

WPI

Modular Geothermal Heat Pumps

A Major Qualifying Project Report Submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the of Bachelor of Science by:

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1: ABSTRACT

The goal of this Major Qualifying Project (MQP) was to design a modular geothermal heat pump system. Existing geothermal heat pumps require specialized equipment for installation, and it is not feasible to conduct maintenance on the ground portion of the system once it is installed. Modularizing this technology would decrease installation cost and increase system life expectancy, as maintenance would be possible. The modularity of the system would also allow for additional modules to be installed as the heating load of the building changes. We created an analytical model of the thermodynamic heat cycle that occurs within a geothermal heat pump using desired heat output rate as a requirement of the system. Our model produces a recommended tube length for a given heat output rate and is highly customizable to meet design requirements of a variety of situations. In addition to this model, our project provides recommendations for further analytical model development as well as prototype design.

2: INTRODUCTION

With the rapid expansion of development in nations across the globe, the dependence on fossil fuels proves concerning as these finite resources are continuously depleted. Energy consumption plays a key role in economic development for all nations and the sheer demand for energy has caused price uncertainty across the world. Energy is required for improving the quality of life in every country, as well as increasing social and economic development. The way that this energy is being produced currently, however, is not sustainable (Omer Ozyurt, 2011). The repercussions of exceedingly increasing energy demands are materializing in industrialized nations worldwide.

According to World Energy Council, the spike in demand for energy caused 25% more greenhouse gas emissions to be emitted into the atmosphere since 1990 (WEC, 2008). These gas emissions directly put biodiversity, water and air quality at risk. In the United States, 82% percent of energy consumed each year is sourced from fossil fuels (EIA- Greenhouse Gases, 2016); these fossil fuels contribute to 94% of the total CO₂ emissions, the leading source of pollution in the atmosphere. (EIA- Greenhouse Gases, 2016). The CO₂ that is released from fossil fuel consumption is a harmful greenhouse gas that has detrimental effects on the environment if permitted to build up in the atmosphere. (Samimi, & Zarinabade, 2012)

These emissions of greenhouse gasses like CO₂ have been increasing since the industrial revolution in the mid 19th century. With the increase in carbon in the atmosphere, the natural cycles like photosynthesis, that naturally neutralize these CO₂ emissions, are unable to successfully process the high quantity of excess carbon. This leads to higher concentrations of carbon that causes harmful environmental effects (EIA-Geothermal, 2016). With the continued pattern of increased

energy consumption, the amount of fossil fuels consumed and contributing to pollution, will increase as well.

Productive actions to mitigate the production of greenhouse gasses, utilize developments in alternative and renewable energy sources as replacements to energy derived from fossil fuels. Fossil fuel shortages are predicted unless drastic action is taken to supplement the energy supply (V.S. Ediger 2007). These concerns have motivated research and the use of alternative sources of energy which have minimal to no greenhouse gas emission or negative effect on the environment (G.P. Hammond 2000). Among these alternative sources are some well-known solutions, for example, wind power and solar power for electricity generation, and even solar-thermal for hot water and heating. A less-known alternative energy solution for residential and commercial applications is producing energy from harnessing sub-surface geothermal temperatures.

Geothermal energy systems are a promising alternative to conventional fossil fuel systems. In the case of geothermal energy, the installed system can provide a residential or commercial space with efficient, cost effective heating or cooling with low emissions (K.J. Chua, 2010). The earth's resources are abundant and heat energy that is stored just below the earth's crust provides untapped potential for energy conversion with limited ground disturbance (Office of Energy Efficiency, 2004) (R.Wu, 2009). Geothermal energy can be used in a wide range of applications from electricity, to direct heating, to indirect heating and cooling (Stuart Self, 2013). For our project we will be focusing on geothermal in indirect heating and cooling applications for residential settings. Indirect heating and cooling systems gather energy from low temperature geothermal resources. Low temperature resources are of interest because it is the most accessible around the world. In addition, the minimal area and depth that it needs to extract the heat energy (R.Wu, 2009) (Stuart Self, 2013).

These systems operate by using the low temperature from the ground and raising it through a series of compressors and pumps to the desired temperature for heating or cooling uses.

For indirect ground source heating and cooling systems, there are two main types of set ups: horizontal and vertical loop systems. Each of these approaches has drawbacks, which motivate our research for an alternative geothermal system. The vertical loop system often ranges from 45 to 75 meters deep for residential cases and exceeds 150 meters deep for commercial applications (Stuart Self, 2013). This depth is not practical for easy installation or maintenance on the system, leading us to try to minimize this depth to efficiently be able to capture the heat and have the installation depth as shallow as possible. The other typical type of geothermal system arrangement is the horizontal loop. This setup can look differently depending on space available in the location, but typically, these systems are shallow in the ground, and very vast in surface area (A.M. Omer, 2008) (Stuart Self, 2013). We saw potential to improve on this system as well in the sense that the expansive surface area could be minimized which would dispel space limitations of where these systems could be located. Our design encompasses these spacing optimizations as well as potential improvements to maintenance the systems and add additional adjacent systems to increase the energy production if needed.

3: LITERATURE REVIEW

A. GROUND SOURCE HEAT PUMP OVERVIEW

Currently, some geothermal heat pump systems consist of pipes placed between 300-900 feet below ground. These pipes contain a heat transfer fluid and are designed in either closed-loop or open-loop configurations (Massachusetts Department of Energy Resources, 2015). In the winter, the fluid absorbs the underground heat, as the temperature profile under the surface of the Earth is a relatively consistent 50°F (Massachusetts Department of Energy Resources, 2015). The fluid that stores the absorbed energy is then compressed through a series of pumps using electricity to provide heat at a temperature suitable for space heating and a hot water source. Figure 1 is a conceptual representation of how the existing geothermal heat pump system operates with reference to the ground and, together with Figure 2, illustrates how the different components within the system work together to provide useable space heating and hot water to the building.

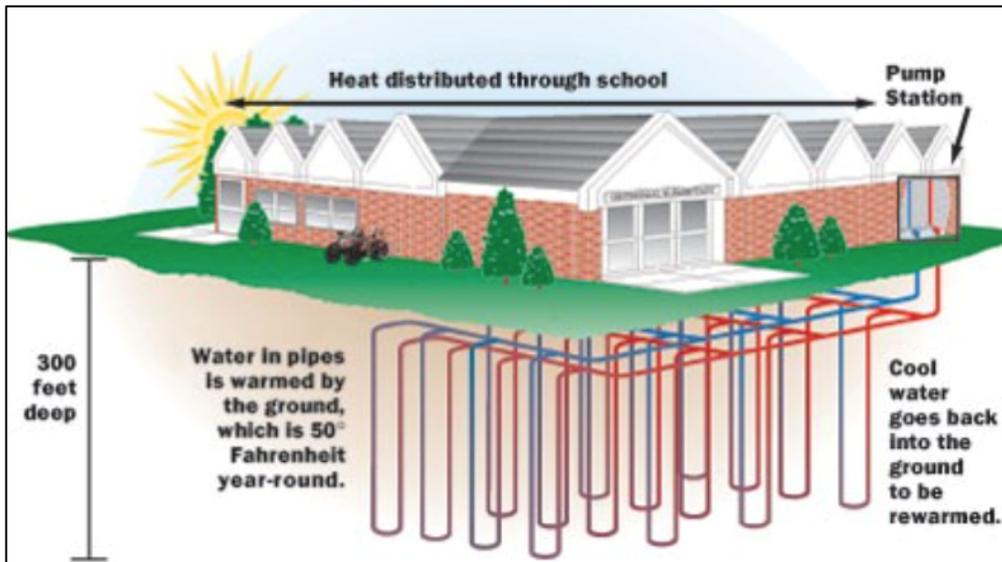


Figure 1: Geothermal Loop System (Massachusetts DOER, 2015)

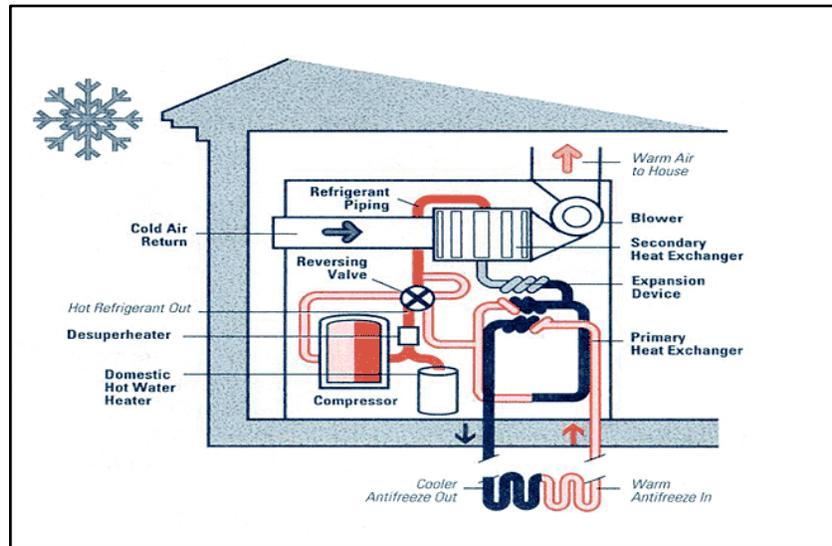


Figure 2: Residential Geothermal Heat Pump Diagram (Massachusetts DOER, 2015)

As illustrated in Figures 3 and 4 below, the heating process explained above can be reversed to provide cooling in the summer. Heat is extracted from within the building and is transferred back to the earth through the working fluid within the pipes (Massachusetts Department of Energy Resources, 2015). During the summer months, the residual heat energy can still be used to provide hot water for little to no additional cost (Massachusetts Department of Energy Resources, 2015). These features increase ground source heat pump (GSHP) marketability as an “all in one” residential temperature control solution.

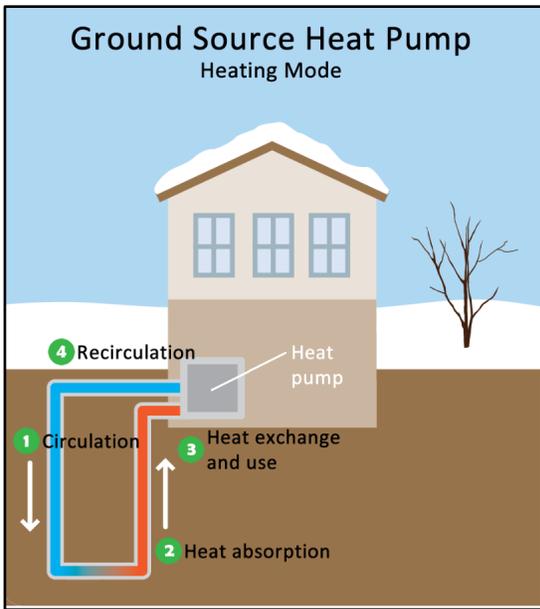


Figure 3: GSHP in Heat Mode (Mass. DOER, 2015)

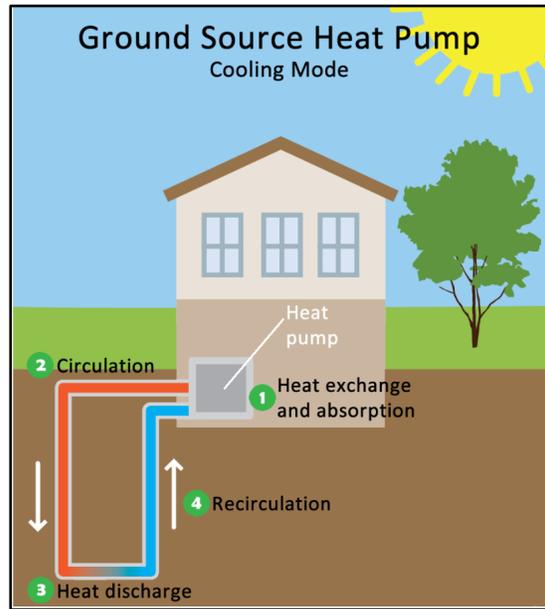


Figure 4: GSHP in Cooling Mode (Mass. DOER, 2015)

Existing geothermal heat pump technology is marketed as a fossil fuel alternative for heating and cooling. As found through the Massachusetts Department of Energy Resources, (Massachusetts DOER), Geothermal heat pumps are 3.5 - 5 times as efficient as the most efficient fossil fuel furnace. Instead of burning a combustible fuel to make heat, they simply transport heat that already exists. By doing so, they provide 3.5 - 5 units of energy for every unit used to power the heat-pump system (Massachusetts DOER, 2015). The systems also have a large lifespan, with a secondary component lifespan of approximately 25 years and an underground component lifespan of more than 50 years (Massachusetts DOER, 2015).

