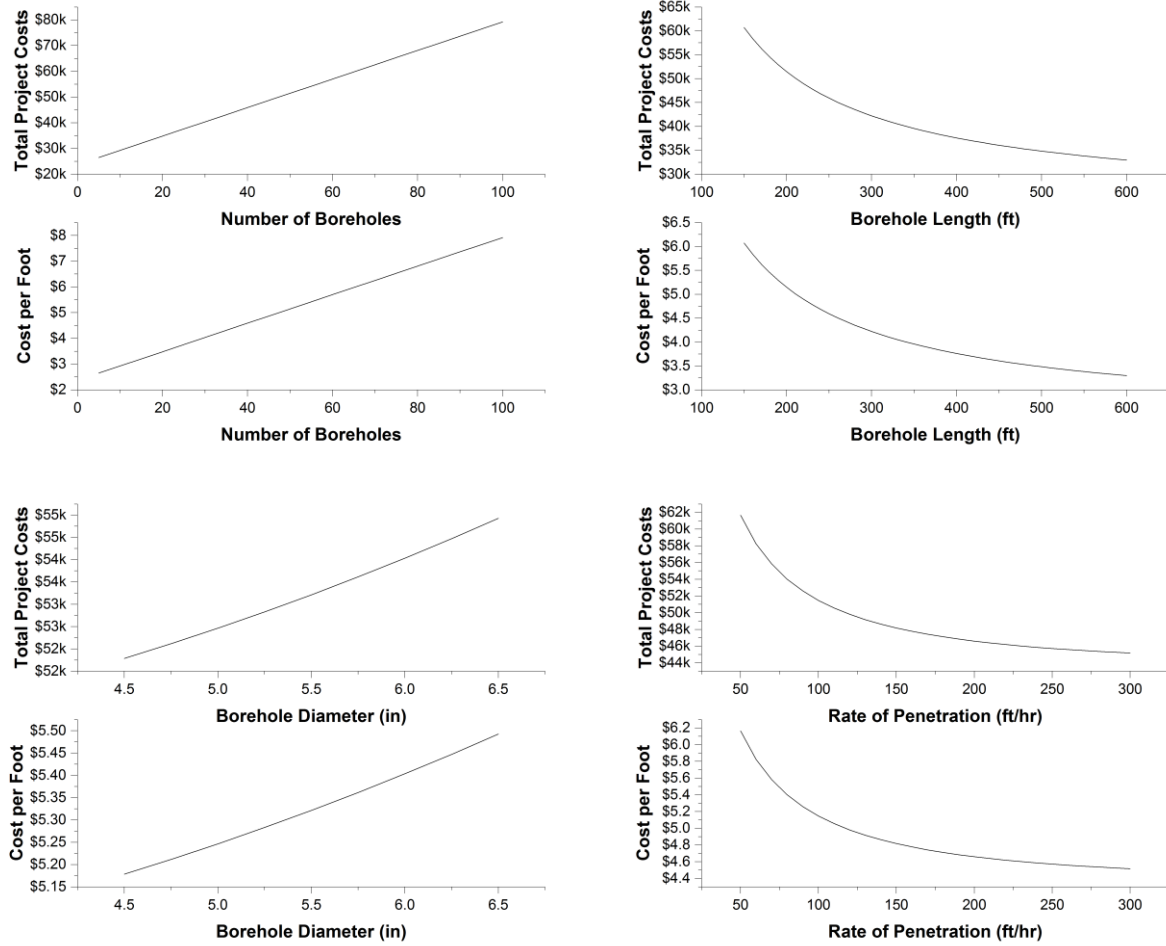


Figure 26. Varying Project Costs with Changes in Select Parameters

sensitive both were once the baseline was compared to a scenario where a given parameter was doubled. As shown in this figure, it was determined that the project costs and the cost per foot were to increase with the number of boreholes and borehole diameter, but to decrease as the borehole length and penetration rate were increased. As each of these parameters affect the cost through separate means, it was important to identify how the costs were affected by each parameter, which will be discussed further in the following sections.

VI. a. i Baseline Costs for an Increasing Borehole Number and Length

As shown in the above figures, the main distinction between the number of boreholes and the borehole length were that the project costs increased linearly with the number of boreholes, while the project costs exponentially decreased with the increase in borehole length. Increasing the number of boreholes from 50 to 100 yields a 54% increase in costs, while an increase in borehole length from 150 to 300 feet results in a cost reduction of 30%, with a further reduction of 22% from 300 to 600 feet. After examining the model, it was determined that this was primarily due to the number of boreholes. As the distributed costs were modified to be a function of the number of boreholes and that the number of boreholes was needed to calculate the total borehole cost, the number of boreholes had a greater effect on the project cost than the borehole length. This meant that a linear increase in the number of boreholes resulted in a linear increase in project costs, but a linear increase in borehole length caused an exponential decrease in costs due to the need to maintain a constant cooling load as dictated by equation 3.

VI. a. ii Baseline Costs for an Increasing Borehole Diameter

Similar to the number of boreholes, the project costs increased with the borehole diameter. Unlike the number of boreholes, the borehole diameter caused the project costs to increase exponentially, with this exponential increase being slight. This exponential increase in costs was due to the diameter used to

calculate the volume of a given borehole, allowing for the material cost to be determined for both the borehole drilling and grouting costs. Out of these two costs, the diameter had the greatest effect on the grouting costs. This was primarily due to the material amount determining both the total cost of the water used when drilling a given borehole and the material costs of grouting the borehole. One thing to note, as well, was when calculating the borehole drilling material costs, the cost of the drill bit was also considered. As water is inexpensive, especially when compared to the cost of the drill bit, the borehole drilling material costs changed little as the borehole diameter was varied. As the grouting cost was more expensive than the cost of the water, this resulted in high material costs for the grout, potentially even higher than the combined water and drill bit costs. As such, the grouting costs varied more than that for the borehole drilling costs, especially when large borehole lengths were used. For most instances, however, the grout material cost remained at the same order of magnitude as both the labor and equipment costs. Overall, the changes in the grout costs found for the baseline were insignificant as the ranges of diameters used were small when compared to the ranges of other parameters, such as the borehole length. Due to this, the borehole diameter had the smallest effect on the project costs. Using the typical range of diameters used for boreholes, the cost only increased by \$3000 from 4.5 to 6.5 inches, or roughly 6% throughout that range. This meant that the borehole diameter was not a key driver for the project costs when compared to the other parameters.

VI. a. iii Baseline Costs for an Increasing Penetration Rate

Similar to the borehole length, the project costs were found to decrease exponentially with increasing penetration rate. As the penetration rate was increased from 50 to 100 ft/hr, the cost was reduced by 17%, and was additionally reduced 10% from 100 ft/hr to 200 ft/hr. This means that, although high penetration rate can achieve a greater savings initially, it will reach a point where there would be minimal savings when increased further. It also means, when slow penetrations are required, the costs will be high. This was primarily due to the penetration rate helping reduce the time required to drill a given borehole, causing the time to exponentially decrease as the penetration rate was increased. This also means that the time needed

to drill a given borehole will change little once large enough penetration rates are used, resulting in minor changes in the borehole drilling costs. At the same time, the hourly equipment costs gradually increase due to the increased maintenance of the drill pipe caused by the higher penetration rates, further dampening the savings caused by the high penetration rates. Even if the penetration rate was increased to greater values to allow for better borehole drilling times, the savings produced by this would be mitigated by the fact that the workers would still need to be paid and the equipment would require funds to be set aside for future maintenance and replacement. This all culminates into ever growing equipment costs, along with minor changes in borehole drilling costs upon reaching high penetration rates, resulting in minimal savings once high penetration rates are reached, as mentioned above.

VI. b Differences in Costs against an Increasing Borehole Number

Using the baseline above, as one parameter was varied, the others were doubled to further understand how the parameters effect the project cost. Beginning with the number of boreholes, the difference and relative differences were found from doubling the other parameters, except for the borehole length due to its connection with the number of boreholes. When viewing both the actual differences and relative differences for the three cases in figure 27, the largest difference occurs at the lower numbers of boreholes, with lessening differences at higher numbers of boreholes. This signifies that for all three cases, both the project costs and cost per foot are the most sensitive to changes when there are fewer boreholes, but have decreasing sensitivity as the number of boreholes was increased. The main exception to this would be the cost per foot of the doubled cooling load which, along with the other cases, is explained in the following sections.

