Cornell University
Center for a Sustainable Future

Utilization of Closed Loop Geothermal Heat Pumps at Verizon Wireless Cellular Towers

Brandon LaBrozzi
Ed Dodge
Jefferson Tester

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PART 1: Geothermal Heat Pumps

1.1 Background and Motivation

The current industry standard for cooling cell tower equipment shelters employs the use of conventional wall mounted air conditioning units in order to remove excess heat build up to prevent the malfunction of the key equipment necessary to the operation of the network. Systems are typically over sized in order to meet any unforeseen heat abnormalities and are installed as an n+1 system for redundancy in the event that there is an HVAC equipment failure. While these systems are readily available, proven reliable and inexpensive to install, they are expensive to operate over the lifetime of the shelter in terms of both power consumption and maintenance. With tens of thousands of these units installed across the country, the scale of this problem is exceedingly large.

1.1.1 Typical Operating Conditions

Air conditioning equipment installed in the cell tower shelters typically operate at a set point of 72 °F and are needed throughout the year. Only during winter months in the coldest regions of the country is heating required within the shelter. Typically these air conditioning units have a rated cooling capacity of approximately 50,000 BTU/hr (14.6 kWt) and have an EER[1] (Energy Efficiency Ratio) of 9. However, the typical load within a shelter is on the order of 28,000 BTU/hr (8.1 kWt). A prototypical shelter located in Boston, Massachusetts requires 11,500 kWh per year of electricity for space cooling, and costing $1150 per year provided a rate of $0.10 per kWh. The shelter is normally constructed from cast concrete and has an insulation rating of R – 13. Infiltration from ambient air conditions only contributes a 5% increase to the cooling load in the worst-case (high temperature) scenario.

1.1.2 Geothermal Heat Pump Advantage

Closed loop, water to air geothermal or ground source heat pumps present a greener, more efficient alternative to conventional air conditioning. Geothermal heat pumps take advantage of heat storage underground at nearly uniform ground

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[1] . The EER is defined as the total thermal cooling provided by the unit (BTU/hr), divided by the power required to operate the unit (Watts)

temperatures, which gives rise to an inherently higher coefficient of performance (COP) over conventional air-to-air systems. The higher COP of heat pumps is provided by waterside condensing (as opposed to airside) which allows GHP's to provide an equal amount of cooling while consuming, on average, one third less electricity. Despite the fact that geothermal heat pumps are more costly upfront, mostly due to installing the ground loop heat exchanger, operating costs are substantially lower and possess the ability to pay for themselves over the lifetime of the unit. Geothermal heat pumps require considerably less maintenance than conventional air conditioning units and last much longer. With the ever-growing push for green energy alternatives and reducing consumption, geothermal heat pumps are an excellent alternative by exploiting the constant low temperature underground heat source that is available.

Geothermal heat pumps require two closed, independent loops in order to function properly. The refrigerant loop, which is housed inside the unit, exchanges heat with the air and ground loop via heat exchangers in the condenser and evaporator. The ground loop circulates water (or other fluid) through the piping where heat is exchanged from the fluid to the ground (or vice versa). The ground loop will be discussed further in Section 1-3 "Approach".

The refrigerant loop circulates R-410A through its four basic components: a compressor, a condenser, a throttling valve and an evaporator, where heat is transferred from one location to another, in this case, from the shelter to the ground. It operates by utilizing the vapor compression cycle of the refrigerant, which takes advantage of its latent heat of vaporization. The latent heat of vaporization is the amount of heat that a substance absorbs while undergoing phase change from a liquid to a gas at constant pressure and temperature. For example, one gram of liquid water at 100°C vaporized into the gas phase at constant pressure, undergoes no temperature change, but absorbs 2,257 Joules of energy (SVNA 133). For comparison, 2,257 Joules is capable of raising the temperature (at constant pressure) of the same gram of liquid water initially at 25°C, to 267°C. The latent heat of vaporization of R 410A is 258 kJ/kg (Elk Refrigerants).

The cycle proceeds as follows (see Figure 1-1): liquid refrigerant evaporates at a constant pressure (1 to 2) that provides a pathway for constant heat absorption at a low, constant temperature. The produced vapor is compressed to a higher pressure (2 to 3) where it is then cooled and condensed (3 to 4) while the heat is rejected at a higher temperature. The liquid returns to its original state by passing through the throttling valve (4 to 1), which lowers the pressure (SVNA 318).

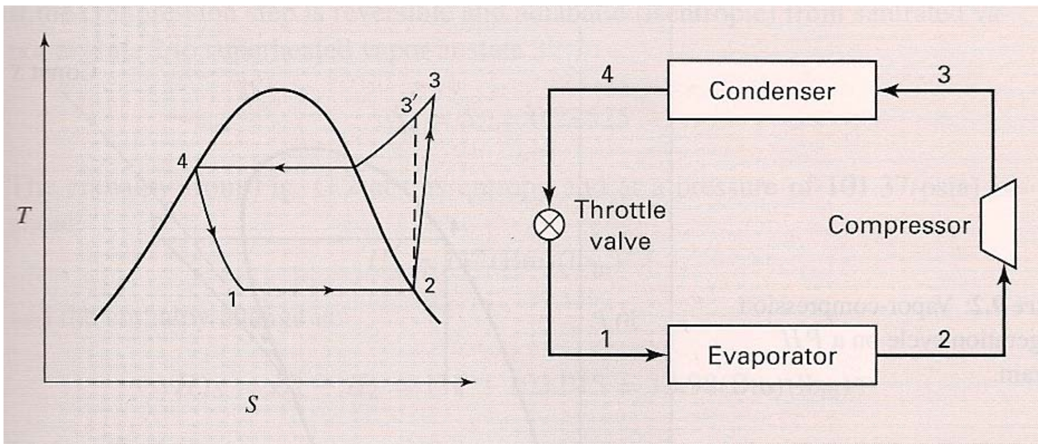

Figure 1-1. Vapor-Compression Cycle from SVNA pg. 319 Figure 9.2

Nearly every commercially available heat pump manufactured utilizes R-410A as the refrigerant in its vapor-compression cycle, therefore, there is relatively little difference in performance amongst different manufacturers when comparing similar models. R-410A has replaced R-22 as the refrigerant of choice because it contains no chlorine, thus has no effect on the ozone layer and exhibits a higher pressure and refrigeration capacity than R-22, increasing the performance of the GHP (Elk Refrigerants).