B. GROUND MODELING FOR USE WITH GROUND SOURCE HEAT PUMPS

Existing ground source heat pumps are used as a mechanism to heat homes in an efficient and reliable way. In order to understand the fundamentals of the heat exchange between different materials and the earth (soil), ground modeling must occur. The potential in geothermal technology relies on the energy stored in the ground - below where solar radiation or seasonal temperature changes can have an effect. At these depths, with undisturbed ground temperature, the exact

temperature is dependent on the surface climate parameters as well as the thermogeologic ground properties (Kurevija, 2012). Below the depth where solar radiation no longer has an effect, the ground temperature change becomes as low as 0.1 °C. This is extremely important to the analysis of geothermal temperature gradients because if the bore holes for the ground loop are in an area that has large temperature variation, the conditions will not produce reliable data. As seen in Figure 5 below, the variance in ground temperature is dependent on depth and at a certain depth is independent of seasonal effects. (Kurevija, 2012)

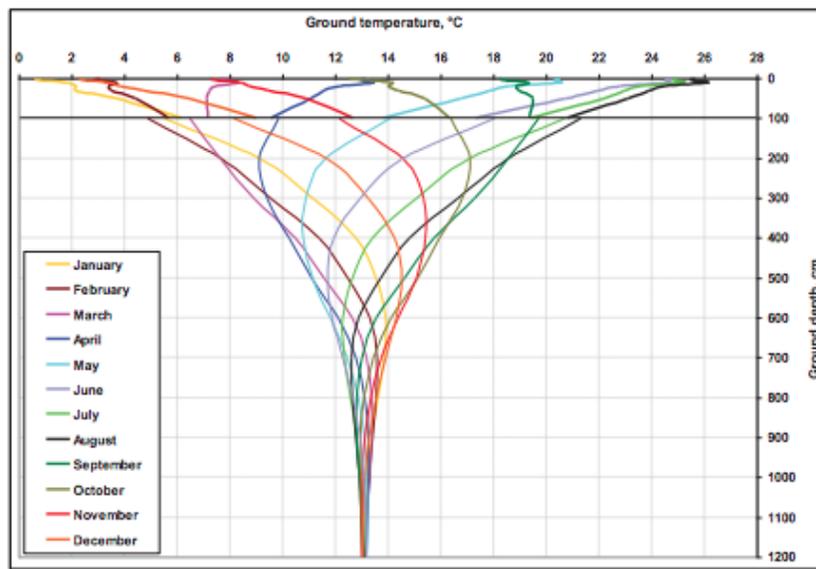


Figure 5: Zagreb Metro Station Ground Temperatures (Kurevija, 2012)

With limited industry ground temperature data available for New England, we chose to utilize data from Ottawa, Canada as a benchmark. As found in S.J. Self’s article, “Geothermal heat pump systems: Status review and comparison with other heating options”, Figure 6 below shows how the ground temperature varies with an increase in depth below the surface. As illustrated in the figure below, the ground temperature range narrows with an increase in depth below the surface, and the data asymptotes around 10 °C (Self, 2013).

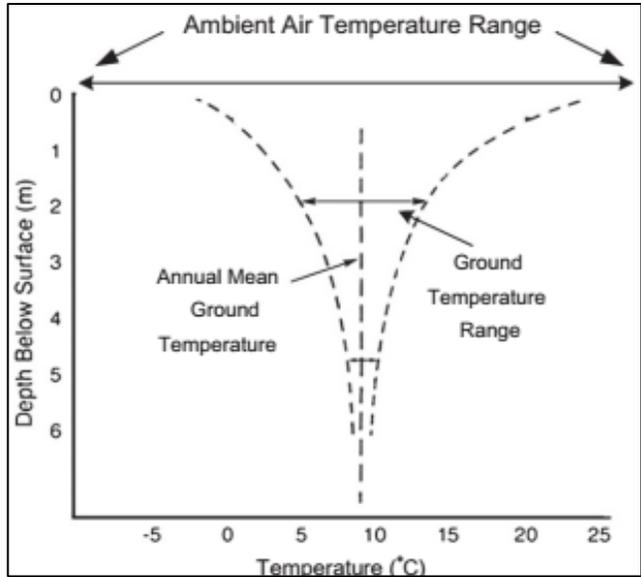


Figure 6: Temperature Range vs Depth Below Ground Surface (Self, 2013)

Additionally, the article provides data regarding ground temperature and its variation throughout the seasons. As seen in Figure 7 below, the ground surface experiences large temperature variations throughout the year. At greater depths, this variation is dampened, and at around 5.0 meters below the surface, the ground temperature variation is minimal. This data is also confirmed below by Kurevija.

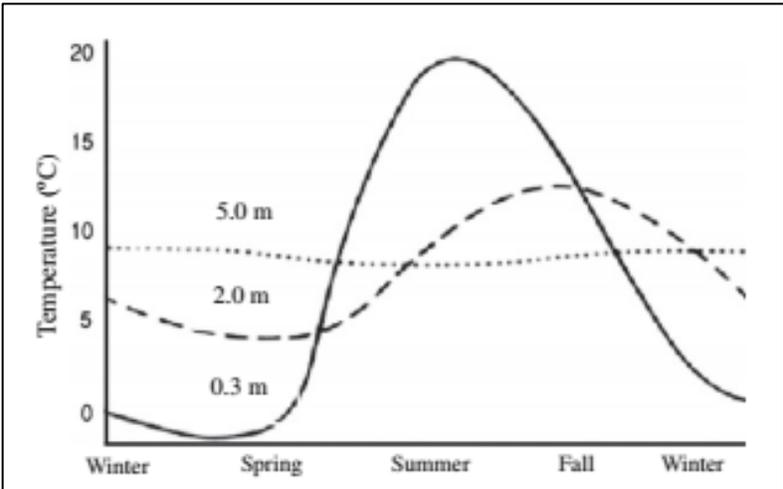


Figure 7: Annual Ground Temperature Range for Varying Ground Depths in Ottawa, Canada (Self, 2013)

Since the ground can be treated as a semi-infinite body, the presence of a geothermal heat pump should not change this ground temperature gradient in this instance, except in the immediate proximity of the loop.

C. GEOTHERMAL HEAT PUMP SYSTEM SIZING

I. System Power Output Required

As mentioned above, geothermal heat pumps operate by utilizing the temperature difference between the ground and the environment. A heat transfer fluid is used within the system in order to achieve optimal results. During the intermediary seasons like fall and spring, the system may not need to be used or is not needed at full power. This seasonal difference in usage illustrates that there is a variance in energy usage throughout the year. In a case study on a 2300 square foot home in the Northeast United States, the peak energy draw took place in the month of January/February, with an 11-year max draw average of 952 KWH/month. The 11-year minimum draw average was ~100 KWH/Month and the year end monthly averaged turned out to be a power draw of about 450 KWH/month over the 11-year span (Heck, 2015). This fluctuation in power requirements provides the challenge of accurately sizing the system to the specific requirements of the house or building it is heating and cooling.

In order to properly size our new design of a geothermal heat exchanger, we need to know how much power is required on average in a standard geothermal heat pump. One piece of data we found in our research was continuous data pulled from the operation of a geothermal heat pump system over the course of 11 years. Based on this case study taken from a sets of data collected monthly over a period of 11 years, we can derive an average amount of electricity used by the geothermal pump exclusively. This data was taken from a household of approximately 2,350 square feet, which will be useful in applying to our knowledge of the average sized house and what it

requires for heating and cooling power (Heck, 2015). With this average data per month, we are also able to see the percentage of total household electricity consumption that the geothermal pump used. An example of this data is shown below.

Geothermal Energy Usage 14-15										
Date	Total Electric Usage	Geothermal Usage	%	Charge/kwh	Avg. Geo Usage/ Day	Geothermal Cost	Avg. Geothermal Cost/ Day	Avg. Temp	Temp Range	Heating/Cooling Degree Days
11/14	1,527 kwh	534 kwh	35%	12.1¢	17.23 kwh	\$64.64	\$2.09	42°	21°-71°	625
12/14	2,050 kwh	827 kwh	40%	11.7¢	25.06kwh	\$96.37	\$2.92	39°	19°-67°	798
1/15	1,710 kwh	888 kwh	52%	11.9¢	32.89 kwh	\$105.67	\$3.91	28°	7°-56°	1137
2/15	2,007 kwh	1,056 kwh	53%	11.6¢	35.20 kwh	\$123.34	\$4.11	22°	0°-43°	1178
3/15	1,510 kwh	462 kwh	31%	12.1¢	14.00 kwh	\$55.89	\$1.69	36°	6°-65°	878
4/15	984 kwh	139 kwh	14%	12.1¢	4.96 kwh	\$18.07	\$0.65	53°	30°-80°	345
5/15	1,275 kwh	245 kwh	19%	15.4¢	7.42 kwh	\$37.72	\$1.14	55°	40°-91°	206
6/15	1,137 kwh	297 kwh	26%	15.4¢	10.61 kwh	\$45.71	\$1.63	72°	50°-92°	249
7/15	1,286 kwh	338 kwh	26%	15.4¢	11.66 kwh	\$52.03	\$1.79	77°	60°-94°	364
8/15	1,480 kwh	453 kwh	31%	15.4¢	15.10 kwh	\$69.76	\$2.33	76°	57°-94°	334
9/15	1,094 kwh	100 kwh	9%	12.7¢	3.03 kwh	\$12.74	\$0.39	72°	51°-94°	212
10/15	895 kwh	100 kwh	11%	14.9¢	3.57 kwh	\$14.86	\$0.53	55°	27°-79°	301
Avg.	1,413 kwh	445 kwh	31%	13.5¢	15.06 kwh	\$58.07	\$1.93	52°		552

Table 1: Example of Data Compiled from Geothermal Heat Pump Recordings (Heck, 2015)

II. Preliminary Calculations of a Geothermal System

The example problem below depicts the analysis of an existing geothermal heat pump system. These numbers from the example problem were modified with our own assumptions taken from industry data. The existing geothermal heat pump analysis is below, and the second analysis is done with the 888 kWh system that was required, noted in the paragraphs above (Heck, 2015). The systems have vastly different mass flow rates associated with them, these systems mainly differ because of the substantial change in heat rate out of the system.

Below is the diagram and values, derived from an example in *Sustainable Energy: Choosing Among Options* (Tester, 2012) that we used for the following calculations, based on the data found in Table 2 and Figure 8.