VI. b. i Doubled Baseline Borehole Diameter

As the borehole diameter increased, the total project costs and cost per foot were found to remain at about \$7700 and \$0.75 above the baseline, respectively. As the number of boreholes was increased, the relative

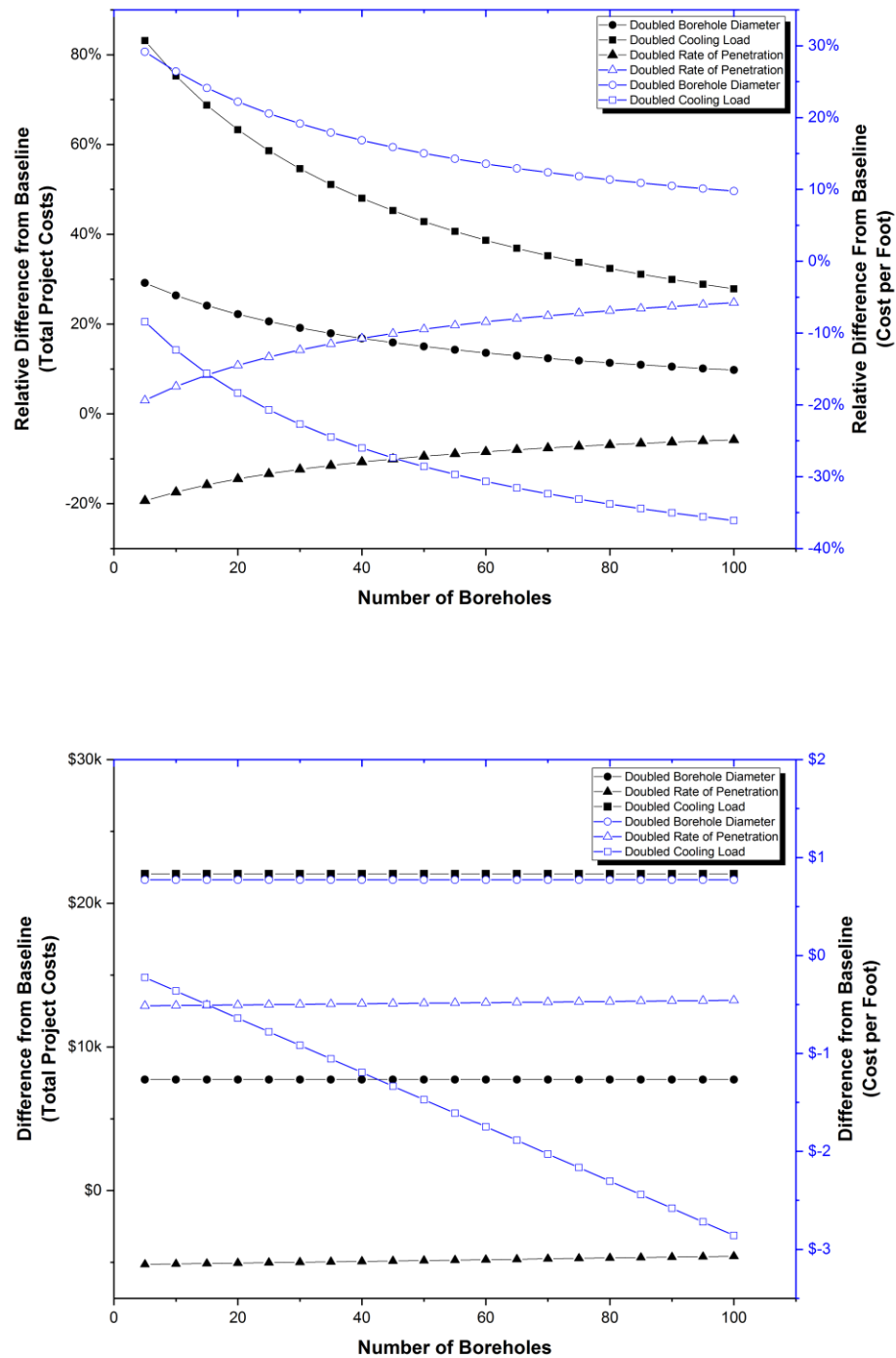


Figure 27. Varying Differences from Baseline with Increasing Number of Boreholes

difference between the diameter and number of boreholes decreased. The relative difference for both the total project costs and the cost per foot began at 30% greater than the baseline at 5 boreholes, with both reaching 10% at 100 boreholes. From these figures, it was demonstrated that the diameter has a greater impact on the project costs when there were fewer boreholes. This was due to the lower distribution costs and an increased cost associated with drilling and grouting because of a larger borehole length and diameter. As the number of boreholes was increased, the borehole length was lowered, causing the grouting and drilling cost for a given borehole to also lower. Simultaneously, the distributed costs rose because of the number of boreholes. This resulted in the borehole diameter having less of an impact on the total project costs at high numbers of boreholes than when there were little. Even though the relative difference began to converge towards the baseline, the actual difference did not. This was primarily due to the total borehole drilling and grout material costs being shifted upwards by a constant amount due to the doubled borehole diameter. Though the doubled diameter used here was primarily used to identify how the project costs would react, it was a diameter that would not typically be used in practice due to it being larger than what would normally be used for a borehole. The range of diameters used for the baseline was a more realistic range of diameters. As such, the differences calculated would be higher than what would normally be expected when using a larger borehole diameter. This means that the difference in costs would realistically be lower than those found above.

VI. b. ii Doubled Baseline Penetration Rate

When varying the number of boreholes, the penetration rate started with a maximum relative difference of -20% at 5 boreholes, reaching a relative difference of -6% at 100 boreholes. Unlike the doubled borehole diameter, the actual difference in costs also varied, decreasing from -\$5100 to -\$4600 with the increase from 5 boreholes to 100 for the project costs. The cause for the project costs and cost per foot approaching the baseline values can be attributed to the decreasing borehole length causing the cost associated with drilling a given borehole to decrease. As the drilling cost was the only item that the doubled penetration

rate could decrease, the reduced borehole length dampened the effect that the penetration rate has on the total project costs. Further adding to this was the increased equipment rate caused by the high penetration rates, as the greater penetration rates lead to more frequent maintenance. As the equipment rate was used to calculate the equipment cost for nearly every item in the installation process, it further dampened the benefits that the increased penetration rate yielded at higher number of boreholes. Due to this, it even reaches a point where, when the number of boreholes surpasses a given number, the equipment rate causes the project costs to become higher than the baseline. For this case of the doubled penetration rate, this point occurred when the number of boreholes reached about 900 boreholes. From this, it can be seen that an increased penetration rate can be beneficial for most instances, with the main reason for not using an increased penetration rate being if a large number of boreholes was desired.

VI. b. iii Doubled Baseline Cooling Load

Beginning with 5 boreholes, the doubled cooling load lead to an 83% increase in costs when compared to the baseline, significantly reducing to 28% at 100 boreholes. This difference became even smaller upon reaching a higher number of boreholes, obtaining differences below 10%. Unlike the decreasing relative difference for the project costs, the cost per foot began with a relative difference slightly less than -10% at 5 boreholes, with it reaching -35% at 100 boreholes. When the number of boreholes rose above 100, the relative difference began to converge towards -50%. Throughout the decreasing relative difference for the project costs, the actual difference remained static at \$22k, while the actual difference for the cost per foot increased with the increased number of boreholes. When examining the cause for this behavior, it was first important to understand how increasing the cooling load would affect the results above. By doubling the cooling load, it caused the borehole length to also double for a given number of boreholes in this specific case. Since the borehole length was increased while the number of boreholes was left effectively unchanged, this resulted in the higher project costs, as seen in figure 2, when the number of boreholes was low. As the number of boreholes was increased, however, the borehole length became smaller, meaning it would result

in a smaller impact on the project costs. At the same time, the distribution costs begin to dominate the project costs when compared to the total project costs at high numbers of boreholes, further decreasing the effect caused by the doubled borehole length. Though the doubled borehole length caused by the increased cooling load might not have had as much of an effect on the project costs at a higher number of boreholes, it did impact the cost per foot at those same number of boreholes. As the project costs began to converge toward the baseline values, the total borehole length remained twice that of the baseline. This, combined with the total project costs converging towards the baseline costs, resulted in the cost per foot mentioned earlier. This suggests that at higher numbers of boreholes, it would be more cost effective to have a higher cooling load. This potentially means that it could be more cost effective to combine projects with higher cooling loads than to have individual projects with smaller cooling loads. However, it is still important to take into consideration that this model does not consider interactions between boreholes, meaning that a doubled cooling load might not directly lead to a doubled cooling load. Despite this, the savings realized by combining projects can still be more cost effective than individual projects.

VI. c Differences in Costs against an Increasing Borehole Length

Similar to before, the different parameters were once again doubled to view the change in project costs when increasing the borehole length, which can be viewed in figure 28. When increasing the borehole length, the differences for the borehole diameter and penetration rate mirrored that of the above case of increasing number of boreholes. This was primarily due to the inverse relationship between the number of boreholes and the borehole length. Unlike the borehole diameter and penetration rate, the cooling load did not follow this pattern. Similar to before, the doubled cooling load began to converge towards the baseline, but not as significantly as with the increasing number of boreholes when comparing the relative differences. Starting at 150 feet, the relative difference was 97%, becoming 95% at 600 feet. The cost per foot also varied very little, with the relative difference changing from -1.4% to -2.6% over the same range. When