1.2 Project Objective and Scope

This study will evaluate the feasibility of replacing conventional wall mounted air conditioning units with closed loop, geothermal heat pumps. In order to be considered successful, several conditions must be met. These include:

1. The GHP must be able to meet a continuous 7- 10 kWt cooling load.

2. The entire installation must be contained within a small footprint at the tower locations.

3. The proposed technology must be widely available and easily deployable across 48 states (excluding Hawaii and Alaska) covering a wide range of weather conditions and ground temperatures.

4. The cost of the entire installation must be repayable via reduced electricity consumption within a certain time frame.

5. Heat transfer to the ground needs to be maximized and the possibility of long term thermal saturation must be considered in order to minimize performance degradation over time.

1.3 Approach

The methodology of the study began with researching the most current design and installation practices used in industry today as well exploring options available from different GHP manufacturers. A significant portion of information was collected from the International Ground Source Heat Pump Association (IGSHPA), Oregon Institute of Technology, National Renewable Energy Laboratory (NREL) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

In order to successfully and accurately model the GHP system, obtaining industry proven design software was integral to the study. Upon reviewing the options available, GLHEPRO v4.0 published by IGSHPA and GLD2009 by Gaia Geothermal presented themselves as the best options for the simulations. The software calculates the required loop length by accounting for monthly heating and cooling loads, ground surface temperature, ground thermal conductivity/diffusivity and specified borehole parameters. Additionally, a set of design manuals authored by IGSHPA was essential to understanding the fundamentals of GHP systems.

Perhaps the most important feature of a GHP system is the ground loop heat exchanger. For that reason, it was of utmost importance to evaluate the subsurface loop design and performance. In doing so, it was necessary to evaluate ground surface temperatures, ambient air temperatures, thermal properties of the ground and several borehole configurations.

Combining the broad scope of this study (48 states) and the vast variability in ground surface temperatures ranging from 4°C to 26°C (39°F to 79°F), ambient air temperatures from -45°C to 54°C (-50°F to 130°F) and soil properties (geology, thermal conductivity, permeability, etc) across these limits, it became necessary to define several sets of parameters to focus the analysis.

When determining the size of the ground loop heat exchanger, one of the most important variables that needs to be considered is the ground temperature near the surface. Equally important is the climatic conditions where the GHP system is to be installed. By comparing maps of both ground surface temperature (Figure 1-2) and climate (Figure 1-3), it was possible to define 5 base case regions to concentrate the study.

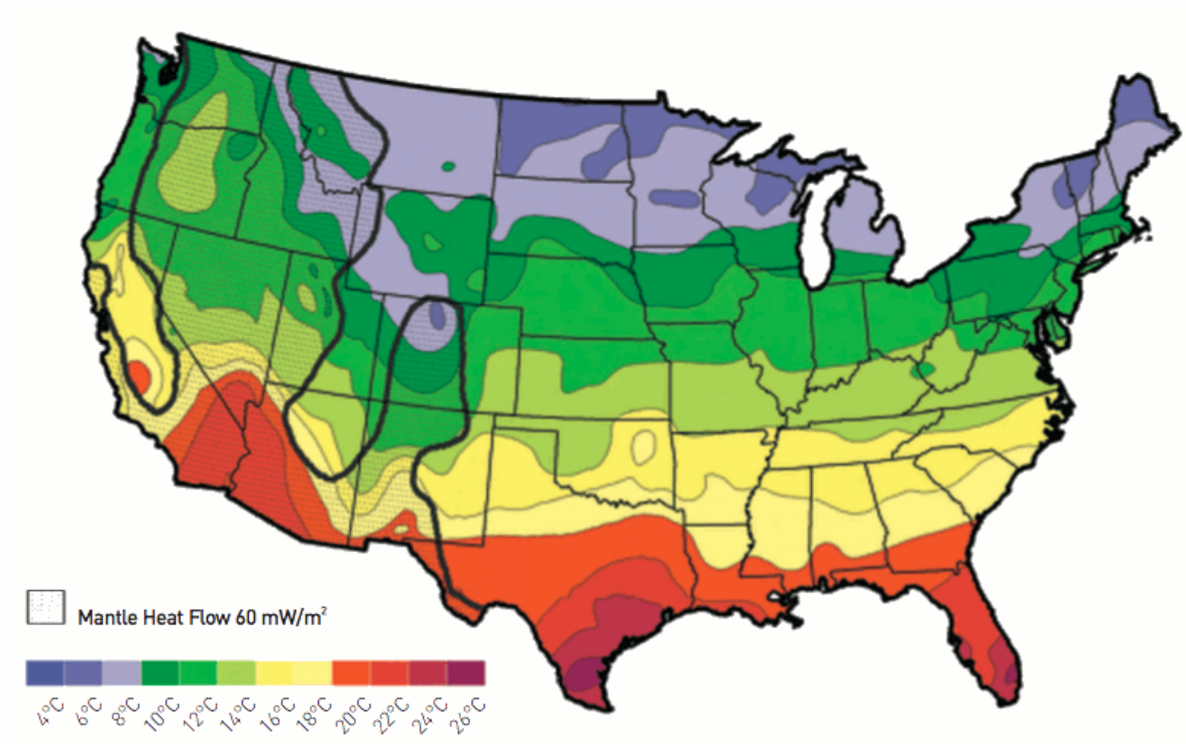

Figure 1-2. Ground Surface Temperatures of the United States from The Future of Geothermal Energy, Tester, et. al. (2006)