State	P (Mpa)	T (Celsius)	H (kJ/kg)	S (kJ/kg*K)	
1	0.5	15.71	259.3	0.924	SH Vapor
2	1.2	60	289.64	0.9614	SH Vapor
3	1.2	24	84.98	0.31958	Comp. Liquid
4	0.5	----	84.98	0.32085	Sat. Liquid

Table 2: Heat Pump Cycle Values (Refrigerant 134a), Original Numbers, Derived from (Tester, 2012)

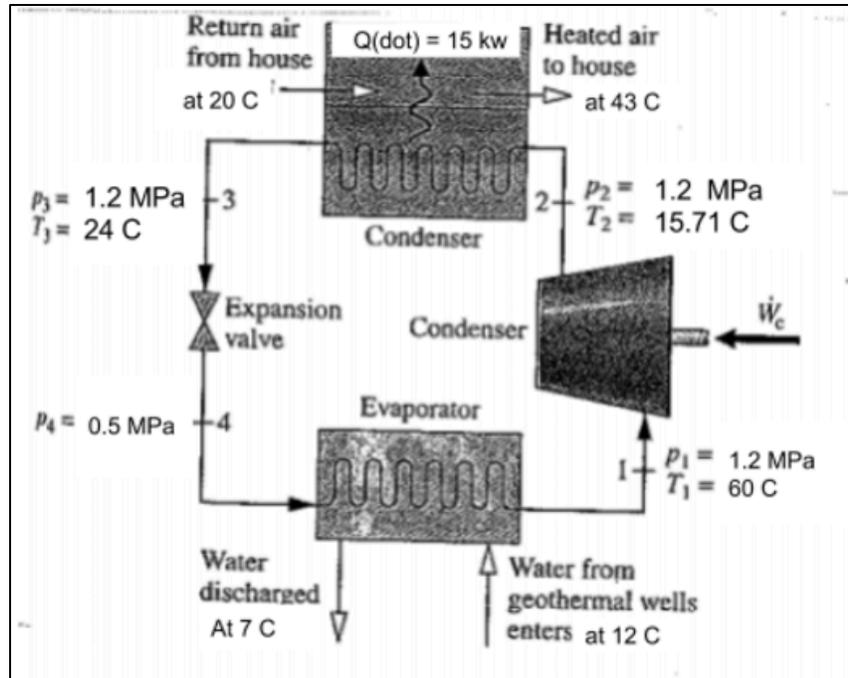


Figure 8: Heat Pump Cycle Diagram, Original Numbers, Image Derived from (Tester, 2012)

Traditional Heat Pump Analysis:

$$h_4 = h(f_4) + x_4 * [h(g_4) - h(f_4)]$$

$$84.98 \text{ kJ/kg} = 73.33 + (x_4) * [259.3 - 73.33]$$

$$x_4 = \mathbf{0.063}$$

$$s_4 = s(f_4) + x_4 * [s(g_4) - s(f_4)]$$

$$s_4 = 0.2803 + 0.063 (0.924 - 0.2803)$$

$$s_4 = \mathbf{0.32085}$$

Finding the mass flow rate of air (\dot{m}_{air}), mass flow rate of Refrigerant 134a (\dot{m}_{R134a}), and the total \dot{W} of the cycle with the data we have found for each state, will better equip our team with the knowledge of what steps we can take to optimize our current state.

Mass flow rate of air: \dot{m}_{air}

$$\dot{m}_{\text{air}} = \dot{Q} / (h_1 - h_4)$$

$$\dot{m}_{\text{air}} = 15 \text{ kW} / (259.3 - 84.98) \text{ kJ/kg}$$

$$\dot{m}_{\text{air}} = \mathbf{0.086 \text{ kg/s}}$$

Mass flow rate of Refrigerant 134a: \dot{m}_{R134a}

$$\dot{m}_{\text{R134a}} = \dot{Q} / (h_2 - h_3)$$

$$\dot{m}_{\text{R134a}} = 15 \text{ kW} / (289.3 - 84.98) \text{ kJ/kg}$$

$$\dot{m}_{\text{R134a}} = \mathbf{0.0733 \text{ kg/s}}$$

Work of the cycle: \dot{W}_{cycle}

$$\dot{W}_{\text{cycle}} = \dot{m}_{\text{R134a}} (h_2 - h_1)$$

$$\dot{W}_{\text{cycle}} = 0.0733 \text{ kg/s} * [289.64 - 259.3 \text{ kJ/kg}]$$

$$\dot{W}_{\text{cycle}} = \mathbf{2.22 \text{ kW}}$$

Coefficient of Performance: COP Calculation

$$\text{COP} = (h_1 - h_4) / (h_2 - h_1) = 4.746$$

This calculation of COP is a representative of time 0 of our system. The COP will vary in a decreasing manner as the duration of system operation increases.

D. EQUIPMENT

I. Pod Material

This section will outline potential materials for the case structure that will disperse the heat into the ground in an effective way, while enabling a modular system design and implementation. The primary characteristic that is being examined is the material's Thermal Conductivity (K). This is the

ability for that object or material to resist the conduction of thermal energy; the higher the number the faster the rate of transfer. Additionally, we will consider the materials ability to survive underground and the cost of the implementation.

Concrete:

Concrete is a composite type material that is made of crushed rock and sand, mixed and bonded together with cement. This mixture is kept viscous and fluid until the final product is needed in a specific location. The mixture is easily moldable and the material will harden in whatever shape or mold it is put into (Holt, 1996). Generally, concrete is very low cost (around \$90/Cubic yard) and has high strength, making it ideal under pressure. It can be reinforced with rebar or other metal material to add tensile strength as well. Additionally, it is able to retain liquids, even when surface cracks form. The thermal conductivity of concrete however is .6-.7, which is very low. The concrete additionally is difficult to remove once installed, thus there would be challenges in monitoring the physical state of it over time. The expected lifespan of concrete is greater than 100 years (Holt, 1996).

Steel

Steel is an alloy, meaning it is a combination material of iron and carbon with additional materials added to fulfill certain requirements in different situations. Steel is created from iron ore in a process called continuous casting, where the molten material is solidified into usable sheets or bars with applied pressure. Steel is easily made into many different shapes and sizes, and is readily available today with a market price of ~\$300 per tonne (Holt,1996). Steel has a thermal conductivity (K) of around 20-50 depending on the amount of carbon, and the addition or omission of additional elements. Steel however has inherent challenges with corrosion, which could affect the structural integrity after time. Additionally, steel needs to have oxygen access to prevent corrosion;

if steel is covered or buried in dirt it may begin to pit, or create holes, as the protective film cannot form. This pitting could create structural problems in the system integrity as well (Holt,1996).

Aluminum

Aluminum is one of the most commonly found element on earth, constructing about 8% of the earth's core mass. The most common aluminum material used in production however is aluminum oxide which is created in a large scale chemical process. Aluminum is priced at \$.75/ pound, and is readily available in most markets (Holt, 1996). It has an excellent thermal conductivity of $K = \sim 200$ which is significantly higher than most other materials. It additionally is able to hold liquid, but has problems with acidic deformation. A substance, such as ethylene-glycol, can be added to the aluminum material to help resist corrosion (Holt, 1996).

Copper

Copper is another metal element that is created from copper ore, and is smelted to the state that is most commonly used. The smelting removed most of the imperfections, and leaves with final product with 99% copper and the remaining 1% a mixture of oxygen and sulfur most often. This leaves the great properties that copper has remaining in the final product. Copper has an extremely high K value of 380-400 W/m-K(Application Data Sheet, 2016). This material has one of the highest thermal conductivity of any material besides pure diamond. Copper additionally has excellent resistance to corrosion and has no reaction to most acids. Copper is also very ductile, meaning it is easy to form into many shapes and sizes. The biggest drawback of copper is the price, averaging \$2.30/lb (Application Data Sheet, 2016).

PVC

PVC, also known as polyvinyl chloride, is a synthetic plastic polymer that is often used with liquid transfer and storage. It is impermeable and has a very high hardness, and with certain chemical structures it is able to resist loads from all sides making it ideal for a storage vessel. Its greatest attribute is that it is chemically resistant to acids, salts, alcohols and most solvents. The thermal conductivity of PVC is low, averaging ~ 0.2 (PVC, 2016). This thermal conductivity is so low because the structure itself does not stay intact, due to poor electron mobility that exists in polymers. This does not make the material readily available to absorb heat. PVC tubing is priced by the linear foot at about \$1 per foot, assuming typical diameters for ground loop dimensions (PVC, 2016).

II. Heat Transfer Liquids

Geothermal heat pump systems rely primarily on convective heat being transferred from an external environment to the heat transfer liquid. There are many types of liquids that have been used in geothermal systems in the past; our system will be composed of the liquid in the tubes as well as the liquid in our pod. For the liquid it must be able to stay in a fluid state, and have properties that allow it to absorb heat quickly, but also store heat long enough for it to be usable in the home's ventilation system. Below is research on multiple fluids, some of which have been used in current iterations of the geothermal heat pump.

Methanol

Methanol has been used in many older versions of geothermal heat pumps for a variety of reasons. First of all, it is a cheap product to buy which was important when first developing these systems and technology for use. This is because methanol is a very simple structure that is only

composed of methyl and hydroxyl. Methanol has a very low viscosity and flows viscous below 15°F, with a freezing point of well below zero the substance has not concerns with year round viscosity. This liquid has a specific heat capacity of 79.5 J/mol•K which is much lower than that of water, representing the faster rate of heat absorption in the tubes (Methanol, 2016). The biggest drawback with methanol is that it is highly toxic, and some municipalities around the country have begun to outlaw its use in any system greater than 20 feet below the ground for fear of water table contamination. Although the toxicity is true, a recent study by Virginia Polytechnic Institute proves that the subsurface biodegradation of methanol occurred within a 30-day period (Methanol, 2016). This suggests that the toxicity of the liquid, should it escape from our closed system may not be a problem on a local water supply.

Ethanol

Ethanol is another example of an antifreeze liquid that has been used in geothermal heat pumps. This is because it also has a heat capacity of less than half that of water, allowing it to change temperature more rapidly. It has a very low freezing temperature which is a beneficial characteristic for geothermal heat pump applications, but at the expense of having less thermal mass. Ethanol however has many drawbacks such as toxicity, explosivity, and corrosivity (Connor, 2012). Additionally, the cost of ethanol is extremely high per volume, so a diluted substrate was used more completely as a denatured ethanol. This denatured ethanol was often denatured with gasoline, rubbing alcohol, and similar chemicals. The problem with those denaturing agents, as was found out through trials, was that the new mixture may dissolve many piping materials.

Propylene Glycol

This liquid is becoming more and more popular in geothermal loop systems for a variety of reasons, but it still has technical problems. Propylene Glycol is a virtually bio-inert substance

making it almost harm free for the environment and human contact. This factor is what is increasing its use in systems today. Additionally, this liquid is used in a mixture with water, most commonly 75% water. This mixture has a freezing point of 13°F, which is suitable for most geothermal heat pump systems (Connor, 2012). Achieving the appropriate mixture ratio can be a challenge when using propylene glycol, as often times the ratio is not calculated correctly. The ratio depends on the environment, how deep the system is, and how large the system is. When an incorrect ratio is created the flow rate will be incorrect, causing the fluid to flow too quickly in one part of the year, and too slowly in another part of the year (Connor, 2012). The ratio is important because the different ratios achieve separate results; the percent ratios can achieve different freezing points, viscosity, density and many other properties. This inefficiency creates unreliable heating and cooling within the geothermal heat pump systems.

Brine Solutions

Brine in a heat transfer application refers to any type of antifreeze water-salt solution; this can refer to any of the chlorides and some acetates. This liquid is better than water for geothermal applications as it has a lower freezing point, but it has a lower heat capacity as well. Additionally, the biggest trade off is that the system would have major corrosion problems, and the brine solution would not be sustainable if it began to deteriorate the pod itself or the inner pipes. (Dimplex, 2016). The solution would need pH inhibitors in order to counteract the corrosion, and that may not even prevent the piping and infrastructure from having critical failures over time.

Water

Water is one of the best heat transfer liquids in its natural state. It has a very high heat capacity and thermal conductivity, and virtually no corrosive nature depending on its origin and the soil composition around it. The limiting factor when using water is the freezing point, as seen in

Figure 9. The graph below shows how the addition of the other chemicals to water lower the freezing point and increase the range of usability. Table 3 below shows how different chemicals impact system efficiency.