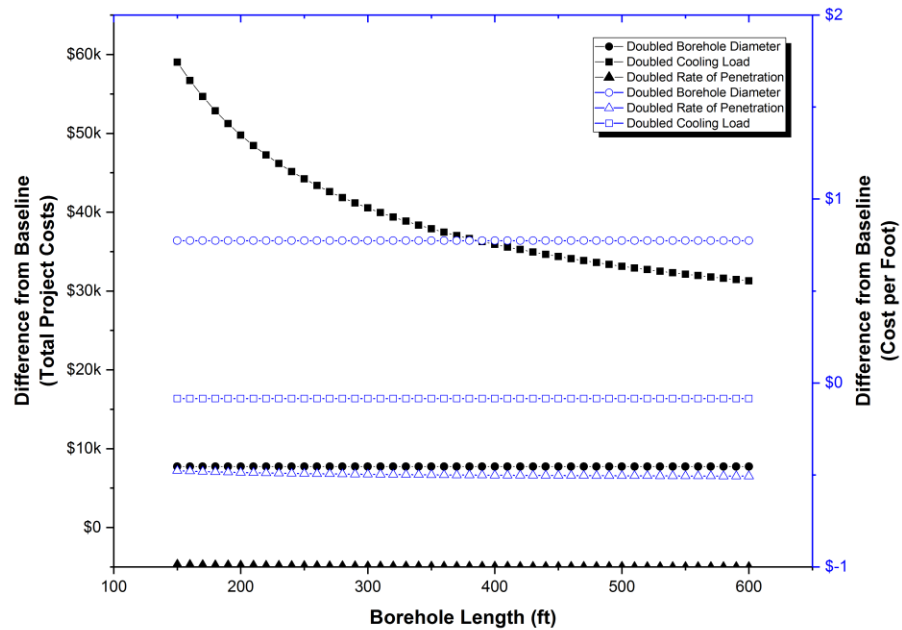
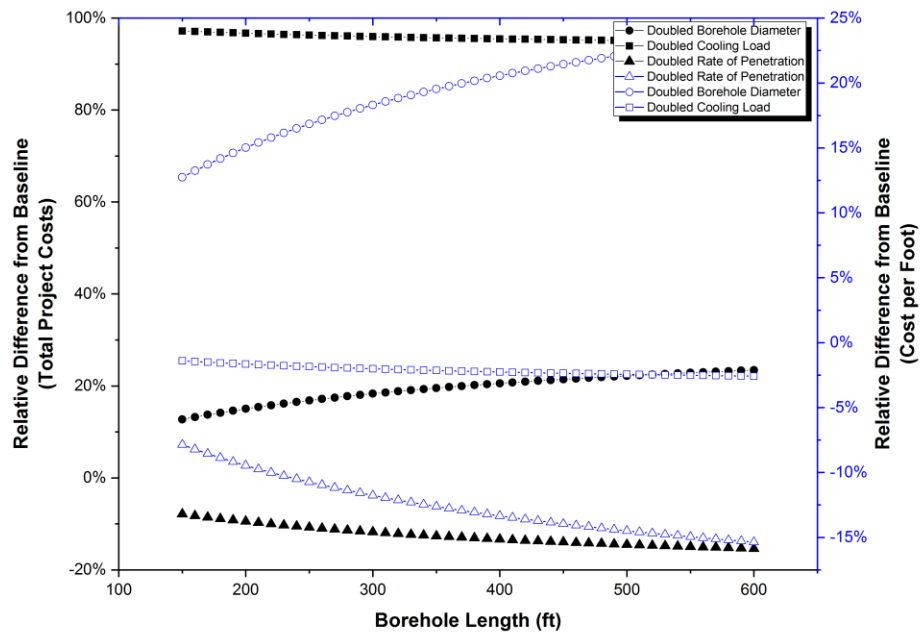


Figure 28. Varying Differences from Baseline with Increasing Borehole Length

comparing the actual difference, though, the project costs for the doubled cooling load varied significantly more than for the increasing number of boreholes. The actual difference went from \$60k at 150 feet to a difference of \$31k at 600 feet. This was primarily due to the doubled number of boreholes caused by the doubled cooling load. When the borehole length was small, the doubled number of boreholes would have a greater effect on the total project costs, with it having less of an effect on the total costs as the borehole length was increased. Once the borehole length became large enough, the number of boreholes barely changed, remaining twice that of the baseline number of boreholes. This resulted in actual differences that were larger when the borehole length was less and smaller actual differences at larger borehole lengths. Though these differences became less as the borehole lengths grew, the relative differences remained double that of the baseline due to the overall importance of the number of boreholes in the cost model. Simply put, since the number of boreholes was needed to determine both the distributed costs and the total borehole costs, doubling this number resulted in the overall project costs being doubled from the baseline values. Overall, the doubled cooling load and borehole diameter led to higher differences when compared to the baseline, while the doubled penetration rate was the only parameter that contributed in effectively reducing both the total project costs and cost per foot.

VI. d Differences in Costs against an Increasing Borehole Diameter

The parameters were once again doubled to view how the total project costs and cost per foot were affected by changes in the borehole diameter, as shown in figure 29. As can be viewed in the figure, the project costs were not as sensitive with changes in the diameter when compared to the previous parameters. Though this figure shows that the borehole diameter was the least important parameter when compared to the others, it was still important to understand why the differences of the doubled parameters changed slightly when the borehole diameter was varied.

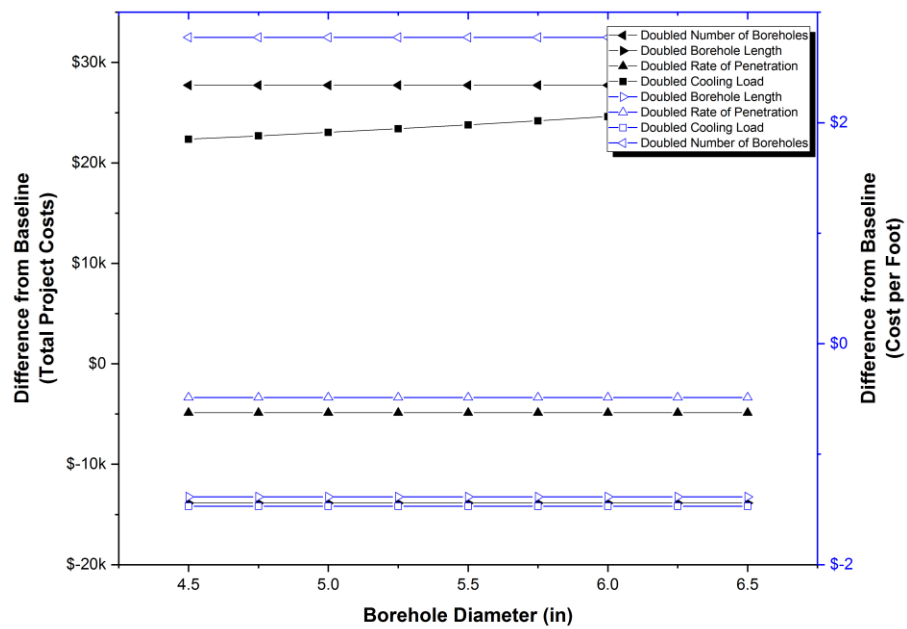
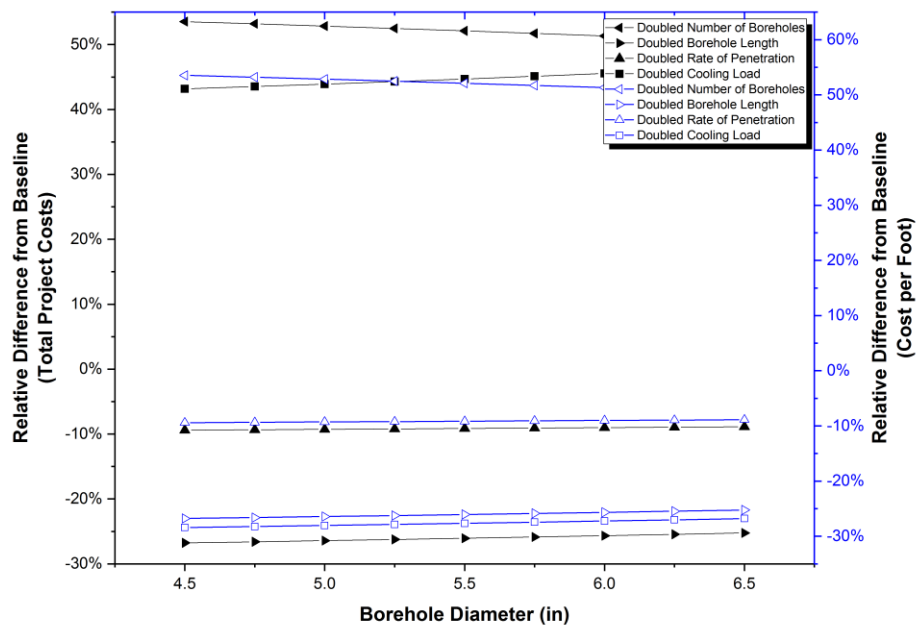


Figure 29. Varying Differences from Baseline with Increasing Borehole Diameter

VI. d. i Doubled Baseline Number of Boreholes

When examining the doubled number of boreholes, it was determined that the relative difference for the project cost and cost per foot were raised by a similar amount, with both converging slightly towards the baseline value. The relative difference for both values began at 54% at 4.5 inches, with a final value of 51% at 6.5 inches. The actual difference for both remained at \$28k and \$2.8, respectively, for the entire range of borehole diameters. This overall cost increase was primarily due to the number of boreholes being the main contributor to the project costs, and that the doubled number of boreholes aided in raising the project costs more as compared to the borehole diameter. The diameter had even less of an impact on the project costs than the baseline due to the halved borehole length. Overall, the project costs were not sensitive for the doubled number of boreholes.

VI. d. ii Doubled Baseline Borehole Length

When determining the effect of a borehole length, both the total project costs and cost per foot were found to be less than the baseline. This was not surprising due to the inverse relationship between the number of boreholes and the borehole length. As such, the reason for the differences in the figures was the same as for the doubled number of boreholes, with the main difference being that the two were mirrored. The only other item to note would be that the relative difference changed even less than that of the doubled number of boreholes, with it varying by about 1.5% throughout the range of diameters, while the actual difference remained at a constant -\$14k.