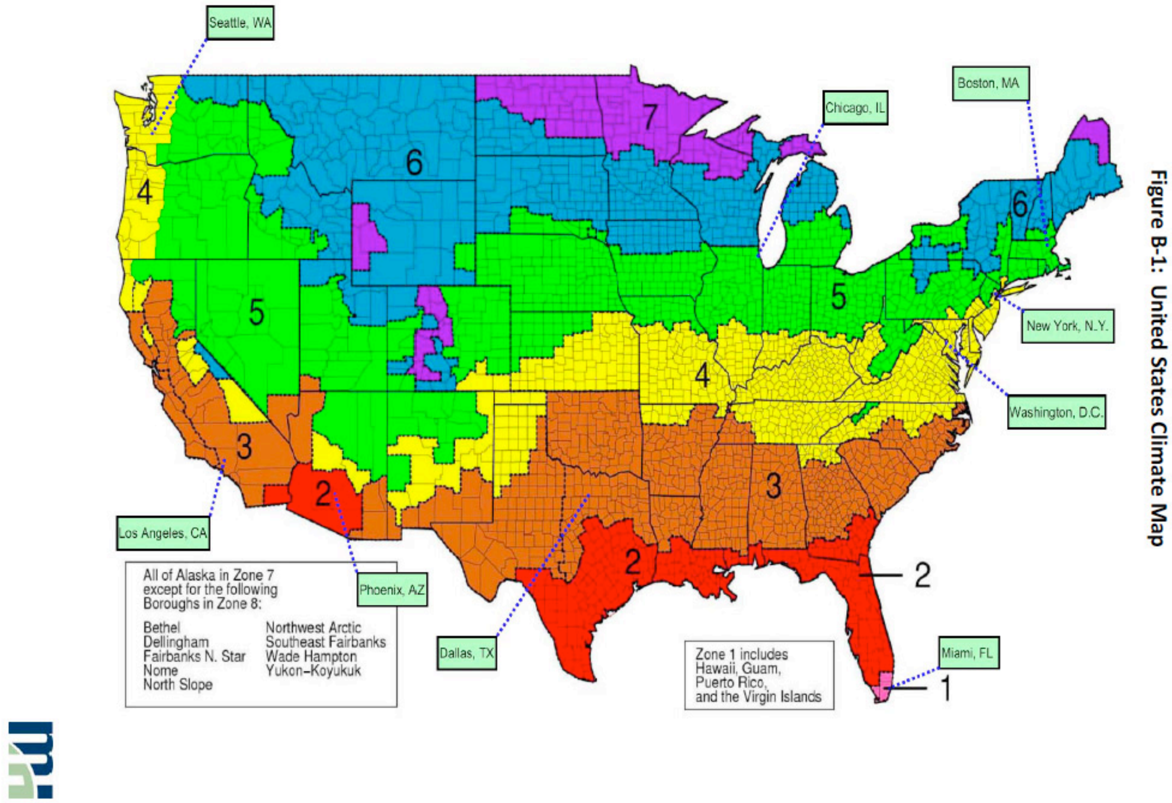

Figure 1-3. Climate Zones of the United States from Morrison Hershfield - Total Cost of Ownership Evaluation for Verizon Wireless

As shown in Figures 1-2 and 1-3, an obvious and expected correlation exists between climate zones and ground surface temperature. The base case zones and ground surface temperatures for this study were defined as follows: Climate zones 1 and 2 were combine as one zone with a ground surface temperature of 23°C (73.4 °F), climate zone 3 at 18°C (64.4 °F), climate zone 4 at 14°C (57.2 °F), climate zone 5 at 11°C (51.8 °F) and climate zone 6 and 7 (combined) at 7° (44.6 °F).

Similar to ground and ambient temperatures, the thermal conductivity of the subsurface material plays a key role in determining the size of the ground loop heat exchanger. Due to the broad extent of the study and immense inconsistency of geology across the United States, specifying values for the thermal conductivities (k) for each base case region was done by defining a range of possibilities that could be encountered. The geologies used are summarized in Table 1-3 (Section 1-5 "Simulations"). Below, Figure 1-4 demonstrates the degree to which the geology varies across the country, where each color represents a different geological formation.