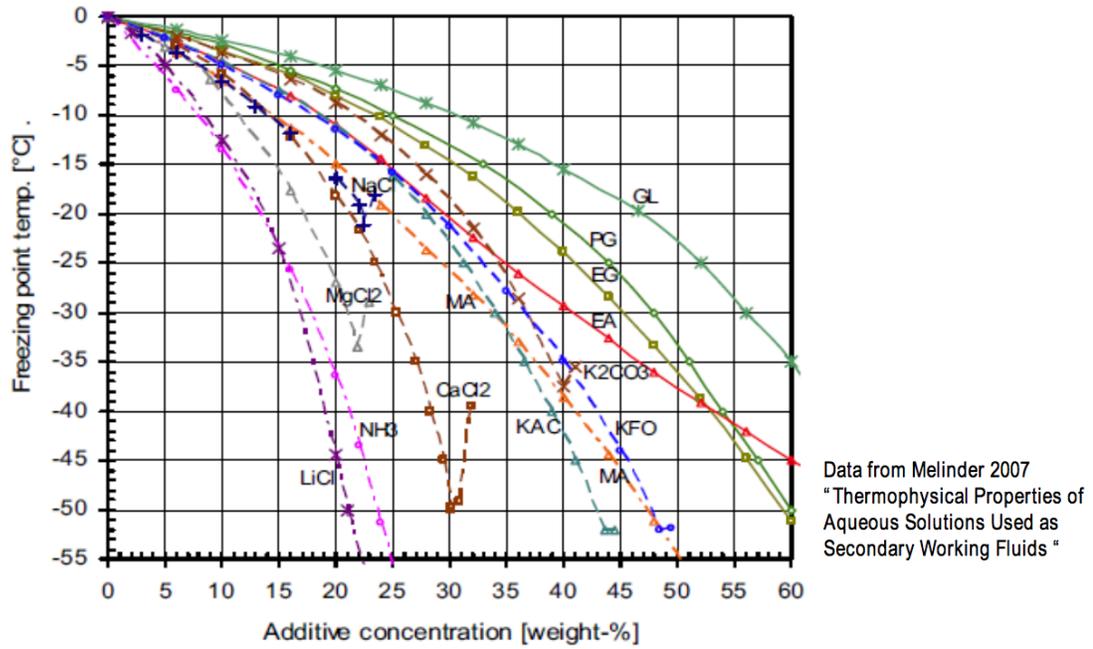


Figure 9: Temperature Impact on Freezing Point (Connor, 2012)

Physical Properties @ 10°C/ 50°F

Fluid Description	Freezing Point (°C)	Thermal Conductivity (W / m.K)	Volumetric Heat Capacity (kJ / L.K)	Viscosity (cP)
water	0	0.582	4.18	1.3
Methanol * 12 wt%	- 7.5	0.525	3.86	1.3
Ethanol * 15 wt%	- 7.5	0.500	3.83	2.7
Ethylene Glycol * 19 wt%	-7.5	0.501	3.94	2.0
Propylene Glycol * 20wt%	-7.5	0.484	3.86	2.8
Glycerol * 26wt%	-7.5	0.481	3.97	3.1
Mineral Oil (VG2)	-15 (pour pt.)	~0.16	~1.6	~28

Table 3: Impacts on System Efficiency (Connor, 2012)

III. Secondary Geothermal Heat Pump Components

The scope of our project is to create an original ground source heat exchanger process, and optimizing these results to create a modular pod. The other components of the heat exchanger will be incorporated from already existing solutions and systems. In addition to the ground components (coils, tubes, and refrigerants), geothermal heat pumps are also composed of secondary components or components that are also found in other forms of heating and cooling systems. A geothermal heat pump heat exchanger is composed of a compressor, a pump, and several valves that aid in maintaining the appropriate configuration. Figure 11 below illustrates how the different fluids (air, refrigerant, and domestic water) cycle throughout the heat exchanger system. In this diagram, the red piping illustrates the heat exchanger’s connection to the ground coils.

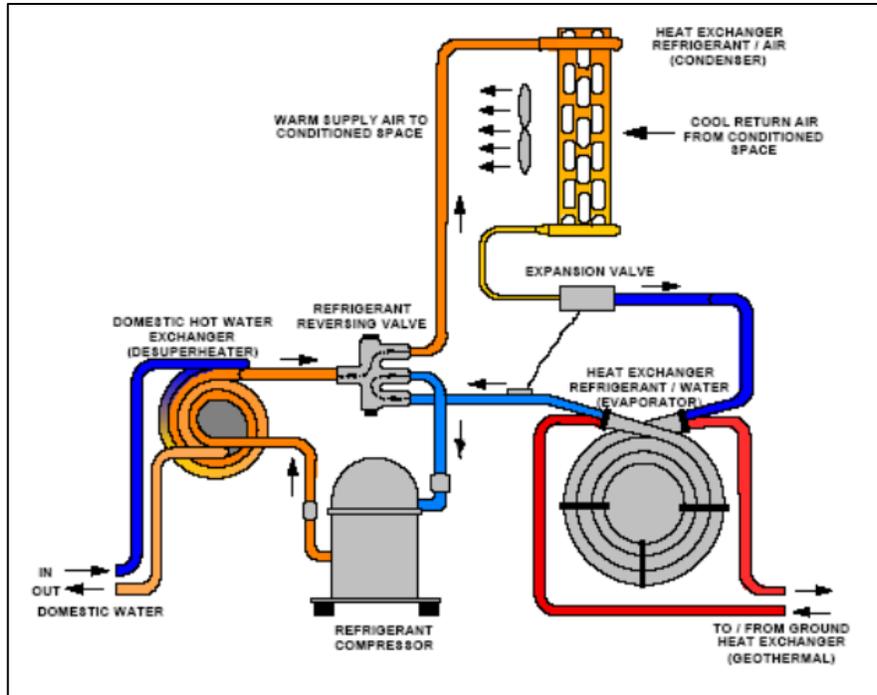


Figure 10: Fluid Flow Through a Heat Exchanger System (Key Components, 2016)

All of the secondary components of a geothermal heat pump exchanger system are packaged nicely in order to easily fit into a residential setting. As illustrated in Figure 11 the configuration of the secondary components is such that they are neatly packaged for residential use. It is also important to note that the process map of the geothermal heat pump, seen above, appears very different from the heat pump in use. For this project, it is necessary that both process flow and the technology in practice are understood.

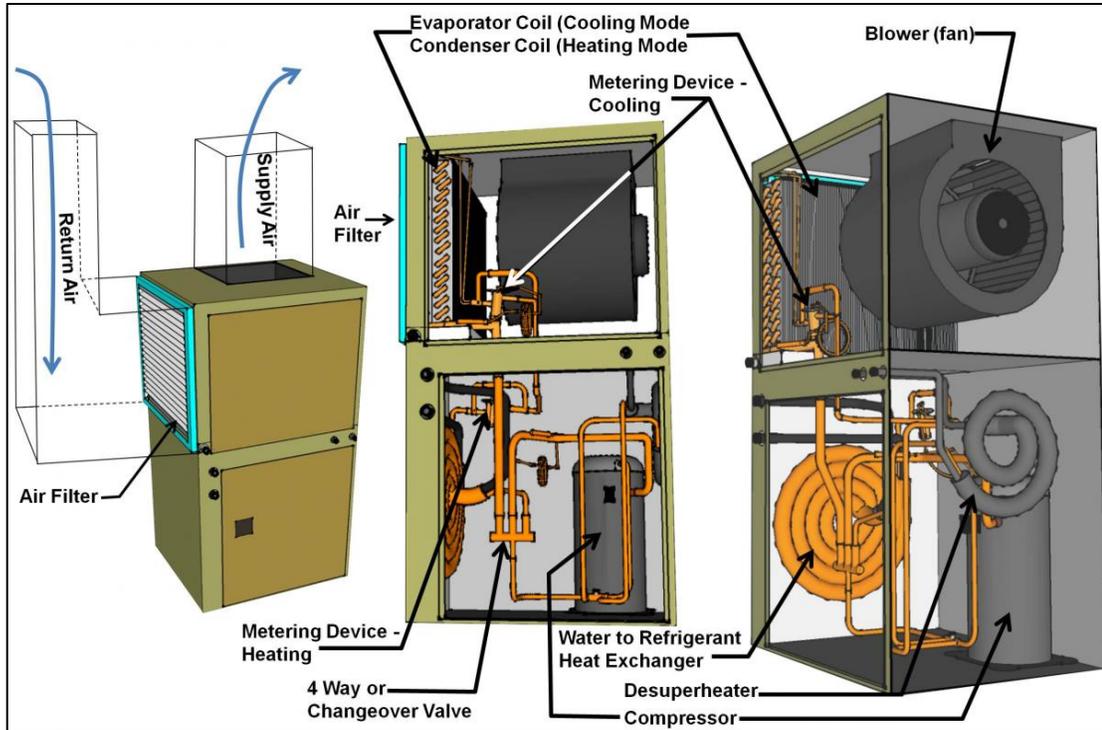


Figure 11: Secondary Components of a Geothermal System (HVAC System Design, 2016)

E. INSTALLATION

I. Average Cost

While the environmental benefits of geothermal heat pumps are clear as they have a higher efficiency and decrease energy consumption, the overall cost of a geothermal heat pump system can be a deterrent for many potential customers. (Energy Homes, 2008) According to energyhomes.org the average geothermal heat pump costs between \$20,000-\$25,000 for both parts and labor. This large initial cost provides a barrier to increasing the number of systems installed within the United States. However, the payback for these systems is between 2-10 years with a life expectancy of 18-23 years, almost double that of a traditional system (Energy Homes, 2008).

II. Equipment Cost

The geothermal heat pumps themselves range commercially from around \$2,000-\$8,000 according to energyhomes.org. In comparison, the average natural gas home heating boiler costs

between \$1,000-\$4,000. While the geothermal heat pump technology itself is more expensive than other home heating technologies, the majority of the total cost is associated with system installation (Energy Homes, 2008).

III. Installation Cost

The majority of the cost associated with purchasing a geothermal heat pump system is the installation. An average installation of a geothermal heat pump system is \$10,000-\$14,000 (Energy Homes, 2008). This price is so high because installation involves both installing the heat pump itself, a process similar to installing a natural gas boiler, along with installing the ground loops. Ground loop installation is expensive and invasive as it involves bringing specialized machinery onto the customer's property and digging a large and relatively deep trench within which the coils are positioned. Prior to installation, other factors need to be considered such as soil conditions, and land availability (Energy Homes, 2008). These factors can also add additional cost to the installation process.

IV. Installation Timeline

Geothermal heat pumps require a licensed professional and heavy machinery for installation. Installation of a horizontal loop system requires digging multiple trenches using specialized machinery and can take around 1-2 days to be completed. Vertical loop systems can be more complicated to install as conditions at greater depths become more complicated as bedrock and aquifers become present. The average vertical loop ground source heat pump system takes around 2 days to install but the timeline is more loosely defined as unknown ground conditions can greatly affect the installation timeline (Energy Homes, 2008).

4: METHODOLOGY

The goal of this project was to design a modular geothermal heat pump system. In order to limit the scope of this project we developed the following design objectives:

1. The system must be modular
2. The modules must be able to be combined
3. Installation of the modules must not require specialized equipment
4. The system must provide enough heat output to last the heating season
5. The system must provide enough cooling output to last the cooling season
6. The system must be able to provide similar results to a traditional system
7. The system must be readily accessible for maintenance activities

A. DETERMINING HEAT OUTPUT REQUIREMENTS

In order to correctly design the size of the modular geothermal heat pump system, our first step was to determine the system's required heat output. For this we decided that we would use a 20 to 30-year-old house in the Hudson Valley Region of the northeast. We used the assumptions of a 2200 square foot house and 9-10 foot floors with a two story building with average sunlight and wind on the house. We then used the below software, coolcalc.com, which derives heating and cooling loads using average weather data in conjunction with the home characteristics. The website calculator uses the 8th edition of the ACCA manual which sets the standards for heating and cooling loads as seen in Figure 12.