VI. d. iii Doubled Baseline Penetration Rate

Doubling the penetration rate caused both the total project costs and cost per foot to be less than the baseline. As the penetration rate was mainly used to determine the time needed to drill a given borehole and to aid in the calculation of the equipment hourly rate, and that it was assumed that the borehole diameter did not

contribute to the time required for drilling, the penetration rate was not greatly affected by the borehole diameter. The main reason for the lowered costs was due to the lowered time needed for drilling. This reduction cost allowed for the actual difference to remain at -\$5k throughout the range of diameters, with the relative difference slowly converging towards the baseline by about 0.5%, with a beginning difference of -9.4%.

VI. d. iv Doubled Cooling Load

When doubling the cooling load, the borehole length was also doubled. As only the borehole length was doubled, and not the number of boreholes, it caused the actual difference to diverge from the baseline. The reason for this was due to that fact that the borehole length was connected to the borehole diameter to calculate the material amount needed for drilling and grouting. Since the number of boreholes was not decreased to compensate for the increased borehole length, the total project costs and the cost per foot diverged from the baseline. This was caused by the grouting costs being about twice that of the baseline costs due to the doubled borehole length, with it slowly becoming a dominate cost as the borehole diameter was increased. Out of all the parameters that were doubled, the cooling load was the most sensitive to the increasing borehole diameter. This can be seen as the relative difference increased by 3.3% from a difference of about 43%, and an actual difference increase from \$22.5k to \$25.5k. As mentioned before, when compared to the other instances where the other parameters were varied, the borehole diameter resulted in the least amount of change in the parameters that were doubled.

VI. e Differences in Costs against an Increasing Penetration Rate

The final parameter, the penetration rate, was varied to determine how the other parameters affect the total project cost and cost per foot when doubled, as can be shown in figure 30. Overall, the figure shown below

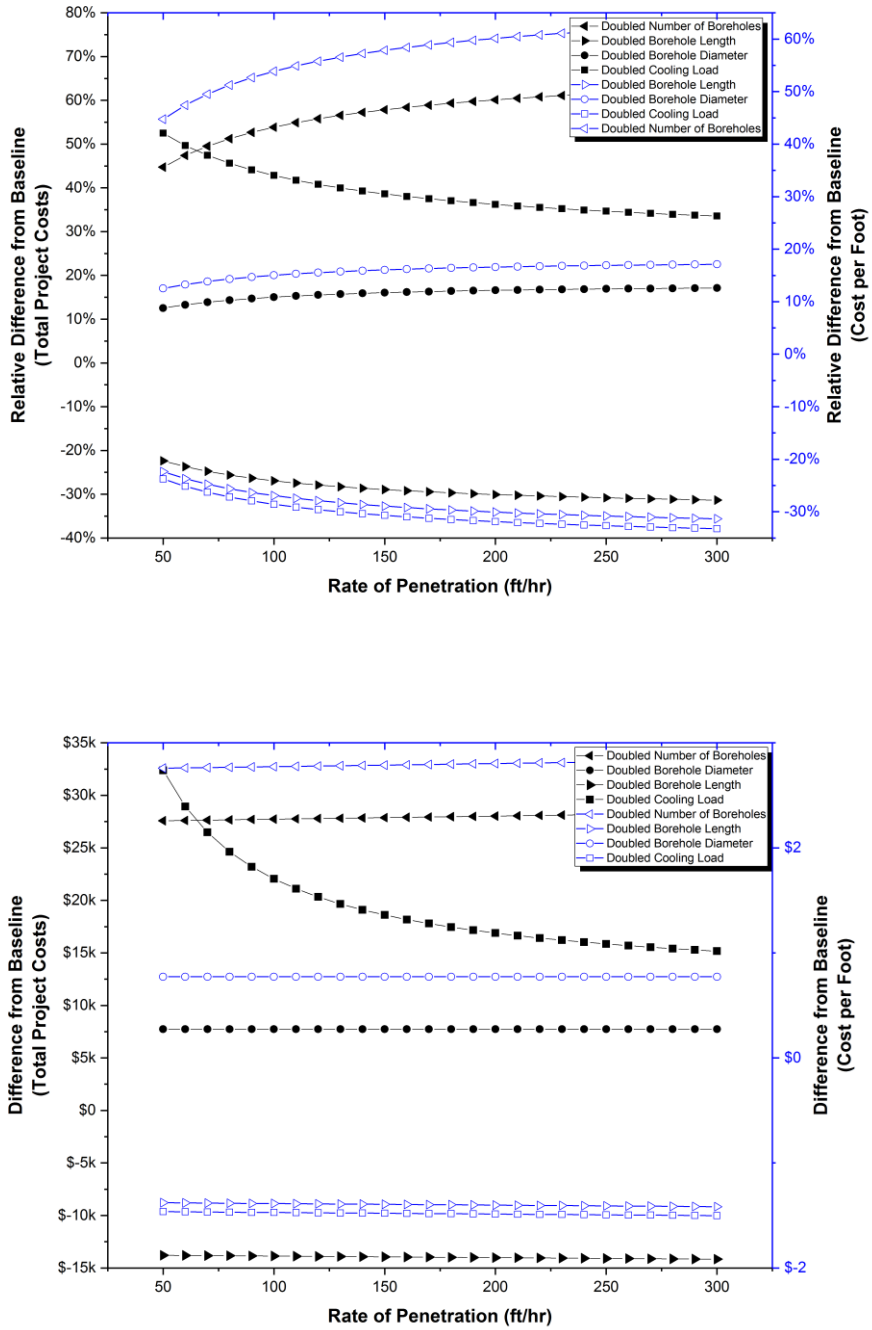


Figure 30. Varying Differences from Baseline with Increasing Rate of Penetration

illustrates that the penetration rate was most beneficial when drilling fewer boreholes that were deep, and that the doubled borehole diameter only had a slight effect on the costs.

VI. e. i Doubled Baseline Number of Boreholes

When doubling the number of boreholes, it was determined that both the actual and relative difference began to deviate from the baseline. Throughout the entire range of penetration rates used, the actual difference only increased from \$27.5k to \$28.3k for the project costs and \$0.07 for the cost per foot. The relative difference, however, increased from a value of about 45% to 54% when increasing the penetration rate to 50 to 100 ft/hr, before reaching 63% at 300 ft/hr. This overall increase in the actual and relative differences was due to the decreased borehole length reducing the benefits of higher penetration rates, along with the doubled number of boreholes amplifying the increased equipment cost, which was partially calculated using the penetration rate. The cause of the lower differences at lower penetration rates was that, when low penetration rates were implemented, the time associated with drilling a given borehole was increased. This led to higher labor and equipment costs, resulting in the borehole drilling costs to become the largest cost for the project. This was the reason why the relative difference showed that the project costs were close to the baseline at first. As the baseline costs began to decrease with the rising penetration rates, the relative difference began to increase as the actual difference became greater when compared to the baseline costs. These diverging differences were due to the doubled number of boreholes further increasing the raised equipment costs caused by the penetration rates. This all resulted in the project costs and the cost per foot to diverge from the baseline results as the penetration rate was increased.

VI. e. ii Doubled Baseline Borehole Length

Since the borehole length was inversely related to the number of boreholes, doubling the borehole length yielded better results than that of the doubled number of boreholes. When increasing the penetration rate from 50 ft/hr to 100 ft/hr, the relative difference reached a value of -27% when starting at a value of -22%. Once the penetration rate was at 300 ft/hr, the relative difference attained a value of -31%. As with the doubled number of boreholes, the actual difference also varied slightly throughout the range of penetration rates, ranging from -\$13.8k to -\$14.2k for the project costs and -\$1.38 to -\$1.42 for the cost per foot. Similar reasoning used when explaining how the doubled number of boreholes affected the project costs can also be used for the doubled borehole length. As the penetration rate was low, it led to longer drilling times for a given borehole, resulting in the drilling costs to become one of the dominating costs, causing the project costs to become near that of the baseline. The two then diverged from one another as the penetration rate was increased due to the reduced drilling costs, along with the doubled borehole length and halved number of boreholes contributing more in reducing the costs at higher penetration rates. The cause of the increasing actual difference can then be explained due to the reduced number of boreholes decreasing the effect of the growing equipment cost caused by the increase in penetration rate.

VI. e. iii Doubled Baseline Borehole Diameter

When the borehole diameter was doubled, the relative difference was determined to increase from 12.5% to 17.1%, while the actual difference was determined to stay at a constant value of \$7700. The main cause for this overall increase in costs was due to the diameter greatly increasing the grouting costs, as mentioned in the previous scenarios. As the drilling costs were decreased due to the increasing penetration rate, the grouting cost remained constant at its new value. This was what resulted in the increased differences in the project costs and cost per foot as described above.

VI. e. iv Doubled Baseline Cooling Load

Similar to previous instances when the cooling load was doubled, the borehole length was also doubled. Though the project costs began at a higher value when compared to the baseline, with a relative difference of 53% at a penetration rate of 50 ft/hr, the costs began to converge towards the baseline, being reduced to 43% at 100 ft/hr before reaching 33% at 300 ft/hr. The actual difference for the project costs also decreased throughout this range of penetration rates, with the actual difference reaching \$15k at 300 ft/hr after beginning at a difference of \$32k. While the profit costs converged towards the baseline, the cost per foot started to diverge from the baseline, reaching a relative difference of -33.2% and an actual difference of -\$1.5. This overall project cost increase was due to the doubled borehole length increasing the drilling costs, with the increased borehole length also decreasing the cost per foot. As the penetration rate increased, it caused the drilling costs to lower, causing the borehole length's contribution to lessen. This resulted in the project costs converging towards the baseline results while having also lowered the cost per foot.