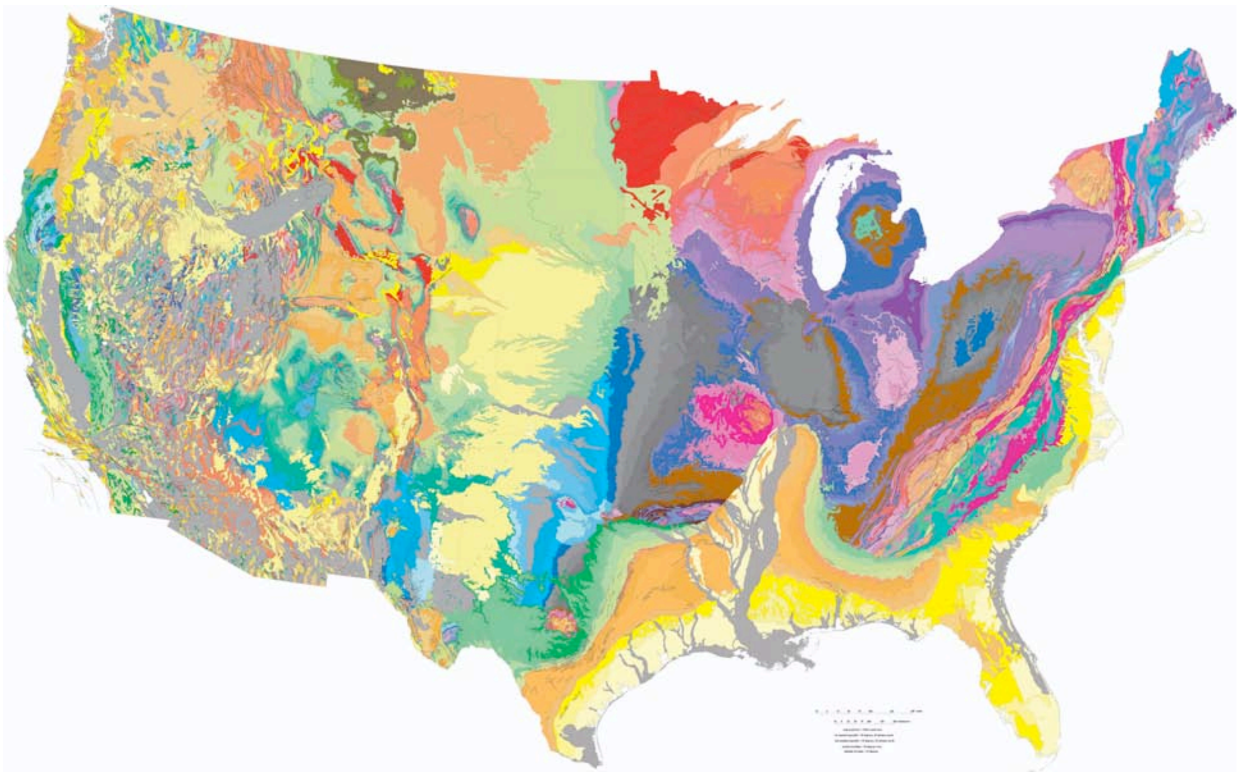

Figure 1-4. Geologic Map of the United States source Beikman and King, USGS 1974

Ground loop heat exchangers can extract or deposit thermal energy in the earth in a number of ways; horizontal loops, vertical loops, standing column loops and pond loops. Given that prototypical cell towers are often leased from other landowners, ground loop locations require a minimal amount of space on the surface, typically fifty feet square or less. The most viable option for installing the ground loop heat exchanger in this application is using a vertical loop due to these limited space constraints. The pipe carrying the working fluid of the system can be arranged in the borehole in a number of ways: single U tube, double U tube and coaxial. All three vertical flow arrangements were evaluated.

A typical GHP installation uses the earth as a heat sink in the warmer months and as a heat source in the cooler months. However, due to the “cooling only” nature of the cell tower equipment shelters, the GHP is always depositing heat into the ground loop. In order to evaluate the effect of this type of operation, it would be necessary to perform a transient heat transfer analysis of the well field to predict the temperature of the ground over time. This analysis was beyond the scope of this project, however, similar work is being conducted at Cornell University that would be applicable to this specific set of circumstances. The transient heat transfer analysis will predict the temperature rise in the rock formation and the extent in which the deposited thermal energy dissipates. If the well field becomes thermally saturated, the performance of the GHP declines dramatically (i.e. as the refrigerant condenser side temperatures increase, the COP of the refrigeration system decreases). This is the same phenomenon that occurs with air-cooled direct-expansion refrigerant HVAC solutions during operation in the summer months when the ambient temperature rises.

While the technology proposed may appear superior in terms of engineering principles, it must also be financially superior. Calculating capital and installation costs, operating costs and life cycle costs have been analyzed in Section 1-7, 1-8 and 2-5, respectively.

1.4 Boreholes

The two most common types of loop designs are horizontal and vertical loops. Horizontal loops run piping parallel to the ground in shallow trenches 6-8 feet deep and require 2500 sq ft/ton. Vertical loops run piping into the ground several hundred feet deep, requiring 250-300 sq ft/ton (McQuay International 6-7). The limited space constraints the study is posed with, dictates that the loop must contain as few vertical boreholes as possible.

Figure 1-5. Diagram of Vertical Loop System source: McQuay International, 2009.

The pipe installed into the borehole is typically a Schedule 40, SDR 11 or SDR 9 high-density polyethylene (HDPE) material ranging in diameters from ¾ to 1-½ inches. Pipe diameter also dictates the approximate minimum flow rate needed for the working fluid.

The piping is typically installed in one of three arrangements, single U tube, double U tube and coaxial flow. Single and double U tube arrangements are most commonly used for vertical GHP systems, whereas coaxial flow is much less common. Coaxial flow arrangement is typically too difficult to implement in practice and few installers utilize this method. Rygan Corporation manufactures a coaxial flow piping system, but few installers are familiar with this product and would be difficult to deploy nationally.

Table 1-1. Minimum Flow Rates

Pipe Size (in.)	Min Flowrate (US gpm)	Pipe Size (in.)	Min Flowrate (US gpm)
¾	4	1 ½	12
1	6	2	18
1 ¼	9	3	40

Source: McQuay International

Grouting the borehole after the installation of the pipes is important for both environmental and performance reasons. Grouting the borehole fills in the annular space between the pipe and the borehole wall, which prevents or restricts the ability of surface and/or groundwater to flow vertically along the borehole. The sealing of the ground loop heat exchanger borehole is required for the same reasons as water wells, which is the sanitary protection of any existing or potential water supply aquifer that is penetrated by a borehole (Hiller 1-1).

In order to maximize the heat transferred to the ground from the pipe, the grout must have a high thermal conductivity that minimizes the resistance of heat flow to the earth. The grouting material also needs to possess a low viscosity during placement as to circumvent creating any void spaces in the borehole, which reduces heat transfer. The selected grout must also remain in constant contact with pipe, not only during expanding and contracting during temperature changes but also during the curing process. The grout must also retain its properties over the lifetime of the well and not degrade in any way (Hiller 1-6).

There are two main types of grouts available for use today; bentonite based grouts and cement-based grouts.

Bentonite is a volcanic phyllosilicate of the montmorillonite group that is found in the western and southern United States. Bentonite mined in the West is more specifically called sodium montmorillonite bentonite, which can swell to fifteen times its dry volume. Southern bentonite, or calcium montmorillonite bentonite does not possess the ability to significantly swell in the presence of water. The extensive swelling of sodium bentonite and low viscosity makes it the leading choice of bentonite in the drilling industry (Hiller 1-9,10).

Cement-based grouts can refer to a variety of binding materials including both Portland and neat cements, glues, epoxies, mortars and aggregates. Neat cements have in the past been favored over bentonite-based grouts where boreholes penetrate consolidated and fractured rock formations with high rates of ground water movement through unsaturated zones (Hiller 2-7). Neat cements form a rigid seal that is typically impervious to ground water erosion, whereas bentonite grouts may erode under such conditions. When used in conjunction with consolidated rock formations, cement is thought to form a better seal with the natural rock formation (Hiller 2-7).

However, cement-based grouts do have their disadvantages. The hydration of neat cements causes the mass to shrink slightly, causing the material to pull away from the pipe, thus creating a void space and inhibiting heat transfer. Furthermore, a significant amount of heat is released during the hydration process that has been shown to damage PVC and HDPE pipes. The biggest factor for the decline in use of cement based grouts is the cost. Bentonite based grouts are generally less expensive per unit volume than cement based grouts (Hiller 2-8). Table 1-2 lists a small number of commercially available grout products.