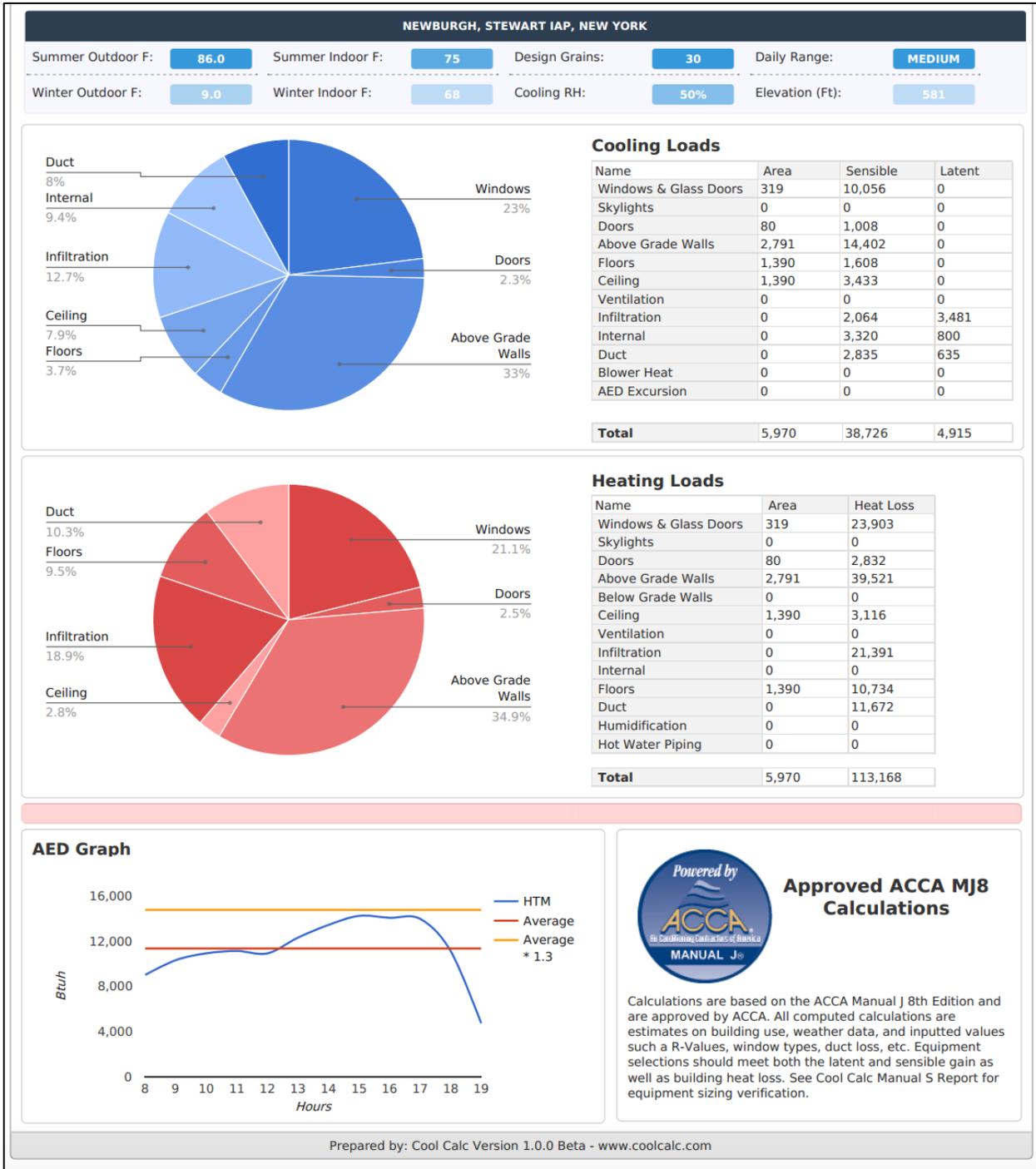


Figure 12: Heating and Cooling Loads in a House (CoolCalc.Com)

We confirmed the scale of the heat output using information found on page 157 of “Sustainable Energy: Choosing Among Options” (Tester, 2012). This text references a required heat

output for residential buildings of 5 kJ/s. We used a conversion factor of 1 kWh = 3412 BTU/H and a time period of 12 hours (from graph above) to evaluate if both estimates were on the same scale.

$$113,168 \text{ BTU/H} * (1/3412) \text{ kWh} * (1/12) \text{ H} = 2.76 \text{ kJ/s}$$

Equation 1: BTU/H Conversion to kJ/s

As seen above in Figure 12, the “CoolCalc” BTU/H estimate equates to 2.76 kJ/s. As this is on the same scale as the textbook estimate of 5 kJ/s we were satisfied with our sources (Tester, 2012). For the purpose of this project we chose to use the more conservative heat output requirement of 5 kJ/s. It should be noted that the heat output requirement can vary greatly depending on the house size, construction of home, and location.

B. PRELIMINARY HEAT TRANSFER CALCULATIONS IN EES

Once the required heat output was determined, we began completing preliminary heat transfer calculations. We created our basic thermodynamic cycle, seen below, by combining information from a generic heat pump example and geothermal industry standards for pressure and temperature within the system.

	P (MPa)	T(°C)
1	0.5	7
2	1.2	60
3	1.2	23.9
4	0.5	4.4

Table 4: Thermodynamic Cycle Values (Original Numbers)

See corresponding diagram on next page.

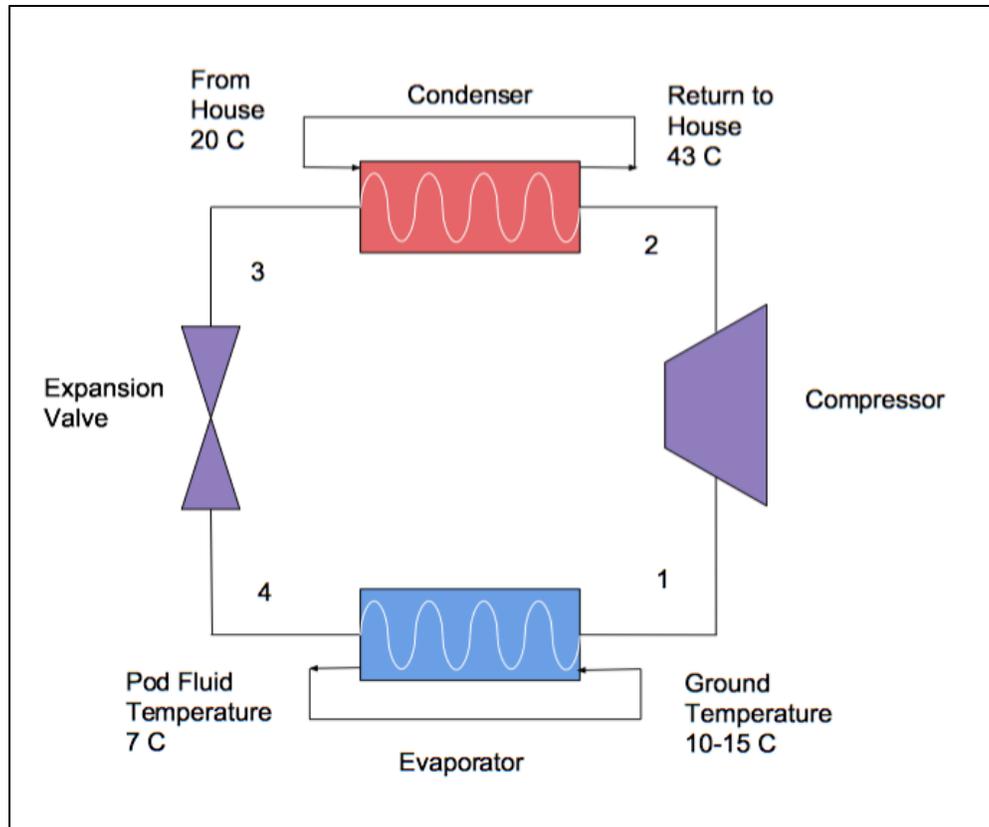


Figure 13: T-S Diagram for Geothermal System (Original Graphic)

I. Initial Trials

For this project we utilized the program Engineering Equation Solver (EES). We chose to use this program as it would allow for the automation of design iterations and it contains material properties for the refrigerants, metals, and other materials we used in our design. Once the assumptions for our calculations were established, we were able to create a more realistic calculation model using EES. We were able to do this by eliminating assumed or unknown variables one at a time while going through standard heat transfer calculations. All of the assumptions that were used are to create a baseline to iterate upon. For the preliminary calculations we chose the ground temperature of 10°C and a pod size of 1.5 meter diameter that is 1 foot below the ground. In addition, we used a saturated brine as the liquid in the pod, and water as the liquid inside of the pipes. For the pipes themselves, we chose aluminum to give a very high thermal

conductivity for our baseline tests, in order to eliminate potential problems that may have arisen from a material with a low K value. These initial variable assumptions are listed from EES below in Figure 14.

```
"Pod to working fluid in the pipes"  
h1b=851.74 [w/m^2K] "assume brine for now"  
Do=.025 [m]  
Ro=.0125 [m]  
Di=.0229 [m]  
Kal=205 [w/mK] "aluminum has been chosen"  
L=1 [m] "this is to be varied"  
A1=pi*(Ro)^2 [m^2]  
R1=(1/(h1b*A1))  
R2=(ln(Do/Di))/(2*pi*Kal*L)
```

Figure 14: Initial Variable Assumptions (Original Work)

The next step in our calculations were to examine the heat output that our designed pod system could create. For this process we consulted multiple heat transfer experts in order to determine our design parameters, and what conclusions we would expect to draw. From these resources, we decided that we wanted a system to be sized at 5 kJ/s of output, and that we would base our calculations on achieving that (Tester, 2012). We determined that there were three main areas of heat transfer that would occur in the pod system. It is important to note that we originally chose to neglect the heat transfer from the ground to the pod system and started with a semi infinite solid. The heat transfer from the ground to the pod was calculated at a later time, and is shown in the calculations section. The three main heat transfer nodes that we calculated were: from the pod wall to the tube containing the heat transfer liquid, through the tube wall, and finally from the tube wall to the inner heat transfer liquid. Below is Figure 15 showing the establishment of the resistances, and the associated thought processes and external information in blue.

"Assume Nusselt number of 3.36 as the boundary wall temperatures are constant"
 "use a K value for water of .591" "replace with 134a"
 "find H32 which is the H value for the 3rd resistance, which is the pipe to inner fluid"
 "Nu=hD/K, so h*(.0229/.591)" "Create a variance if turbulent flow"
 H32=3.36*.591/Di
 "R3=1/hA, where h was just solved for and A is pi*d*L"

$$R1 = \frac{1}{h1b \cdot A1}$$

$$R2 = \frac{\ln \left[\frac{Do}{Di} \right]}{2 \cdot \pi \cdot Ka1 \cdot L}$$

$$R3 = \frac{1}{H32 \cdot \pi \cdot Di \cdot L}$$

$$RT = R1 + R2 + R3$$

Figure 15: Establishment of the Resistances (Original Work)

Although there is a solution that the entire inner system is submerged in, it was determined that the thermal gradients through this region would be negligible, as the temperature should be constant at all times. As seen in Figure 16 below the pipe size we chose was a 1-inch diameter pipe for convenience and ease of acquiring the material. It is also important to note that for these initial calculations we used the overall pipe length as one (1) meter to establish a baseline and enable us to iterate different variables as we progressed.

```

"Heat flux for soil to pod"
D=3 [m] "Diameter of the total pod"
z=1 [m] "Depth of the pod from the surface"
Tg=15 [C] "Temperature of the ground"
Kg=2.2 [W/mK] "Thermal conductivity of the ground, average"
S=(2*pi*D)/(1-(D/4*z))
q=S*Kg*(Tg-T1) "Heat output of the pod"

"Pod to working fluid in the pipes"
h1b=851.74 [w/m^2K] "assume brine for now"
Do=.025 [m] "Outer Pipe diameter"
Ro=.0125 [m] "Outer pipe radius"
Di=.0229 [m] "innter pipe diameter"
Kal=205 [w/mK] "aluminum has been chosen"
L=1 [m] "this is to be varied as it is in the paremetric tabel right now"
A1=pi*(Ro)^2 [m^2] "Area of the pipe"

```

Figure 16: Establishing Variable Values in EES, Assuming Cylindrical Pod (Original Work)

It should be noted that our team took different shape factors of the pod into consideration when making our calculations for pod area in order to estimate the heat transfer from the pod and surrounding area. We examined multiple options, and determined that the most accurate way to analyze the pod system was to approximate it as a sphere buried in a semi-infinite medium. Although we have anticipated the use of a cylinder shape, the surface area can be approximated from the sphere shape factor. However, if maximum surface area is desired for maximum ground contact, a cubical design method should be considered.