VI. f Parametric Study Conclusions

This parametric study was conducted to aid in the determination of how different key parameters would impact the cost of installation. The goal of doing this was to determine what the ideal design of a given ground source heat exchanger would be, allowing for the installation costs to be minimized. Some of the parameters that were examined, such as the borehole diameter, had little impact on the overall cost, while others, such as the number of boreholes, had a significant influence on the cost. After comparing the results of the parametric study, tables 17 and 18 were created to aid in ranking which parameters resulted in higher values.

Using these results, it was determined that the ideal ground source heat exchangers would minimize the

Table 17. Ranking of Parameters Leading to Higher Total Project Cost

Parameter	Ranking
Number of Boreholes	1
Cooling Load	2
Borehole Diameter	3
Rate of Penetration	4
Borehole Length	5

Table 18. Ranking of Parameters Leading to Higher Cost per Foot

Parameter	Ranking
Number of Boreholes	1
Borehole Diameter	2
Rate of Penetration	3
Borehole Length	4
Cooling Load	5

cooling load, the number of boreholes, and borehole diameter while also having a maximized borehole length and penetration rate. If multiple projects were combined to create one project with an increased cooling load as suggested earlier, it would allow for a more cost effective means of installation. Even though the costs would be similar between the multiple projects and the combined project, the combined project would be cheaper by the foot. As a result, combined projects would allow for a more cost effective means of installation.

VII. Analysis of Parametric Study/Guideline

Using the information provided by the previous sections and from ref [32], a guideline can now be created. This guideline will be divided into three separate sections that will touch upon different areas that have the greatest potential in lowering costs, with these areas being when either few, deep boreholes or many, short boreholes are used, and emerging technologies that have the potential to improve installation costs. The reason for the focus on the borehole parameters instead of the penetration rate is that the penetration rate can vary depending on the rock type and drill rig used and cannot be controlled as well as the borehole parameters. The best that can be done in terms of penetration rate is to carefully choose the drill rig that is best suited for the geology. The drill rigs that are to be used when installing ground source heat exchangers, alongside other parameters such as borehole diameter and heat exchanger type, will be discussed in the upcoming sections.

VII. a Deep and Few Boreholes

As can be viewed from figure 26, having few boreholes that are deep are beneficial in that they are the most cost effective means of drilling as deeper, and thus less, boreholes are less expensive as compared to several short boreholes. To further minimize the costs of drilling these deep boreholes, it is important to maximize the penetration rate like that shown in figure 26. If this is not done, the costs of installing ground source heat exchangers would be much higher than what it would be otherwise. If it is assumed that 17 600-foot deep boreholes that are 5 inches in diameter are to be drilled in shale with a brand new rotary drill rig, the cost of doing so would be about \$150,000. If the borehole were mainly composed of hard rocks where the penetration rates are, at best, about 15 ft/hr, the costs of drilling these boreholes are about \$350,000, which is a 140% increase from the previous cost estimate. This difference is even greater when drilling in rocks that are much harder. As such, to make drilling these deep boreholes as cost effective as possible, it is imperative to drill in formations that allow for high penetration rates, like soils

and soft rocks. If deep boreholes are still desired, even in these harder rocks, using drill rigs other than rotary drill rigs, such as DTH hammers, can still be utilized to maintain reasonable penetration rates. Drilling these deep boreholes also have the added benefit of being able to install heat exchangers in locations that are limited in size, which is to be expected if they are to be installed in residential areas. The ability to drill in these limited sizes and their lower costs when compared to using multiple, short boreholes make this method of installing ground source heat exchangers more appealing for individuals and companies wanting to install these heat exchangers on an individual level. When it comes to the heat exchangers themselves, using heat exchanger designs like that of the geothex or especially the twisted heat exchanger designs would be useful if implemented. Heat exchanger designs similar to these can potentially help keep the cooling load of a heat exchanger system to a minimum. The importance of installing GSHEs for buildings that have low cooling loads for this section can be seen from the parametric study, as increasing the cooling load to twice the initial amount lead to the installation costs to roughly double. It is important to note, though, that this only occurs when increasing the number of boreholes while maintaining the same borehole length so that a larger cooling load can be achieved. When doing the reverse, where the borehole length is increased while maintaining the same number of boreholes, the cost increase is not as pronounced. Due to this, if GSHPs are required for buildings that have large cooling load requirements while simultaneously being limited in the land size, it is important to maximize the borehole length while also minimizing the number of boreholes. Along with installing GSHEs for buildings with low cooling loads and/or size restricting areas, the borehole diameter should be as small as possible, as stated in the parametric study. Though the borehole diameter is not the largest contributor in terms of costs, it was shown that the larger borehole diameters tend to increase costs, however slight it may be. This was primarily due to the higher diameter boreholes requiring more materials than what would be needed for smaller diameter boreholes. By minimizing the diameter, it can help reduce costs and materials used. As stated earlier, however, borehole diameter does not greatly contribute to the overall installation cost. As such, even though borehole diameter should be minimized, more attention should be directed to other items that have greater potential in reducing the overall cost of

installation. Finally, as previously stated, minimizing the number of boreholes drilled while maximizing the depth of these boreholes allow for the greatest cost benefits when it comes to the installation of ground source heat exchangers. This was primarily due to the number of boreholes being the dominating factor in determining the installation costs with the cost model. This means that, as the number of boreholes is decreased while the borehole depth is increased to maintain the same cooling load, the installation costs are reduced. Overall, having long and few boreholes are cheaper when compared to using multiple, short boreholes, and allow for the installation of ground source heat exchangers in areas that have limited spaces.

VII. b Many and Short Boreholes

Though having multiple, short boreholes are expensive as compared to having a few long boreholes, they do have their own advantages that may make them preferable. The area in which these multiple boreholes really shine are when it is desired to combine multiple heat exchanger systems to create a borefield. Given that the provided area is sufficient, the borefield can potentially become a cost effective means of drilling, similar to being items in bulk. As shown with the above parametric study, the installation costs increase linearly with the number of boreholes. If a sufficient number of boreholes are used, the overall cost of installation differs only slightly when the other parameters are varied. The only exception to this is the cost per foot of installing the ground source heat exchangers when the cooling load is changed. The cost per foot was shown to be decreased by up to 40% after reaching a high enough number of boreholes when doubling the cooling load. This shows that, when drilling a sufficient enough number of boreholes, any increase in the cooling has a minimal effect on the overall cost of installation while simultaneously greatly reducing the cost per foot. This suggests that combining projects have the potential to become a more cost effective when compared to having multiple single projects. These savings only occur, however, when the borehole length is increased while the number of boreholes remain constant to compensate for the larger cooling load. When using the cost model to examine the impact of penetration

rate on drilling these boreholes, it was shown that an increase in penetration rate actually provides little savings when drilling multiple, short boreholes. This suggests that penetration rate would not have much of an effect on the overall cost of installation when drilling a high enough number of boreholes. This would mean that drilling in any given formation would not have that great of an impact on installation costs. Along with this, another thing that would result from this is that cheaper, slower drill rigs might be beneficial when drilling these boreholes. This is due to the fact that as number of boreholes that are to be drilled increases, the equipment costs grow alongside it. It can even grow to the point to where the benefits of drilling at high penetration rates won't greatly affect these costs. By using drill rigs that are cheaper than those that would be used otherwise, it would potentially have a greater impact in lowering costs as compared to the penetration rate. This only occurs, though, when high number of boreholes are drilled. If a more expensive drill rig is desired, a reduction in equipment costs can still be achieved if the lifespan of the drill rig can be extended more than it would otherwise have been. Overall, it is important to keep an eye on the potential savings that can be achieved when using either a slow drill rig that is cheap or a faster drill rig that is more expensive, and that increasing the lifespan of either drill rig can aid in reducing costs. When it comes to heat exchanger design, one potential design that could be implemented in these short boreholes are heat basket. This is due to the fact that heat baskets are specifically designed to be short in length. The main downside is the diameter of the heat baskets, which can be on the upwards of 1.3 m [15], causing costs to be higher than what they would be otherwise. This spike in costs can be minimized, however, by maximizing the number of boreholes drilled like that shown in the above parametric study. A similarly designed heat exchanger to that of the heat baskets can be beneficial, though the heat basket diameter should be minimized to prevent the costs from using such a design from increasing too much. To summarize, combining multiple projects to form a borefield composed of multiple, short boreholes can be a cost effective means of installation. Given that the number of boreholes is sufficient, maximizing the cooling load would lead to a minimal increase in costs while also causing the cost per foot to decrease by a reasonable amount. Though a high penetration rate is still preferred, the savings received from having a high penetration rate is minimal when a large enough

amount of boreholes are preferred. Due to this, cheaper drill rigs that produce slow penetration rates can be chosen over more expensive rigs. This is due to the fact that these cheaper rigs can allow for greater savings due to reduced equipment costs and that high penetration rates only result in minimal savings. These expensive rigs can still be used, though it is suggested that the lifespan of these rigs be maximized to allow for the equipment costs be minimized. Using a heat exchanger design similar to the heat basket can potentially be useful, though the heat basket diameter should be minimized to further reduce costs.