Table 1-2. Commercially Available Bentonite Grout

Product	Solids (%)	Water (Gal)	Yield[1] (Gal)	Grout[1] Weight (lb/Gal)	Thermal[1,2] Conductivity (Btu/hr ft F)	Permeability[1,2,3] (cm/s)
Aquaguard	30	14	16.8	9.92	0.43	1×10^{-6}
Aquagrout	22.7	20	23.2	9.50	0.43	8×10^{-8}
Benseal/EZ Mud	15.3	33	36.6	8.94	0.38	6×10^{-8}
BH Grout	30	14	16.8	9.93	0.45	3×10^{-8}
Enviroplug	30	14	16.9	9.86	0.44	1×10^{-8}
Groutwell[4]	18	27	30.7	9.05	0.41	1×10^{-7}
Puregold	30	14	16.9	9.87	0.44	2×10^{-8}
Quick Grout	20	23	27.0	9.25	0.41	3×10^{-7}
Volclay Grout	20	23	27.5	9.08	0.43	1×10^{-7}

1. Paul and Remund et al (1996). 2. Remund et al (1993). 3. Measured permeability after approximately 80 hours. 4. Groutwell is a powdered bentonite product. Groutwell DF is a granular form of the same bentonite grout product, and displays the same physical properties.

Source: Hiller 2-3 (Note: Permeability in Table 1-2 refers to hydraulic conductivity)

Thermal conductivity testing is used to determine a more accurate value for the heat transfer rate associated with the specific geology where the unit is to be installed. While this process can be completed in 24-48 hours, costs are often prohibitive for installations of this size and as a consequence these tests are not normally used.

The working fluid used to transport heat through the ground loop is either pure water, a mixture of water and methanol or ethanol or a mixture of water and propylene or ethylene glycol. Pure water should not be used if the fluid temperature is expected to fall below 42 °F to avoid freezing. Glycol solutions work well in warmer climates but increase in viscosity as the temperature decreases thus causing the circulating pump efficiency to fall. Alcohol-based solutions tend to perform well in all temperature conditions (McQuay International 12,19).

1.5 Simulations

A standard set of base parameters were needed to be defined in order to evaluate the effects of altering the variables of the simulation. The primary design program used was GLHEPRO v4.0 and GLD 2009 was used to validate the results. While each program required slightly different inputs in order to perform the calculations, all efforts were made to ensure that identical parameters were used between programs.

Due to the large variation of geology and thermal conductivity (k) across each defined climate zone, three sets of soil conditions were selected to represent the range of variables that could be encountered. Specifying exact soil and rock compositions for each zone was unrealistic in this case, thus generalizations were made.

Table 1-3. Geological Properties Used

Geology	**Conductivity** BTU/hr*ft*°F	**Density** lb/ft³	**Specific Heat** BTU/lb*°F	**Volumetric Heat** BTU/°F*ft³
Light, Damp Soil	0.50	100.0	0.25	24.98
Average Rock	1.40	175.0	0.20	34.93
Dense Rock	2.00	200.0	0.20	39.93

1.5.1 Base Case Design

Within GLHEPRO v4.0, the base case GHP used was a WaterFurnace Premier 2 series unit, sized at 28,000 BTU/hr. The chosen working fluid was a 20%wt solution of methanol and water, circulating at 10 gpm through 1 ½ inch, Schedule 40 HDPE pipe (pipe thermal conductivity 0.225 BTU/hr*ft*°F) in a 6 inch borehole. A single borehole was assumed to be sealed with a grout that had a thermal conductivity of 0.43 BTU/hr*ft*°F. The simulation was performed over 120 months and used a maximum fluid temperature entering the heat pump of 90 °F and a minimum temperature of 20 °F. The system load used was a continuous, 8.1 kWt (~28,000 BTU/hr) cooling load.

The calculation was performed to determine the depth of the borehole (in feet), for the given parameters. Each region was evaluated at the specified ground temperature and soil conditions defined above for a single U tube installation.

Table 1-4. Base Case Borehole Depth

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3450	1570	1230
3	2380	1080	850
4	1900	860	680
5	1660	750	590
6 and 7	1410	640	500

Note – k has units of BTU/hr*ft*°F

As shown in Table 1-4, designing the system to a worst possible U.S. case regarding ground temperature and geological conditions, the depth of borehole required for the system to adequately operate is 3450 feet, which is beyond the realm of practicality. Once the simulation was run using rock as the heat transfer medium the depth of the boreholes becomes more sensible.

1.5.2 Double U Tube

Intuition implies that doubling the length of HDPE pipe within the borehole would decrease the overall depth of borehole, but assuming a linear relationship between the two variables would prove misguided. All variables used in the base case were held constant except for the borehole flow arrangement.

Table 1-5. Base Case with Double U Exchanger

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3270	1400	1220
3	2260	960	740
4	1820	770	590
5	1570	670	510
6 and 7	1340	570	430

Note – k has units of BTU/hr*ft*°F

Changing the borehole flow arrangement from a single U to a double U exchanger decreases the depth of borehole in light, damp soil by ~ 5%, average rock by ~ 10% and dense rock by ~ 13%.

1.5.3 Grout

There are many options available regarding grout products, the most important factor to consider when calculating borehole depth is the thermal conductivity. Many manufacturers offer a range of grouts with differing conductivities that can be altered by varying the amount of water, aggregate and other additives to the mixture. To compensate for the range of options available, three different values for thermal conductivity were used in the simulation: standard grout with k = 0.43 BTU/hr*ft*°F (base case), and two thermally enhanced grouts with k = 1.0 BTU/hr*ft*°F and k = 1.4 BTU/hr*ft*°F.

Grout Simulations

The base case parameters were held constant except for the thermal conductivity of the grout.

Table 1-6. Base Case, Grout k = 1.0 BTU/hr*ft*°F

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3370	1390	1080
3	2250	960	730
4	1830	780	590
5	1570	660	500
6 and 7	1340	570	430

Note – k has units of BTU/hr*ft*°F

Increasing the thermal conductivity of the grout from 0.43 to 1.0 BTU/hr*ft*°F decreased the depth of borehole for light damp soil by ~ 5%, average rock by ~ 11% and dense rock by ~ 14%.

Table 1-7. Base Case, Grout k = 1.4 BTU/hr*ft*°F

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3170	1300	1060
3	2190	900	670
4	1750	710	530
5	1520	620	460
6 and 7	1300	530	390

Note – k has units of BTU/hr*ft*°F

By using a thermally enhanced grout (Table 1-7) in place of a standard conductivity grout the reduction in borehole depth for light, damp soil was ~ 6%, average rock ~ 14% and dense rock ~ 18%.