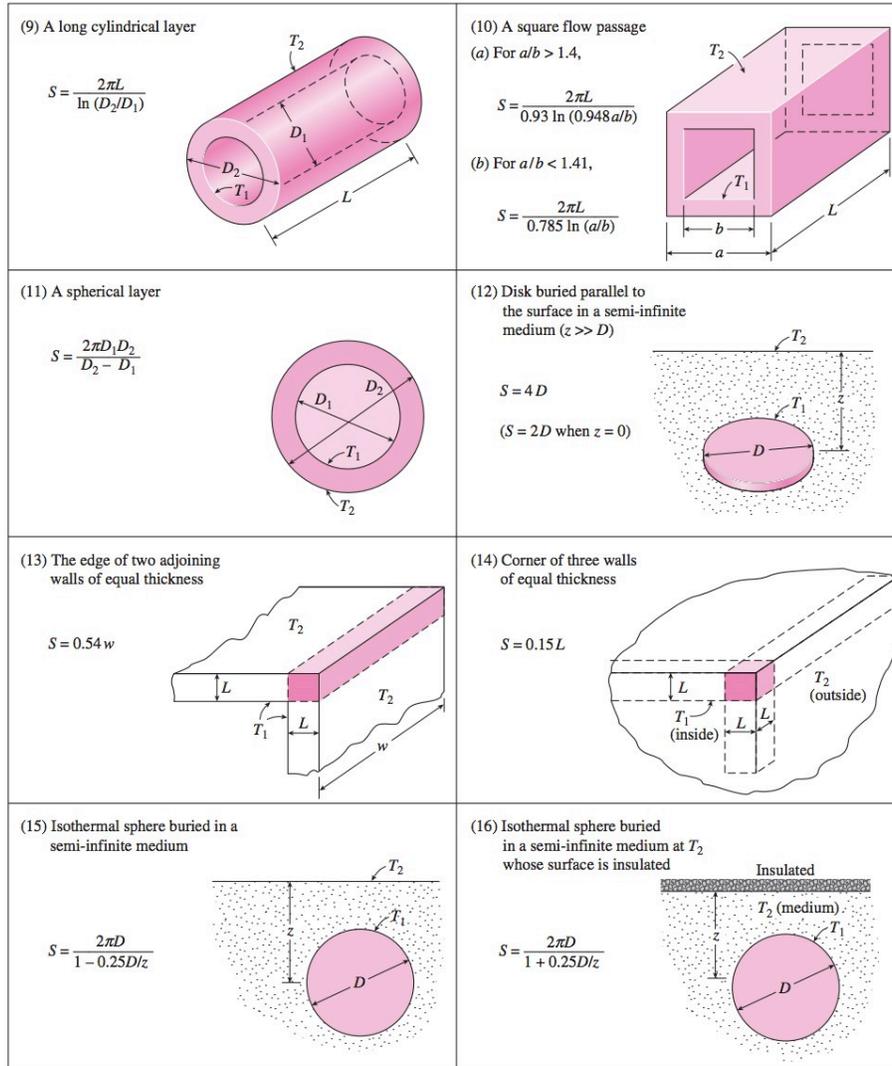


Figure 17: Shape Factor Examples (Holman, J.P., 2008)

After setting the initial variable parameters, the next step in determining the heat output of the system was to assign temperature values to the fluid in the pipe and to calculate the log mean temperature difference (LMTD). The LMTD is the form of the temperature variation used to determine the heat output in the loop system, allowing Q to be calculated from Newton's law of cooling; this is because the temperature difference between the fluid inside and outside of the pipe decays exponentially along the pipe. Below in Figure 18 is the reasoning used initially, along with the equations entered into the EES program.

```

"dT=Qo/(A2*U)" "This is the log mean temperature difference"
"Here we will assign temperature values in order to get the LMTD. I have decided to use the inlet and outlet temperatures of the
pipe as my Th and Tc, which will be subtracted and divided from the brine temperature in the LMTD. My Tc( Inlet temp) will be 7
deg C, the Pod or brine temp will be 15 deg c and the outlet temp, Tc will be 14 deg c. ALL TEMPS TO BE VARIED"
Tc=7[C]
Th=14[C]
Tp=15[C]
dT=(Tc-Th)/ln((Tp-Th)/(Tp-Tc))

"Qo=A2*U*dT"

```

Figure 18: Log Mean Temperature Difference Reasoning and Equations in EES (Original Work)

Once the LMTD was established we believed that we had all of the necessary variables and information in order to optimize the heat output of our system, and that the following set of variables would yield the heat output, q . We then thought that we would be able to determine the optimal length based on the heat output. Below in Figure 18 the mass flow rate was established from information found from McQuay International “Geothermal Heat Pump Design Manual”, (McQuay, 2002) and all of the variables were believed to be accounted for.

```

mdot=.504 [kg/s]
Cp134a=1367 [J/KgK]
q134a=mdot*Cp134a*(Th-Tc) "is 4.8 KJ/s which is good"
L134a=q/(U*3.14*Do*dT)

```

Figure 19: Calculation of Mass Flow Rate in EES (Original Work)

What we came to realize was that the above method would not work, as we were looking to solve for the optimal length in the final equation, and thus we decided upon a different approach.

II. Advanced Approaches

In order to find a suitable way to solve the biggest problem of determining length, it was determined that we should derive the answer in a different way. Instead of assuming a length of 1 meter in order to get the heat resistances, we did not solve for any of the resistances prior to the final equation. Our original iterated equation looked as follows:

$$L134a = \frac{q}{U \cdot 3.14 \cdot Do \cdot dT}$$

Equation 2: Original pipe Length calculation in EES (Original Work)

Once we found the error in our assumptions, the equation was re-derived to the following form:

$$q = \left[\frac{1}{\frac{1}{H1b \cdot A1} + \frac{\ln\left(\frac{Do}{Di}\right)}{2 \cdot \pi \cdot Kal \cdot L} + \frac{1}{H32 \cdot \pi \cdot Di \cdot L}} \right] \cdot dT \cdot 2 \cdot \pi \cdot Ro \cdot L$$

Equation 3: Heat Rate Equation in EES (Original Work)

This new form was the missing link in our equation solver, because now there was nothing assumed at this step. We used a parametric table, shown below, to find the optimal length vs q-output that we desired.

	1	2
	L	q
	[m]	[J/s]
Run 1	10	91.04
Run 2	23.38	497.6
Run 3	36.76	1230
Run 4	50.14	2288
Run 5	63.51	3673
Run 6	76.89	5383
Run 7	90.27	7419
Run 8	103.6	9781
Run 9	117	12469
Run 10	130.4	15483
Run 11	143.8	18822
Run 12	157.2	22488
Run 13	170.5	26479
Run 14	183.9	30797
Run 15	197.3	35440
Run 16	210.7	40409
Run 17	224.1	45704
Run 18	237.4	51325
Run 19	250.8	57272
Run 20	264.2	63545
Run 21	277.6	70144

Table 5: Optimal Length vs q-output in EES (Original Work)

As evident in the table image above, we iterated upon the length to determine if any trends existed. The trends in the L vs q-output were logarithmic as shown by the plotted graph below:

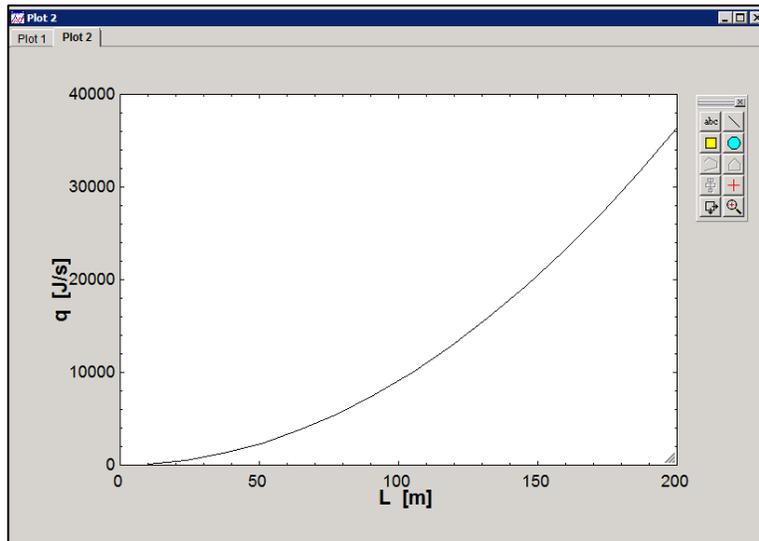


Figure 20: Length vs q-output in EES (Original Work)

Once we had a working equation solver, it was then possible to go back and make more

changes that were originally assumptions. After modeling the heat cycle in the house as seen below, it was possible to obtain temperature values. We were able to use these temperatures to use as our input values in the loop system, and thus calculate the LMTD with accurate values. These values in the system were similar to our assumptions and to expected data found in the textbook reference as noted above. We additionally calculated associated outputs such as the coefficient of performance, the work used, and the compressor efficiency. Although this is not critical for the loop output, and can be varied, we thought it would be helpful to have the calculation ability available as it will be important for future design work.

```

"Heating Mode, this is the heat cycle in the house. Refer to the digram in the paper for reference"
T1=4.4 [C] "Value taken from example problem, can be rho=Density(R134a,T=T,P=P) a design decision"
P1=500 "Value taken from example problem, can be a design decision"
T3 = 23.9 [C] "condenser outlet temperature"
P3=1200 "Using compressed liquid at state 3"
"this fixes states 1 and 3"
h3=h4 "isenthalpic expansion"
T4=7 [C] "if the evap remains entirely under the dome-ask if we can use x4 to fix the state instead"
x4=quality(R134a,T=T4,h=h4) "not needed, just used as a reference"
"this fixes state 4"
P2=P3
s1=s2s "isentropic compression"
"state 1"
s1=entropy(R134a,T=T1,P=P1)
h1=enthalpy(R134a,T=T1,P=P1)
"state 2"
T_sat2=t_sat(R134a,P=P2)
h2=enthalpy(R134a,T=T2,P=P2)
T2=temperature(R134a,P=P2,h=h2)
h2s=h2
h3=enthalpy(R134a,T=T3,P=P3) "state 3"
P4=pressure(R134a,T=T4,h=h4) "state 4"
"Qo"
Qo=5 "this value taken from our renewable energy textbook page 157, it is the desired heat output for the system"
COP=(h1-h4)/(h1-h2) "coefficient of performance"
nc=(h2s-h1)/(h2-h1) "compressor efficiency, not critical here,but available for reference"

```

Figure 21: Outputs of EES, COP, Work, Compressor Efficiency (Original Work)

One of the final things we chose to do was to test the materials and fluids used, and see the variance that they could have. Originally we chose aluminum as the pipe material, this was because of the high K value, thermal conductivity, that is possessed (around 205 W/m-K). It was

determined through material iteration that the K value actually had a nominal or negligible effect on the overall q output of the system, even when the value changed from 205 to 5. We concluded that the small size of the pipe wall, and the very small resistance that existed because of that, did not stop the temperature change. This was an interesting revelation as it meant that our system could utilize readily available materials such as PVC or plastics with little effect to the heat output, but offers improvements to cost and corrosion considerations. Additionally, we used the property lookup function in EES to alter the fluids, both that were in the brine solution and in the pipe itself. The lookup function, as seen below, allows the program to easily change materials and find the optimal ones for functionality. For the purposes of this iteration, we chose the fluid methanol to be in the pipe. This is a common loop fluid and has properties that are acceptable for the temperature constraints that we would need for year round operation. For the material lookups for a fluid, you must give the temperatures, the saturation amount and the pressure at which it will enter.