VII. c Emerging Technologies

Currently, there are a variety of technologies being researched that have the potential to be integrated with the installation process. As drilling has a greater impact on installation costs as compared to other variables contributing to the overall cost of installation, there are numerous means of drilling currently undergoing research to determine their effectiveness in creating boreholes. Though there are several drilling methods that can be beneficial in the creation of these boreholes, many other methods have certain aspects that make them unattractive. The cause for many of these drilling rigs being undesirable can be due to a variety of factors, with more common issues being slow penetration rates, unsafe working conditions, and inefficiencies while drilling. Allocating more resources in the novel drilling rigs that possess the potential to greatly reduce drilling time can aid in lowering costs associated with installation. The industry that is doing just this is the oil and gas industry. One type of drilling that is currently being tested for this industry is the laser mechanical drilling rig due to their increased penetration rates in very hard rocks. Though this type of drilling may be beneficial when drilling in hard rock for the oil and gas industry, the main issues to tackle when using this rig for the purposes of installing ground source heat exchangers are the cost of the rig and nitrogen. As this type of drill rig is still new, the cost of the drill rig would still be high, especially due to the lasers attached to the drill bit. Along with this, the high flow rate of nitrogen that was maintained during the testing of this rig lead to higher than desired costs. If the cost of the laser mechanical drill rig can be reduced to become more competitive while also minimizing the

nitrogen requirements of this drill rig, it would allow for it to become more feasible when installing ground source heat exchangers. For the time being, however, laser mechanical drill rigs are unattractive for installing ground source heat exchangers.

Though laser mechanical drill rigs may currently be unattractive, a possible solution to this is the potential of using multiple lasers to drill the needed boreholes. Though no real testing has been conducted to show the real world potential of using a multi-laser configuration to create boreholes large enough to install heat exchangers, the researched literature have shown how useful a single laser can be while drilling. As a single laser can produce penetration rates up to 10 times that of more conventional drill rigs. If this can be maintained when using a larger configuration of lasers, it would allow for great cost savings, especially in hard rock. Despite this great potential, using a configuration of lasers to create boreholes possess similar disadvantages when compared to the laser mechanical drill rig, the first of which being the cost of the lasers. At \$50/watt, using a configuration that consists of multiple lasers, with the lasers researched possessing power outputs of 1.6 kW, the cost of adding a laser to a given configuration can quickly rise. Along with this, the borehole diameter created by a single laser is small, with a diameter of about 0.5 inches. Due to this, it is important to determine the minimum diameter required to install the ground source heat exchangers so that the number of lasers required can also be minimized. Along with this, the flow rate can also harm the cost benefits that can arise from using lasers. If this flow rate can be lowered without sacrificing penetration rate, it would greatly aid in lowering costs. Given that the penetration rate is high enough, however, the savings that would be received from doing this would be minimal. Overall, more testing needs to be conducted to show the potential of laser drilling, with laser costs and nitrogen flow rate needing to be minimized to allow for laser drilling to become more feasible. If this can be done, laser drilling can become a competitive means of drilling, especially in hard rocks.

Though laser drilling was primarily focused upon in terms of emerging drill rigs, other novel drill rigs do exist that can be used to greatly increase penetration rates if perfected upon. This can be seen with erosion drills, where high pressure water jets are used to create boreholes. As shown in ref [30], the penetration

rates provided by this drill are high, especially in hard rocks. Even if they are not desired to be used by themselves, they can be combined with more conventional drill rigs to aid in drilling. Though this is a promising means of drilling, it does suffer from problems that need to be overcome before it can become more widespread, which are further detailed in ref [11]. If more work can be accomplished to make erosion drilling realistic, it would allow for greater cost savings, especially in hard rock. Another type of drill rig that is starting to receive more attention is coil tubing drill rigs. As coil tubing drill rigs can allow for continuous drilling without the need to pull the entire drill stem out, it would allow for greatly reduced drilling times. This would, in turn, allow for installation costs to be significantly lowered, especially if deep boreholes are drilled. The main issue with coil tubing drilling is that using this drill rig is expensive. If the cost of the coil tubing drill rig, or more specifically, the cost of the downhole motor can be reduced, it would allow for this means of drilling to become more realistic. Combining the coil tubing drill rig with other means of drilling, such as laser drilling, can potentially aid in this endeavor as it would reduce the amount of surface equipment required while drilling. If the cost of using coil tubing drill rigs can be reduced enough, it would have the potential to become just as good, if not better, as more conventional drill rigs.

VIII. Summary

Though GSHPs have the ability to become a popular means of heating and cooling, the installation costs of the GSHPs largely prevent this from happening. To overcome this obstacle, there are several options that would allow for reduced installation costs. The first of these options is by maximizing the borehole length while simultaneously minimizing the number of boreholes, which would help in reducing the cost of installation. Along with this, it would be greatly beneficial if cooling load and borehole diameter were also minimized, as doing so would aid in lowering installation costs as well. As to the size of these boreholes, it is greatly beneficial if a drill rig with high penetration rates were utilized, such as rotary drill rigs. When it comes to the heat exchanger design, it would be beneficial to utilize designs similar to the geotext or twister designs as the aim is to reduce the cooling load by as much as possible. If this option was to be implemented, it would allow for the ground source heat exchangers to be installed in size restricted areas with the overall cost being greatly reduced. This allows individuals living in residential areas or similarly constricted areas to install heat exchangers at more reasonable costs. The second option considers if multiple installation projects are to be combined into a single project, as creating a large borefield was shown to be a cost effective means of installing heat exchangers. When these projects are combined, it is important to maximize the number of boreholes while also minimizing the length of these boreholes and diameter. The cooling load should also be maximized, increasing the borehole length in the process, to minimize the cost per foot. Though high penetration rates are still preferred, the savings that can be achieved from having such a penetration rate can be obtained by using a cheaper, slower drill rig. This is primarily due to equipment costs having a larger impact on installation costs than the penetration rate. For heat exchanger designs, the previously mentioned designs can still be used, with one additional design that can be used for these short boreholes being heat baskets. Though the installation costs for this option would be higher when compared to the first option, the advantages that would arise from choosing this option would be the low cost per foot. Given that a large enough area was provided, this would potentially allow for a more cost effective means of drilling as individuals would have to pay less per foot

when compared to option one. Though option one may be desirable on a per person basis, this option would be more cost effective when installing heat exchangers for multiple people, such as for multiple residential homes. Despite which option is chosen, drilling is still an important part of the installation process. Due to this, several means of drilling are being developed in the hopes of creating a more cost effective means of drilling, with some showing more promise than others. Though testing still needs to be conducted to further show their potential, initial cost estimates show that lasers possess the potential to become a cost effective means of drilling. If the overall cost of the lasers along with the nitrogen flow rate can be reduced, it would allow for these lasers to become more realistic when used to install ground source heat exchangers. Though not analyzed, other means of drilling that show promise are erosion and coil tubing drill rigs. If the problems associated with these drill rigs can be addressed, they would possess the ability to greatly lower installation costs. Given that these drill rigs were not analyzed as heavily as the laser drilling, a more accurate cost analysis should be conducted to understand how much these rigs can save. In addition to this, more research should be conducted on other possible means of drilling that possess the ability to greatly decrease costs. More importantly, it would be more beneficial if the cost model used in this paper can be further improved upon to account for the several assumptions made during its use, such as the means in which the drilling time was determined. Despite the limitations of the cost model, the data that was calculated from it can still allow for the needed insight on how to best lower costs. If the above guideline is to be followed, a reduction in installation costs should be more easily achieved.

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Appendices

Appendix I – Conventional Drilling Rig Descriptions

During the installation of GSHEs, drilling rigs are utilized to create the boreholes which will house the heat exchangers. As there are many types of geologies that have to be considered during the creation of these boreholes, there are a variety of drilling rigs that can be chosen to best tackle the geology in which the borehole is created in. Though there are many different types of drilling rigs being used worldwide, only a handful of drilling rigs are in common use to install GSHEs, as many of these drilling rigs are currently being used to drill for oil, geothermal purposes, mining, etc. and have not been miniaturized or are newly created and have not been widely used. Common drilling rigs used to install GSHE as of the writing of this report are as follows: auger, cable tool, DTH hammer, air and mud rotary, and sonic drilling rigs. As each of these drilling rigs differ from one another, whether it be the type of geology each are able to operate in or the cost of the rig, it is important to understand the differences between each rig so that each rig can be used as effectively as possible. As such, the descriptions of each drilling rig will be provided below.