Selecting the type of grout for the given application should be done on a case-by-case basis. As previously mentioned, neat cement based grouts can perform better in certain situations (areas of high groundwater flow) than bentonite-based grouts. Furthermore, the thermal conductivity of the grout should roughly match that of the rock formation and the permeability of the grout should be at least one order of magnitude lower than that of the formation (Hiller 1-15). Table 1-8 lists some common geologies and their respective permeability. As demonstrated by the results in Table 1-6 and 1-7, utilizing enhanced grouts in formations with low thermal conductivities only provides a 5% and 6% respective decrease in borehole depth as compared with the base case values. However, using enhanced grouts in higher conductivity formations can yield an 18% decrease in borehole depth versus the base case conditions, as shown in Table 1-7.

Table 1-8. Permeability of Geological Formation Materials

Geological Formation	**Hydraulic Conductivity** m/s	**Permeability** Darcy = m^2
Gravel	10^{-4} to 1	10^{-11} to 10^{-7}
Clean Sand	10^{-6} to10^{-4}	10^{-13} to 10^{-11}
Silty Sand	10^{-7} to 10^{-3}	10^{-14} to 10^{-10}
Glacial Till	10^{-12} to 10^{-9}	10^{-19} to 10^{-16}
Unweathered Marine Clay	10^{-13} to 10^{-10}	10^{-20} to 10^{-17}
Shale	10^{-14} to 10^{-10}	10^{-21} to 10^{-17}
Igneous Rock (unfractured)	10^{-10} to 10^{-6}	10^{-17} to 10^{-13}
Sandstone	10^{-9} to 10^{-6}	10^{-16} to 10^{-13}
Limestone or Dolomite	10^{-9} to 10^{-6}	10^{-16} to 10^{-13}
Karst Limestone	10^{-6} to 10^{-2}	10^{-13} to 10^{-9}

Source: Hiller 1-15

1.5.4 Borehole Diameter

Determining the diameter of the borehole used requires the consideration of several factors. Perhaps the most dominant driving force when determining the diameter is the capabilities of the drilling equipment available in a given area. According to Daniel Fien of eVanHee Energy Solutions in Rochester, NY, a 4 to 6 inch borehole is a typical standard in the GHP industry and is common for drilling contractors. In terms of the effect the diameter has on the overall depth of the borehole, efforts should be made to keep it minimized. Increasing the diameter increases the distance the heat must flow from the exchanger pipe to the rock formation, thus increasing the borehole thermal resistance. Table 1-9 provides a summary of the base case simulations performed with a borehole diameter of 10 inches.

Table 1-9. Base Case, Borehole Diameter = 10 Inches

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3700	1810	1500
3	2410	1240	1040
4	1930	1000	830
5	1680	870	720
6 and 7	1430	740	610

Note – k has units of BTU/hr*ft*°F

As compared to the base case simulations with a 6 inch borehole, the 10 inch borehole yielded a 7% increase in borehole depth in light, damp soil, a 14% increase in average rock and a 19% increase in dense rock.

1.5.5 Ground Loop Exchanger Pipe Diameter

As opposed to the borehole diameter, as the diameter of the HDPE pipe used in the ground loop heat exchanger increases, the borehole thermal resistance decreases due to the increased surface area of the exchanger pipe. Thus improving the heat conduction with the ground and decreasing the depth of the borehole.

Table 1-10. Base Case, ¾" Diameter Exchanger Pipe

Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3770	1900	1570
3	2610	1310	1090
4	2090	1050	870
5	1820	910	760
6 and 7	1550	780	640

Note – k has units of BTU/hr*ft*°F

Table 1-10 shows that decreasing the diameter of the exchanger piping from 1 ½" in the base case to ¾" produces an increase regarding borehole depth in light, damp soil of 9%, an increase of 18% in average rock and an increase of 22% in dense rock.

1.6 Validation of Design

In order to validate the GLHEPRO design recommendations presented, the simulations were run once more using GLD 2009. While differences existed in the required inputs for each modeling program, all efforts were made to ensure identical operating conditions were mimicked. The results obtained using GLD 2009 replicated those found using GLHEPRO very well. When comparing the calculated total depth of borehole from both programs, the results averaged a seven percent difference in values, having a standard deviation of three. Obtaining similar values from both design programs ensures that the results are accurate. Additional GHLEPRO output as well as output from GLD2009 can be found in Appendix D and Appendix E, respectively. The results were also confirmed by eVanHee Energy Solutions to be appropriate for the specified conditions and were within five to ten percent of the results obtained from their software simulations under the same conditions. Furthermore, Robin Curtis and Tony Batchelor of EarthEnergy Ltd performed the same calculations, which resulted in only a thirteen percent difference between the results of this study, well within the realm of acceptable error.

1.7 Capital Costs

Cost information was gathered by surveying installers and retailers from different parts of the country. Prices can and will vary depending upon location and volume. Most notably, purchasing in volume can lower the price of the heat pump unit itself. EIA data collected on the geothermal heat pump industry indicates that approximately 100,000 units were manufactured in 2008. Thus, ordering several hundred units would be a very significant increase for a single manufacturer. David Neale of eVanHee Energy Solutions suggests that purchasing 100-400 units could lower the cost to approximately $3000 each, less than half of purchasing the average unit individually.

Capital costs of conventional air conditioning units are significantly lower than that of a GHP. The price of air conditioning units installed in the shelters ranges from $1,700 to $4,200 ($3,000 average) sized between 36,000 to 60,000 BTU/hr (10 to 18 kW). The low capital costs of air conditioning units drive consumers to choose them over GHP's, without considering long term operating expenses.

Table 1-11. Average Costs for GHP Surface and Subsurface Equipment

Water to Air, 28-30 kBTU/hr GHP	Retail: $6000-$8500 Average: $7400
Bentonite Base Grout (k~0.43 BTU/hr*ft*°F) Thermally Enhanced (k~1.0–1.4 BTU/hr*ft*°F)	Average: $3-$4.50 per cubic foot Average: $7.50-$9.75 per cubic foot
HDPE Pipe	Average: $0.22 per foot
Drilling	Average: $11-$18 per foot

1.7.1 Cost Analysis by Zone

As noted previously, the variations in geology that exist across the scope of the project do not allow for practical consideration of specific geologies in the simulations. By utilizing several values for ground surface thermal conductivity, it is possible to cover the range of conditions that may be encountered in the field. Similarly, taking into account the effect of ground water movement across the well field further complicates the analysis. Making use of Figure 1-2: Ground Surface Temperature Map of the United States and Figure 1-3: Climate Zones of the United States, as well as average monthly temperature data collected for each zone (Appendix A), it was possible to estimate operating conditions.