`H1b=enthalpy(CaCl2,T=Tc,C=30 [%],P=100 [Kpa])`

Equation 4: Example of Material Lookup in EES (Original Work)

Our group has considered the fact that the ground temperature near the pod will change as the systems work throughout the year, getting colder or hotter depending on the mode that the system is in. It is predicted that the ground temperature will become cooler in a heating cycle (and vice versa) as the season goes on and heat is drawn out of the ground further away from the pod walls. In this system, there are three heat sources, including the transfer of heat from the ground to the pod, energy storage within the brine contained within the pod, and energy released due to phase change occurring within the brine and the ground surrounding the pod. As seen in Appendix C, a

basic calculation was completed to determine the required pod diameter utilizing a steady ground temperature and spherical shape factor while only considering energy storage within the pod. This calculation provided a required pod diameter of around 7m. This result is far too large to be logistically and economically feasible, illustrating the necessity of ground phase change in this model. This calculation did not consider the impact that phase change will have on the system, and thus this will be an important consideration for future work on this subject.

5: RESULTS AND RECOMMENDATIONS

After optimizing iterations on design decisions within our EES code and iterations within the structure of the code itself, we arrived at our final design, which represents a preliminary system. As seen in Figure 21 below, the first section of our EES code utilizes given temperatures and pressures to define and fix states within the heat cycle of a geothermal heat pump. The code then uses EES's built-in properties to calculate enthalpies, entropies, and qualities at each stage of the thermodynamic cycle. This information is combined with a required heat output of the system and is then utilized in the second half of the code.

```

[Heating Mode, this is the heat cycle in the house. Refer to the digram in the paper for reference"
T1=4.4 [C] "Value taken from example problem, can be rho=Density(R134a,T=T,P=P) a design decision"
P1=500 "Value taken from example problem, can be a design decision"
T3 = 23.9 [C] "condenser outlet temperature"
P3=1200 "Using compressed liquid at state 3"
"this fixes states 1 and 3"
h3=h4 "isenthalpic expansion"
T4=7 [C] "if the evap remains entirely under the dome-ask if we can use x4 to fix the state instead"
x4=quality(R134a,T=T4,h=h4) " not needed, just used as a reference"
"this fixes state 4"
P2=P3
s1=s2s "isentropic compression"
"state 1"
s1=entropy(R134a,T=T1,P=P1)
h1=enthalpy(R134a,T=T1,P=P1)
"state 2"
T_sat2=t_sat(R134a,P=P2)
h2=enthalpy(R134a,T=T2,P=P2)
T2=temperature(R134a,P=P2,h=h2)
h2s=h2
h3=enthalpy(R134a,T=T3,P=P3) "state 3"
P4=pressure(R134a,T=T4,h=h4) "state 4"
"Qo"
Qo=5 "this value taken from our renewable energy textbook page 157, it is the desired heat output for the system"
COP=(h1-h4)/(h1-h2) "coefficient of performance"
nc=(h2s-h1)/(h2-h1) "compressor efficiency, not critical here,but available for reference"
P2e=P2*convert(kPa, psi)

"This Section is virtually independent of the section above. This is about the loop and pod temperature in the ground."
"The only information that is used from above, below, is the temperature input desired for the loop"
"As a reminder this is set in heating mode"

"Use Methanol as the fluid in the loops for now, the loop is defined as the heat transfer pipe, the traditional method"
"use CACL2 for the brine that will exist in the pod"
mdot=.504[kg/s] "mdot values are found in the Geothermal-Heat-Pump-Design-Manual.pdf"
"P1=500[Kpa]" "From the P1 given above"
Tc=4[c] "Tc is the same as T1, it is just labeled Tc here so that it is distinct at the cold tmerpature entering the Pipe system"

```

Figure 22: Section 1 Final EES Code (Original Work)

The second section of the EES code utilizes the input temperature for the loop, taken from the first section of the code, combined with enthalpy calculations and pipe length and diameter specifications to calculate the Nusselt Number, total thermal resistance of the system, and ultimately the heat output of the system. This process can be seen below in Figure 22.

"This Section is virtually independent of the section above. This is about the loop and pod temperature in the ground."
 "The only information that is used from above, below, is the temperature input desired for the loop"
 "As a reminder this is set in heating mode"

"Use Methanol as the fluid in the loops for now, the loop is defined as the heat transfer pipe, the traditional method"
 "use CAQL2 for the brine that will exist in the pod"

$\dot{m}=.504[\text{kg/s}]$ "mdot values are found in the Geothermal-Heat-Pump-Design-Manual.pdf"

"P1=500[Kpa]" "From the P1 given above"

$T_c=4[\text{c}]$ "Tc is the same as T1, it is just labeled Tc here so that it is distinct at the cold temperature entering the Pipe system"

$H_{1b}=\text{enthalpy}(\text{CaCl}_2, T=T_c, C=30 [\%], P=100 [\text{Kpa}])$

$D_o=.025 [\text{m}]$ "We have chosen a Pipe with this Outer Diameter as it is a common sized pipe, with a .98in sizing)"

$R_o=.0125 [\text{m}]$ "Outer Radius"

$D_i=.0229 [\text{m}]$ "inner Diameter of the pipe, as given by common pipe sizing (can be varied)"

$K_{al}=205 [\text{w/m-K}]$ "aluminum has been chosen, but you can use any material. The answer is pretty stable regardless as the pipe wall is so thin"

$L=75$ "length of the pipe, straight segment"

$A_1=(2*\pi*(R_o)*L)$ "Surface area of the pipe"

" $R_1=(1/(H_{1b}*A_1))$ This is the resistance for R1, it is used below as the answers all originally varied based on length which was not known"

" $R_2=(\ln(D_o/D_i))/(2*\pi*K_{al}*L)$ Same as above, but for R2"

$K_{meth}=.202$ "thermal conductivity of methanol, which is needed to find the resistance"

$Nu=3.36[-]$ "Assume Nusselt number of 3.36 as the boundary wall temperatures are constant and flow is laminar"

$H_{32}=Nu*K_{meth}/D_i$ "Used to calculate the 3rd resistance, notated as H32 because H3 is used in the House Loop above"

" $R_3=1/(H_{32}*\pi*D_i*L)$ used for third resistance below"

$T_h=7[\text{C}]$ "this is the hot temperature, or the exit temperature in the loop system"

$T_p=15[\text{C}]$ "This is the Temperature of the ground that surrounds the pod"

$dT=(T_c-T_h)/\ln((T_p-T_h)/(T_p-T_c))$ "This is the LMTD used"

" $R_T=(1/(H_{1b}*A_1))+((\ln(D_o/D_i))/(2*\pi*K_{al}*L))+1/(H_{32}*\pi*D_i*L))$ "

" $U=1/R_T$ "

" $L=q/(U*3.14*D_o*dT)$ "

" $dT=5602/(U*3.14*D_o*L)$ Used to find the LMTD "

" $q=((1/((1/(H_{1b}*A_1))+((\ln(D_o/D_i))/(2*\pi*K_{al}*L))+1/(H_{32}*\pi*D_i*L))))*(\pi*D_o*dt)*L$ "

" $q=UAdt$ Surface area of pipe, DT is the LMTD"

$q=(1/((1/(H_{1b}*A_1))+((\ln(D_o/D_i))/(2*\pi*K_{al}*L))+1/(H_{32}*\pi*D_i*L))))*dt*(2*\pi*R_o*L)$

Figure 23: Section 2 Final EES Code (Original Work)

Using this final edition of the EES code we were able to arrive at our final preliminary design of the system. Seen below in Figure 23 is the variable information for our final design. The length was iterated upon and optimized to produce the desired q value. As listed in our methodology, the required heat output for our system was 5 kJ/s. As seen below, with a length of 75 meters we are able to achieve a heat output of 5121 J/s or 5.121 kJ/s, fulfilling our requirement. We

were able to achieve a brine temperature of 7 °C, with a mass flow rate of .504 kg/s. This flow rate was achieved with an inner pipe diameter of .0229 m. The variables below are at time zero (0) with the initial system turn on. As noted earlier the ground temperature will change as the time goes on and thus the results will change.

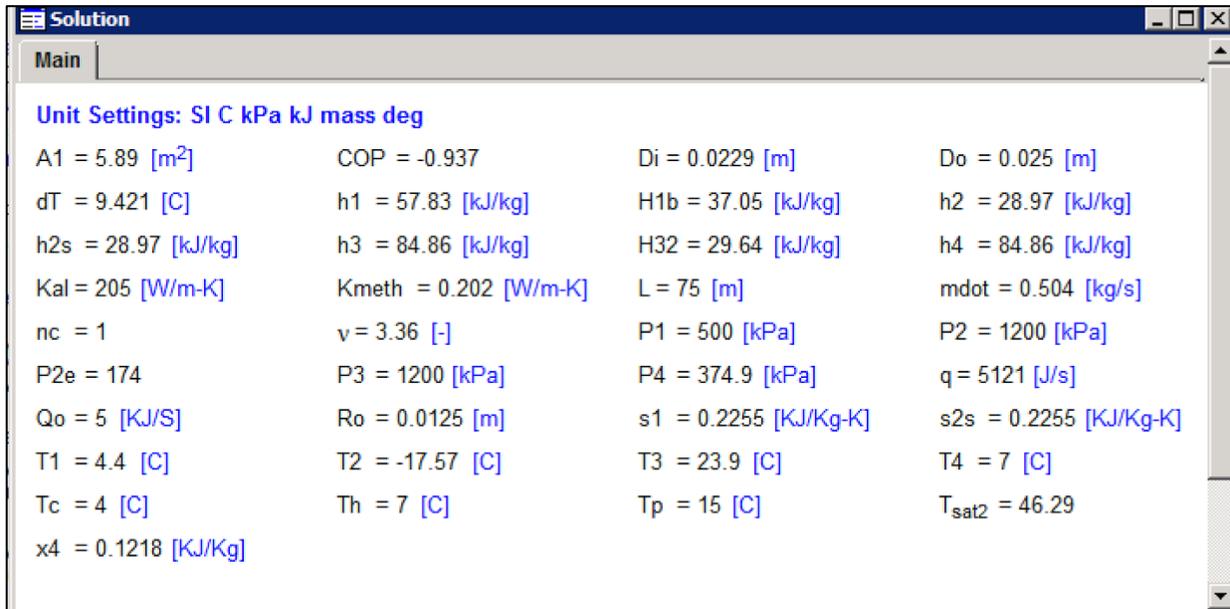


Figure 24: Variable Information for Final Design in EES (Original Work)

In researching technical background information on geothermal heat pumps, our team discovered that there is a dearth of available technical data and operating condition information available to the public. Additionally, efforts to reach out to industry directly to gain access to this information did not come to fruition. These factors combined with limited time available to continue work on the project contribute to our preliminary design being just that, preliminary. In an effort to support the continuation of research and development on the heat cycle design and eventual prototype production, our team has produced the following list of recommendations:

A. EXPERIMENTAL DATA COLLECTION

As mentioned previously, there was a lack of industry data available on many aspects of geothermal heat pump operation including but not limited to seasonal temperature ground profile at varying depths in New England, and ground freezing information at varying depths in New England. Our team recommends that future teams consider conducting experimental data collection to produce this data on-site at WPI. The ground profile information is integral in system design and collecting accurate data on this information would ensure that the EES code contains more realistic input information. It is important to mention that a near surface system would save excavation costs, but would be more sensitive to changing temperatures as the ground may not be in its constant temperature depth.

B. CONTINUED HEAT CYCLE RESEARCH

It is recommended that the heat cycle temperature and pressure specifications be researched further and compared to industry data. As no industry data was available, our team utilized a combination of general heat cycle information and logic to produce our values. Fine tuning these values would only further increase the accuracy of the system as a whole.