I. a Cable Tool Drilling Rig

[6] As one of the earliest drilling methods still in use today, cable tool drilling rigs are one of the most simplistic means of drilling. As demonstrated by figure 31, cable tools operate by raising and dropping a drill string multiple times to create fragments in the ground, allowing for a borehole to form. The drill string is important as it is comprised of several necessary components needed to properly drill the borehole. One of these components is the drilling cable, which allows for the manipulation of motion of the remaining tools that make up the drill string, such as lifting and rotating the drill string. The next component is the swivel socket, which connects the drill string to the cable. Another component of the drill string is the drill stem. The drill stem aids in the drilling process by providing additional weight to the drill bit along with steadying the drill bit so that a straight borehole can be achieved. The final component, the drill bit, is the actual part of the drilling rig that makes contact with the ground. For the

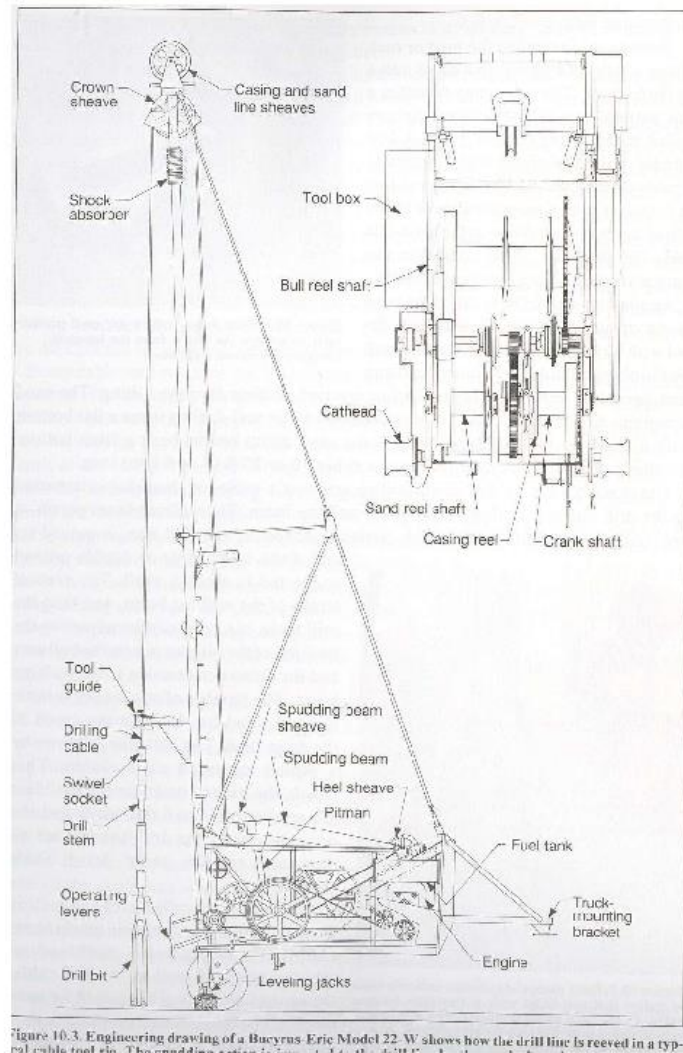


Figure 31. Cable Tool Drilling Rig [6]

cable tool drill bit, it is typically large and heavy to allow for the rocks encountered while drilling to be crushed. Since cable tools often utilize water or other types of fluid while drilling to aid in drilling, a tool called a bailer is used to remove mud and rock slurries. There are different varieties of bailers depending on how the mud and slurries mix, with the bailer being placed into the borehole to remove the mixtures after the removal of the drill string. Since cable tools are simplistic in their use, only one person is typically needed to operate it. It is important though, when the cable tool is used, that the drilling motion of the cable tool is synchronized with the freefall of the drill string to achieve the best penetration possible for the cable tool. When using cable tool drilling rigs to create a given borehole, the process in which it is done depends on the surrounding geology. If the surrounding geology is hard rock, then no casing is needed and the cable tool acts as a crusher. If the geology is something else in which the cable tool cannot simply crush, like soil, then casing is needed during the drilling process. When casing is utilized, a drive shoe and head is added to the casing to prevent damage to the bottom and top of the casing, respectively. A drive clamp is also added to the drill string, allowing it to act as the hammer face when driving the casing into the ground. After the casing is driven into the surrounding geology, water or whatever fluid is to be used is then added to the borehole. This mixture is then removed from the borehole through the use of a bailer.

I. b Rotary Drilling Rig

[4][6] Currently, rotary drilling rigs are one of the most popular drilling rigs in use today, with the typical rotary drill rig being pictured in figure 32. Similar to the cable tool drilling rig, the same techniques utilized in rotary drilling rigs have also been around for millennia. Their widespread usage is due to drilling rig's effectiveness during its operation. Rotary drilling rigs operate by rotating a sharp drill bit to cut into the surrounding formation. This means of drilling is effective as it allows for the penetration of a wide variety of formations, even hard rock. As such, it can be used in various locations. In order to properly operate a rotary drilling rig, four separate components are typically needed: prime movers,

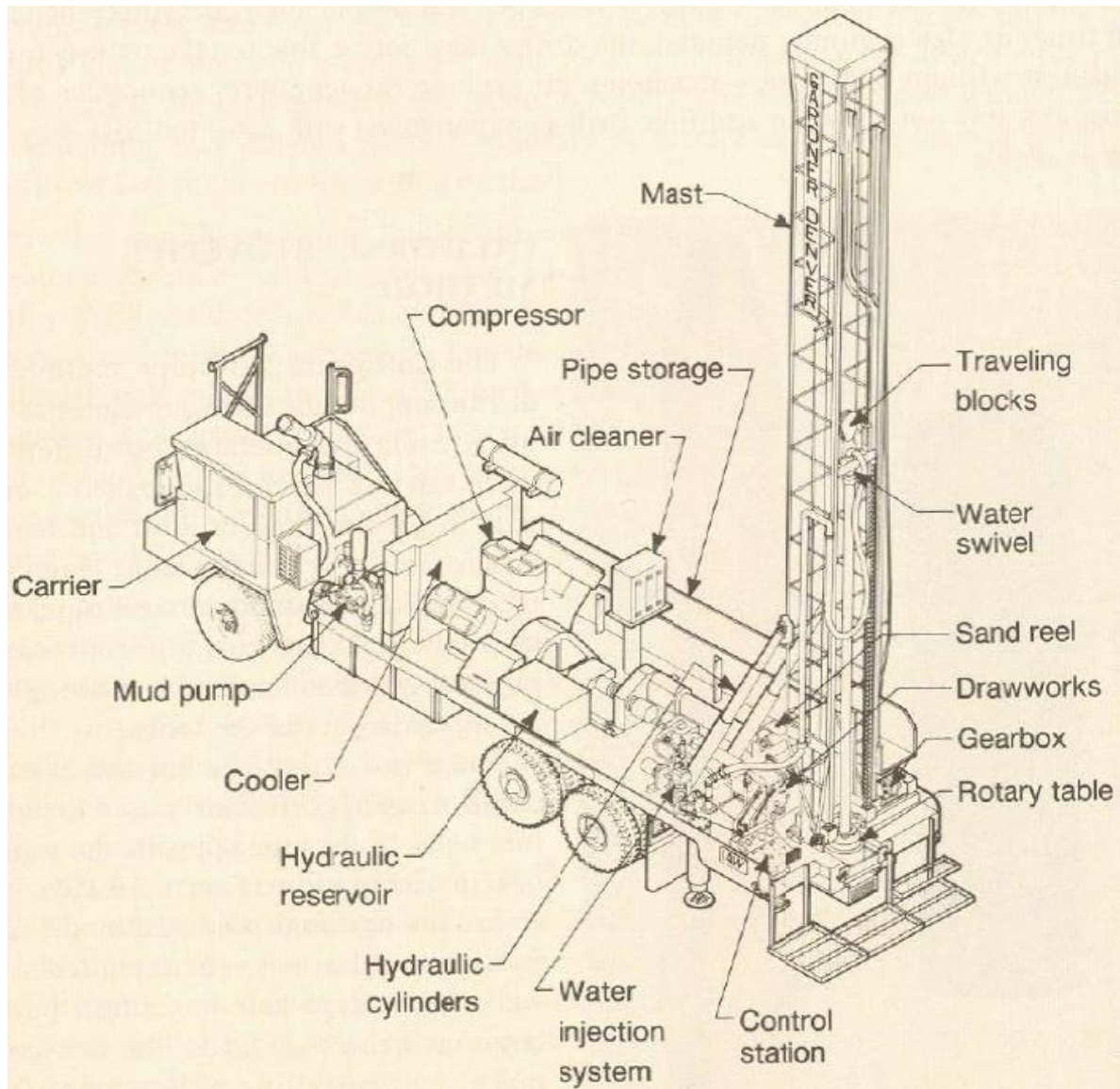


Figure 32. Rotary Drilling Rig [6]

hoisting equipment, rotating equipment, and circulating equipment. Prime movers are necessary for rotary drilling rigs as the movers are composed of multiple pieces of equipment which provide the needed power for the drilling rig. The most common type of engine in use today in modern rotary drilling rigs are diesel engines, with other types of engines including oil and natural gas. The energy provided by the prime movers are then used to power the other pieces of equipment that compose the drilling rig and, if the prime mover provides enough energy, can power any other equipment that is not directly associated with the drilling rig. The hoisting equipment comprises the different equipment needed to move the needed equipment in and out of the borehole created by the drilling rig, such as the derrick, cables, and pulleys. The hoisting equipment allows for the entire drill string to be lowered into the borehole to drill or to be removed to either add additional sections to the drill string or replace a part of the drill string, such as the drill bit. When it comes to using the rotating the drill bit to drill, the multiple components that comprise the rotating equipment are utilized. One of these components, the rotary, allows for the rotation of the drill pipe by using the power generated by the prime mover. Another of these components that make up the rotating equipment is the swivel. Being attached to the hoisting equipment, it carries the entirety of the drill string while simultaneously allowing the rotary to rotate the string. Being attached to the end of the drill string, the rotary drill bits are designed to take advantage of this rotation, with four main types of drill bits to match the surrounding formations (drag bits, steel tooth rotary bits, polycrystalline diamond compact bit, diamond bits). The last piece of equipment needed for a rotary drilling rig is the circulating system. This circulating system aids in lubricating the drill bit and removing the cuttings created by the drill bit. In order to accomplish this, the circulating system circulates drilling fluid throughout the borehole as the drilling rig is utilized. An added benefit of circulating the drilling fluid is the coating of the borehole in mud along with cooling the drill bit while drilling. To allow for the drilling fluid to circulate throughout the borehole, the two main components of the circulating system to manage the circulation of the fluid were the drilling fluid pumps and compressors.