Calculation of the capital costs used the information listed in Table 1-11. The price used for the GHP unit was taken as an average of $7400. Grout was priced at $3 per cubic foot and $9.75 per cubic foot for thermally enhanced grout. Ground loop exchanger pipe was priced at $0.22 per foot and drilling at $11 per foot.

Zones 1 and 2

Zone 1 and 2 pose the most challenges when designing a GHP system; mainly due to the high ground surface temperature associated with the region, averaging 23 °C (73.4 °F). Clearly, these high temperatures are not as conducive for cooling applications as lower temperatures. Formation thermal conductivity is key to minimizing the overall depth of the borehole, which essentially dictates system capital costs.

Table 1-12. Capital Costs and Borehole Depth Zone 1 and 2

	Depth in ft Light, Damp Soil k = 0.50	Cost	Depth in ft Average Rock k = 1.4	Cost	Depth in ft Dense Rock k = 2.0	Cost
Single U	3450	$48,800	1570	$26,300	1230	$22,200
Double U	3270	$48,200	1400	$24,900	1220	$22,600
Double U w/ Enhanced Grout	3140	$50,800	1280	$25,000	960	$20,600

Note – k has units of BTU/hr*ft*°F

Table 1-12 shows that even when formation thermal conductivity approaches 2.0 BTU/hr*ft*°F the borehole depth required to satisfy the system is still rather large at 1230 feet. In this set of circumstances, implementing a double U tube ground loop exchanger does not yield a lower capital cost. The depth of borehole decreases by 10 feet to 1220 feet; this small difference in borehole depth does not allow the decrease in drilling depth to counter the cost of doubling the amount exchanger pipe in the ground. The capital required to install a double U system in these conditions is $22,600, an increase of $400.

The design can be improved upon by replacing the standard conductivity grout to a thermally enhanced grout with a conductivity of 1.4 BTU/hr*ft*°F. To reduce costs further, utilizing a double U tube ground loop exchanger and enhanced grouts will bring the capital cost of the system to $20,600.

It is worth noting, that using enhanced grout in low conductivity geology does not lead to a decrease in cost. The base case design in light, damp soil would require $48,800 while changing over to thermally enhanced grout would increase the cost to $50,800. As previously mentioned in section 1.5.3 *Grout Simulations*, efforts should be made to match the thermal conductivity of the grout with that of the geology at the installation site.

Zone 3

Zone 3 provides conditions that are slightly more favorable to GHP use than Zone 1 and 2, with an average ground temperature of 18°C (64.4°F).

Table 1-13. Capital Costs and Borehole Depth: Zone 3

	Depth in ft Light, Damp Soil k = 0.50	Cost	Depth in ft Average Rock k = 1.4	Cost	Depth in ft Dense Rock k = 2.0	Cost
Single U	2380	$36,000	1080	$20,400	850	$17,600
Double U	2260	$35,600	960	$19,300	740	$16,600
Double U w/ Enhanced Grout	2170	$37,300	880	$19,500	650	$16,400

Note – k has units of BTU/hr*ft*°F

Just as in Zone 1 and 2, installing the system in poor conductivity soil or rock is cost prohibitive. Installations in medium to high conductivity rock can reduce the cost of the system by half. Making use of the double U ground loop exchanger will decrease the cost of the system by $1,000 (in dense rock scenario) to $16,600. Using thermally enhanced grouts and/or coupling these two variables together can make further improvements.

Zone 4

Intuitively, as the latitude increases, the ground temperature decreases, thus improving the ability of the geothermal heat pump to effectively cool the shelter. The average ground surface temperature expected in Zone 4 is 14°C (57.2°F).

Table 1-14. Capital Costs and Borehole Depth: Zone 4

	Depth in ft Light, Damp Soil k = 0.50	Cost	Depth in ft Average Rock k = 1.4	Cost	Depth in ft Dense Rock k = 2.0	Cost
Single U	1900	$30,300	860	$17,800	680	$15,600
Double U	1820	$30,100	770	$17,000	590	$14,800
Double U w/ Enhanced Grout	1740	$31,400	700	$17,100	520	$14,500

Note – k has units of BTU/hr*ft*°F

Continuing the same pattern as before, borehole depth decreases as improvements are implemented to the design, which in turn reduces costs. Employing both a double U ground loop exchanger and thermally enhanced grout in a dense rock geological scenario, it is possible to save about $1,000 in comparison with the base, single U and standard grout design.

Zone 5

The average ground surface temperature expected to be found in Zone 5 is 11°C (51.8°F), which proves to provide an excellent source for geothermal cooling.

Table 1-15. Capital Costs and Borehole Depth: Zone 5

	Depth in ft Light, Damp Soil k = 0.50	Cost	Depth in ft Average Rock k = 1.4	Cost	Depth in ft Dense Rock k = 2.0	Cost
Single U	1660	$27,300	750	$16,400	590	$14,500
Double U	1570	$27,000	670	$15,800	510	$13,800
Double U w/ Enhanced Grout	1510	$28,300	610	$15,800	450	$13,600

Note – k has units of BTU/hr*ft*°F

The cost to install a system in average to dense rock at the ground surface temperatures encountered in Zone 5 continues to decrease making the decision to use geothermal heat pumps more appealing. In both situations, the decrease in system cost by using both enhanced grout and double U ground loop exchangers is approximately $1,000.

Zone 6 and 7

It is of no surprise to find that the least expensive geothermal heat pump systems to install are located in Zone 6 and 7. The average ground temperature in these zones is 7°C (44.6°F). This low temperature allows for the depth of the borehole to be just a few hundred feet, as opposed to its southern counterparts where depths can extend 1000+ feet.