C. COOLING CYCLE DEVELOPMENT

Currently the EES code acts as a model for the heating cycle of a geothermal heat pump. In theory, simply reversing the direction of the heat cycle should provide information on the cooling cycle of a geothermal heat pump that would be used in the Summer. It is recommended to confirm the functionality of the cooling cycle model as well as add any variance in ground temperature that occurs in the summer months in New England.

D. TESTING MULTIPLE POD SCENARIOS

The benefit of designing “pods”, or geothermal heat pump modules, is that multiple modules can be added on as heat load increases. It is recommended to test that the current model allows for multiple pods to be used at once. It is also recommended to model the effect of the “pods” on the ground in order to determine necessary spacing between the modules.

E. SECONDARY COMPONENT OPTIMIZATION

The current model includes all of the components of a geothermal heat pump that interact directly with the ground; it does not include secondary components such as the compressor, condenser, or expansion valve. It is recommended that further research be done on the different models of these secondary components and how they would influence the effectiveness of the system as a whole.

F. PROTOTYPE DESIGN

It is recommended to produce several prototype designs utilizing different materials and tube configurations to act as a proof-of-concept of a modular geothermal heat pump system.

G. PROTOTYPE TESTING

Once prototypes have been designed and created, it is recommended that multiple prototypes consisting of different materials and configurations be tested. This will provide data on if a modular geothermal heat pump is feasible to use as a primary heating source and also provide data on the specifics of how material and configuration influence system efficiency and effectiveness.

H. ECONOMIC ANALYSIS

In order to ensure that a modular geothermal heat pump would be economically viable to use as a primary heating and cooling source in residential settings, it is recommended that an economic analysis be conducted on the cost of the systems and the market itself. It is imperative that the potential customer pool be analyzed such that design decisions in the future can be made with customer preferences and pricing in mind. The final system sizing must include an economic analysis in order to prove viability.

6: APPENDICES

A. GUIDE FOR USING ENGINEERING EQUATIONS SOLVER (EES)

This is a list of things for future groups to consider and use for future use with EES. This is a that is great for iterating heat transfer and thermodynamic problems. The key value that this adds is the limitless material property lookup that exists in the program itself. This allows for easy iteration between materials and saves time. Additionally, it is very user friendly and the interface is easy to use and interpret.

- When working on problem solutions be sure to work chronologically. Working out of order may become confusing, even though the program will still solve for solutions it will be hard to organize.
- A great key to use is F2, it is the solve function. It is recommended to solve frequently to ensure that you are on the right track. This makes “debugging” easier.
- When you solve your systems of equations you may get a message that says, “unit problems detected.” This may mean that your units don’t match or that you have not assigned units. It is recommended to assign units right away.
- To assign units you can use [] after the equation, or you can double click and select variable info, and edit it in that space.
- Sometimes when you have a difficult, longer equation, it is nice to view the equations in formatted equations view. The function is F10, and this give the equations in traditional notation.
- When you are solving for things, you must assign the variable to a value before it can be used in an equation.

- Using “ ” allows you to comment on a line item. It is recommended to comment often in order to explain what you are doing, or where you got information from. It also allows other readers to understand your train of thought and following along with your work.
- Save often.
- You can comment out (“x”) anything at any time. You can have extra equations and such in the program and comment it out when you don't need it.
- Iteration is one of the biggest tools of this program. To iterate it is suggested to use the the parametric table function. This allows you to choose one variable to change; for example, see how length, resistance, and temperature change when you are iterating the viscosity (totally made up). First of all, you need to call out (“x”) the variable you wish to change in your program. Then you select “Make new parametric table”. Once the options box appears you first select the variable that you wish to vary, and then any amount of variable that you would like to see the effect on. Once the table is generated you will assign values to the first column and press the green arrow to run the table. The result will show you the results of the iteration.
- Similarly, you can create plots with the plot function that will show the iterations from the table you have just created, one variable at a time.

B. ENGINEERING EQUATION SOLVER (EES) FULL TEXT CODE

(Supplemental if given EES File is lost or unusable, the full text of EES code is below)

"Heating Mode, this is the heat cycle in the house. Refer to the diagram in the paper for reference"
T1=4.4 [C] "Value taken from example problem, can be rho=Density(R134a,T=T,P=P) a design decision"

P1=500 "Value taken from example problem, can be a design decision"

T3 = 23.9 [C] "condenser outlet temperature"

P3=1200 "Using compressed liquid at state 3"

"this fixes states 1 and 3"

h3=h4 "isenthalpic expansion"

T4=7 [C] "if the evap remains entirely under the dome-ask if we can use x4 to fix the state instead"

"x4=quality(R134a,T=T4,h=h4)" " not needed, just used as a reference"

" T=Temperature(R134a,P=P2,h=h2)" "TESTING"

"this fixes state 4"

P2=P3

s1=s2s "isentropic compression"

"state 1"

"h=Enthalpy(R134a,x=.9,P=P2)" "TESTING"

s1=entropy(R134a,T=T1,P=P1)

h1=enthalpy(R134a,T=T1,P=P1)

"state 2"

h2=enthalpy(R134a,T=T2,P=P2)

"T2=temperature(R134a,P=P2,h=h2)"

T2=60

h2s=h2

h3=enthalpy(R134a,T=T3,P=P3) "state 3"

P4=pressure(R134a,T=T4,h=h4) "state 4"

"Qo"

Qo=5 "this value taken from our renewable energy textbook page 157, it is the desired heat output for the system"

"COP=(h1-h4)/(h2-h1)" "coefficient of performance for the house loop"

nc=(h2s-h1)/(h2-h1) "compressor efficiency, not critical here,but available for reference"

"This Section is virtually independent of the section above. This is about the loop and pod temperature in the ground."

"The only information that is used from above, below, is the temperature input desired for the loop"

"As a reminder this is set in heating mode"

"Use Methanol as the fluid in the loops for now, the loop is defined as the heat transfer pipe, the traditional method"

"use CACL2 for the brine that will exist in the pod"

$\dot{m} = .504$ [kg/s] "mdot values are found in the Geothermal-Heat-Pump-Design-Manual.pdf"

"P1=500[Kpa]" "From the P1 given above"

$T_c = 4$ [C] "Tc is the same as T1, it is just labeled Tc here so that it is distinct at the cold temperature entering the Pipe system"

$H1b = \text{enthalpy}(\text{CaCl}_2, T=T_c, C=30 \text{ [\%]}, P=100 \text{ [Kpa]})$

$D_o = .025$ [m] "We have chosen a Pipe with this Outer Diameter as it is a common sized pipe, with a .98in sizing"

$R_o = .0125$ [m] "Outer Radius"

$D_i = .0229$ [m] "inner Diameter of the pipe, as given by common pipe sizing (can be varied)"

$K_{al} = 205$ [w/m-K] "aluminum has been chosen, but you can use any material. The answer is pretty stable regardless as the pipe wall is so thin"

$L = 75$ "length of the pipe, straight segment"

$A_1 = (2 * \pi * (R_o) * L)$ "Surface area of the pipe"

" $R_1 = (1 / (H1b * A_1))$ This the resistance for R1, it is used below as the answers all originally varied based on length which was not known"

" $R_2 = (\ln(D_o / D_i)) / (2 * \pi * K_{al} * L)$ Same as above, but for R2"

$K_{meth} = .202$ "thermal conductivity of methanol, which is needed to find the resistance"

$Nu = 3.36$ [-] "Assume Nusselt number of 3.36 as the boundary wall temperatures are constant and flow is laminar"

$H_{32} = Nu * K_{meth} / D_i$ "Used to calculate the 3rd resistance, notated as H32 because H3 is used in the House Loop above"

" $R_3 = 1 / (H_{32} * \pi * D_i * L)$ used for third resistance below"

$T_h = 7$ [C] "this is the hot temperature, or the exit temperature in the loop system"

$T_p = 15$ [C] "This is the Temperature of the ground that surrounds the pod"

$dT = (T_c - T_h) / \ln((T_p - T_h) / (T_p - T_c))$ "This is the LMTD used"

" $R_T = (1 / (H1b * A_1)) + ((\ln(D_o / D_i)) / (2 * \pi * K_{al} * L)) + (1 / (H_{32} * \pi * D_i * L))$ "

" $U = 1 / R_T$ "

" $L = q / (U * 3.14 * D_o * dT)$ "

" $dT = 5602 / (U * 3.14 * D_o * L)$ Used to find the LMTD "

" $q = ((1 / ((1 / (H1b * A_1)) + ((\ln(D_o / D_i)) / (2 * \pi * K_{al} * L)) + (1 / (H_{32} * \pi * D_i * L)))) * (\pi * D_o * dt)) * L$ "

" $q = U A dT$ Surface area of pipe , DT is the LMTD"

$q = (1 / ((1 / (H1b * A_1)) + ((\ln(D_o / D_i)) / (2 * \pi * K_{al} * L)) + (1 / (H_{32} * \pi * D_i * L)))) * dt * (2 * \pi * R_o * L)$

"use scroll compressor found from Marc Gelin, with a BTU/hr rate of 3682"

$q_{BTU} = q * 3.412$ "converting our q to Btu/hr for COP comparison"

$COP = q_{BTU} / 3682$ "Shows that dimensions do not work as the BTU hr rate above is just a number"

"This is to find the limitations of the tank size (volume) and the total Q"

"this equation is $Q = C_p \rho \Delta T V$, where ΔT is the change in temp and V is the volume of the tank"

$Q_{pod} = 1000000$

$C_p \text{CaCl}_2 = 3.06$

$\rho \text{CaCl}_2 = 2.21$

$\Delta T_{pod} = 5$

$V = Q_{pod} / (C_p \text{CaCl}_2 * \rho \text{CaCl}_2 * \Delta T_{pod})$

"Above shows that the ground is a critical part of the system as the Volume would have to be massive to meet the Q output"

C. CALCULATION OF POD DIAMETER, IGNORING GROUND FREEZING

"this uses the shape factor for a sphere buried in a semi-infinite medium to estimate heat transfer between the pod/ground"

"dimensions and parameters"

```
T_ground=50 [F]
T_groundC=converttemp(F, C, T_ground)
"D = 10" "pod diameter"
pod_depth= 20 [ft] "depth of center of pod"
z=pod_depth*convert(ft, m)
"T_1=0 [C]" "pod casing outer temperature"
```

```
Q_req=5000 [W]
Q=Q_req
Q=s*k*(T_groundC-T_1) "the heat transfer rate"
s=(2*pi*D)/(1+0.25*(D/z)) "shape factor"
k=conductivity(Soil, T=T_groundC)
```

"energy stored in pod"

```
V_pod=4/3*pi*(D/2)^3
rho=density(Water, T=T_0, P=P_atm)
P_atm=101.3 [kPa]
T_0=0 [C]
m=V_pod*rho
HF=enthalpy_fusion(Water)
E=m*HF
```

"heating oil"

```
heating_value=140000 [Btu/gal]
oil_burned=500 [gal] "per heating season"
energy_req=heating_value*oil_burned*eta
eta=.85 "oil burner efficiency"
E_req=energy_req*convert(btu, kJ)
E_req=E "to solve for pod size"
```

Unit Settings: SI C kPa kJ mass deg

D = 7.11 [m]	E = 6.278E+07 [kJ]	energy _{req} = 5.950E+07 [btu]
η = 0.85 [-]	E _{req} = 6.278E+07 [kJ]	heating _{value} = 140000 [Btu/gal]
HF = 333.6 [kJ/kg]	k = 0.52 [w/m°C]	m = 188174 [kg]
oil _{burned} = 500 [gal]	pod _{depth} = 20 [ft]	P _{atm} = 101.3 [kPa]
Q = 5000 [W]	Q _{req} = 5000 [W]	ρ = 1000 [kg/m ³]
s = 34.59 [m]	T ₀ = 0 [C]	T ₁ = -268 [C]
T _{ground} = 50 [F]	T _{groundC} = 10 [C]	V _{pod} = 188.2 [m ³]
z = 6.096 [m]		

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