As can be assumed from the equipment involved with the rotary drilling rig, drilling occurs through the rotation of the drill bit, allowing for the creation of cuttings. Pressure is also needed to aid in the drilling process, with the ideal amount of pressure usually required by the drill rig being dependent on a given formation. As the rotation of the drill bit is important for the rotary drilling rig, there are several common means in which the rotation of the rotary is transmitted to the drill string, whether it be passing a kelly bar through a rotating table and attaching it to the drill string or directly attaching a hydraulic unit to the top of the drill string. When feeding the drill string into the borehole, the force generated to do so is created by the weight by the drill string, along with the weight of the equipment attached to the string. Upon reaching certain depths, the drill string is brought back to the surface to add predetermined lengths of drill pipe to the string, allowing for the rig to drill even deeper holes. When becoming long enough, the drill string's weight is great enough to create the force needed to drill the borehole. When beginning a new borehole, though, the required force to drive the drill bit into the ground is generated by the drill rig. This method of providing the needed force to drive the drill bit also allows the driver of the rig to control the penetration rate, as higher forces generated by the rig can potentially create higher penetration rates, though this can be harmful to the rig itself if used incorrectly in the wrong formations.

As stated before, drilling fluid is used to remove the cuttings produced by the rotary drilling rig, though the fluids used and the means in which the fluid is circulated through the borehole vary depending on the drilling rig used. The first type of fluid circulation that is typically used is the direct circulation mud rotary. Before the circulation of the drilling fluid, the drilling fluid ingredients are stored inside a mud pit before being mixed. This means of circulation then has the drilling fluid pumped down through the drill string and then up through the annular space between the drill string and the borehole, bringing the cuttings up with the fluid. Upon reaching the surface, the drilling fluid is directed to either a settling pit or a tank to allow for the cuttings to settle to the surface, allowing for the drilling fluid to be reused. The next means of circulation is the reverse mud circulation, which is identical to the previous method of circulation except that the drilling fluid is pumped down the annular space between the borehole and drill

string and brought back up through the drill bit. The next method of circulation is the direct air rotary. This method operates through the use of a large compressor which generates the air that is forced down the drill string, out the bottom of the drill bit, and back up the borehole, carrying the cuttings along with the air, similar to the direct mud circulation. The cuttings are then collected upon reaching the surface of the borehole. Since the viscosity of the air is less than that of water, the air velocity has to be much greater in order to achieve the same effect as water. To aid in this endeavor, additives are typically added to the air, creating a foam that has a higher viscosity when compared to the air. This allows for cuttings to be lifted to the surface more easily than what it would otherwise while also reducing the air requirement of the drilling rig. The final method of circulation is the reverse air drilling. When enough water is provided, air is used to create a partial vacuum inside a tremie pipe which is inserted inside the drill pipe to aid in drawing up the cuttings created up through the drill string as the water is pumped down the sides of the borehole and drill string. Similar to how segments of drill pipe are added upon reaching a certain depth, tremie pipes are also added at these same depths.

I. c Down the Hole Hammer Drilling Rig

[2][6] When operating a DTH hammer drilling rig (also known as a rotary percussive drilling rig), it is used similarly to a jack hammer. As the DTH hammer is lowered into the borehole, the hammer, powered by an air compressed piston, is used to crush the rock below it. Combined with the rotation of the drill string to aid in the hammer cleanly penetrating the surrounding formation, this method of drilling is efficient when drilling in rock and other hard formations. The drill bit of the hammer is typically made of alloy steel with carbide to act as a cutting surface, with two main concerns over the drill bit being the wear of the carbide and corrosion of the drill bit itself. If the drill bit is properly taken care of, though, the drill bits used for the hammer tend to last.

I. d Auger Drilling Rig

[1-2][4][6] With two main types of augers, the general method in which augers operate is somewhat similar manner to that of rotary drilling rig, where the drill string needs to be rotated along with requiring a downward force to allow it to drill in order to work properly. The difference, though, is in the drill bit. The drill bit is similar in design to a helical screw, which can be viewed in figure 33. This allows it to have fast penetration rates into the surrounding formation, assuming if the auger is used in suitable formations like unconsolidated formations and weak rocks, as the drill bit is rotated. Unlike the rotary drilling rig, drilling fluid are either not needed or used in small quantities when augers are used. This is primarily due to the two main types of augers, continuous flight and bucket augers, that are in use to remove the cuttings produced by the drilling rig. Continuous flight augers remove the cuttings by using helical flights, with a rotary being used to rotate these helical flights to bring the cuttings to the surface.



Figure 33. Auger Drilling Rig [6]

Continuous flight augers can be further broken down to two different types of continuous flight augers: hollow stem and solid stem augers. The key difference between the hollow and solid stem augers is that

the hollow stem has an opening along the string of the auger to allow for easy access to the bottom of the borehole, allowing for sampling of the formation when needed. Hollow stem augers, though, are typically larger than the solid stem augers. Bucket augers, as the name implies, removes cuttings through the use of a bucket, with this type of auger typically being used for large diameter boreholes. The main downside of this type of auger is that the bucket has to be lifted out of the borehole in order to remove the cuttings, meaning that drilling has to be stopped while the cuttings are removed. Overall, auger drilling rigs are limited to certain formations, but when they are used in the correct formations, they tend to be one of the more efficient drilling rigs.

I. e Direct Push Drilling Rig

[1] Typically being small in size, direct push drilling rigs operate by driving a rod into the ground through the use of a hammer or the weight of the rig itself. This means of drilling allows for high penetration rates with the added benefit of requiring no drilling fluid. The rods used to drill the borehole tend to have small diameters though, meaning that the boreholes also have small diameters when the direct push drilling rig is used. One of the limitations of using direct push drilling rigs is that they are designed to operate in unconsolidated formations, meaning that this method of drilling is not effective in rock and other formations. Though direct push drilling rigs are limited to the formations in which they can drill in, their small size allows them to be easily mounted to different vehicles with the small size also aiding in accessing sites that many other drilling rigs cannot reach.

I. f Sonic Drilling Rig

[1][21] Sonic drilling rigs operate by applying a vibratory energy, which is produced by oscillations, to the top of the drill string, allowing for the drill bit to deliver multiple blow every second to the surround formation. The oscillations needed for the drilling are created inside the drill head, where motors cause off-center rollers to follow a predetermined circular path, also known as a roller orbit. These rollers create

greater oscillations due to the higher and higher centrifugal forces caused by the increasing speed of the rollers as they move along their orbits. In order to achieve the best effect when using this method, the rollers' movements are synchronized with the rollers counter-rotating as they move along their orbits. The sonic head can allow frequencies on the upward of 150 cycles per second, allowing for the drilling rig to drill through a wide variety of formations, whether it be unconsolidated formations or even rock. These frequencies also allow for high penetration rates when drilling through the surrounding formations, often times higher when compared to other drilling rigs. Along with the high penetration rates, sonic drilling rigs also have the additional benefits of not requiring drilling fluid. When operating the drilling rig, it only requires a minimum of two individuals in order to run it due to the rig being easy to operate and the added benefit of being easy to move when moving the drilling rig. Overall, sonic drilling rigs allow for a more cost-effective means of drilling.

Appendix II - Drill Rig Survey Comments

- Boreholes 300' or less are the most cost effective depth. The cost increases over these depths
- This survey is not going to identify the major cost associated with drilling that could reduce ground loop installation. The drilling rigs are very expensive, access to job sites and landscape is expensive. All of the little things add up.
- Perhaps CT wasn't a good choice for your survey. We have a verity of bedrock and glacial till containing large boulders. In addition to that, our bedrock contains large sources of water that further complicate the drill process and we have a moral obligation to protect ground water. In ct, we mud rotor to bedrock, hammer to 500 ft. Its the only way, no other drills work in CT.
- We drill in several states, so we encounter various soil types, such as: gravel, sands, clay, & shale. I hope this helps. Thanks!!

Appendix III – Drill Rig Specification Responses

Table 19. Drill Rig Manufacturer and Model

Drill Rig	Manufacturer	Model
Mud Rotary	Versa Drill, Reichdrill, Reich, IR, Schramm, Ardco, Speedstar, Gefco, Deeprock	V-100, 690, T650, T2W, 1000, SS 135, 1250, DR 120
Air Rotary	Reichdrill, DrillMax, Speedstar, Badger, Reed, Reich, Davey, Ingersoll Rand	690, 400, SS 135, 1250, SK35, T650, DK30, T4BH
Mud & Air Rotary	Ingersoll Rand, Atlas Copco, Gardner Denver, Midway, Badger	T3W, T3W, 1500, 1000, 1250
DTH Hammer	AtlasCopco, Schramm, Ardco, Ingersoll Rand, Reich	NA, T450, 1000, T3, T650DII

Vita

Josh McDonald was born in Knoxville, Tennessee on June 11, 1994. He graduated from Central High School in Knoxville, Tennessee in 2013. After obtaining his Bachelor's Degree in Aerospace Engineering in 2016, Josh continued his education by pursuing his Master's Degree in Aerospace Engineering. During his time as a graduate student at the University of Tennessee, he accepted a graduate research assistantship at the Oak Ridge National Laboratory to aid in determining how to best reduce the cost of installation for ground source heat exchangers. Upon graduating with his Master's Degree in 2018, Josh will further pursue his interests related to supersonic vehicles and gas dynamics.