Table 1-16. Capital Costs and Borehole Depth: Zone 6 and 7

	Depth in ft Light, Damp Soil k = 0.50	Cost	Depth in ft Average Rock k = 1.4	Cost	Depth in ft Dense Rock k = 2.0	Cost
Single U	1410	$24,400	640	$15,100	500	$13,400
Double U	1340	$24,100	570	$14,500	430	$12,800
Double U w/ Enhanced Grout	1300	$25,200	520	$14,500	380	$12,700

Note – k has units of BTU/hr*ft*°F

In comparison to the results shown in Zone 1 and 2, there is approximately an $8,000 difference between the northern and southern latitudes of the United States.

1.8 Geothermal Heat Pump Energy Consumption and Operating Costs

As one of the driving factors behind this project, energy consumption by space conditioning equipment at cellular towers contributes a large portion of the overall energy use, as detailed in Figure 1-6. Clearly, the network equipment, rectifiers and auxiliary equipment operate with efficiencies less than 100%. The energy is lost as heat, which necessitates the use of HVAC equipment in order to cool the shelters. Installing more efficient equipment in the shelter would effectively reduce the amount of energy consumed by the HVAC system.

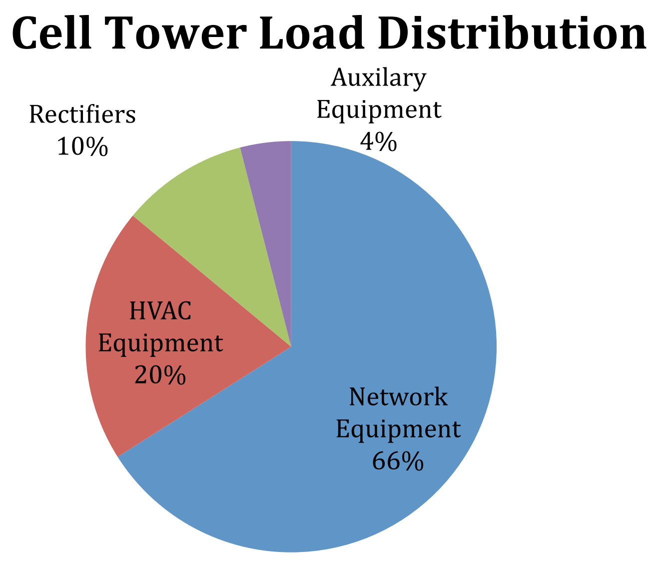

Figure 1-6. Cell Tower Energy Consumption from Verizon Wireless

Shelters operate at an HVAC set point of 72°F in order to maintain satisfactory conditions for successful equipment operation. The average site consumes electricity priced at $0.10/kWh and contains a wall mounted air conditioning unit rated with an EER of 9. Verizon Wireless provided a report in which energy related data was collected from a prototypical shelter located in Boston, Massachusetts. The report showed that the cost of cooling the shelter for one year was $1,149. Calculating the cost associated with cooling the shelter based upon an EER of 9 results in $1,153 per year.

Table 1-17. HVAC Performance and Energy Use

	EER	kWe	kWhr/year	$/year
Geothermal Heat Pump	26	1.07	3991	400
Air Conditioning	9	3.11	11531	1153

Geothermal heat pumps higher EER value allows them to cool the shelter much more efficiently. Using the above information, it is possible to determine that the air conditioning unit operated for 3700 hours during the year in which data was collected (approximately 10 hours per day). Using the average geothermal heat pump EER of 26 and the required cooling load of 28,000 BTU/hr at $0.10/kWh, the operating cost of the heat pump is $400 per year, a savings of $750. Taking these figures over a 15 year period, geothermal heat pumps are capable of saving $11,300. Table 1-17 summarizes this information.

PART 2: Hybrid Systems; Geothermal Heat Pumps and Air Economizers

2.1 The Case for Air Economizers

With the climatic conditions experienced in a large part of the United States for at least half of the year, cooling the shelters with outside air provides a simple solution. This can be accomplished by the use of air economizers, which is essentially a fan that expels warm air from inside the shelter and draws in cool air from the environment. The fans operate with relatively low power consumption, averaging 0.25 horsepower (0.18 kWe) at 1500 cubic feet per minute (cfm). Due to their simplicity and lack of a compressor, the capital cost of air economizer units are very low, approximately $300-$400 each. Coupling air economizers with other cooling methods can reduce energy consumption, which saves money.

2.2 Intel Proof of Concept

Intel Corporation has already demonstrated that air economizers can provide adequate cooling in temperatures up to 90°F in one of their 10 MW server locations. The exact location of the server was not revealed within the report, but claimed it was located "in a temperate desert climate with generally low humidity". The system was designed such that the air economizer would operate between 65°F and 90°F. When the ambient temperature fell below 65°F, the incoming air was preconditioned with the exiting air. When the ambient temperature exceeded 90°F, the air economizer was shut down and an air cooled chiller turned on. The server location was subjected to variations in humidity ranging between four and ninety percent and had limited air quality control, utilizing only a standard household HVAC air filter to capture large particulate matter (Atwood 1-4).

The study began in October of 2007 and commenced in August 2008. At the end of the study it was found that despite the servers being exposed to large variations in humidity and air quality conditions (a layer of dust covered the servers), the server failure rate inside the air cooled building was 4.46 percent. The failure rate at the main data center, with air conditioning (no economizers) and better air quality control, was 3.83 percent (Atwood 1-4). Clearly, air economizers present a low cost cooling solution with almost no impact on the failure rate of electronic equipment.

2.3 Analysis

In order to determine the amount of cooling provided by the ambient air conditions, it was necessary to define the volumetric flow rate of the fan. Daniel Fein and David Neale of eVanHee Energy Solutions suggested that a flow rate of 1500 cfm (0.708 m^3/s) would be appropriate for this application. It was then possible to apply the First Law of Thermodynamics and use the following equation to solve for the heat:

$$\dot{Q} = \dot{m} C_v \Delta T$$

Where $\dot{Q}$ = heat (kWt)

$\dot{m}$ = mass flow rate = 0.708 kg/s

C_v = constant volume heat capacity = 1.005 kJ/kg*K

ΔT= ($T_2 - T_1$) = temperature change (°C)

T_2 = Set point inside shelter = 80°F (27°C)

T_1 = Ambient air temperature

The heat supplied by the ambient air was calculated on a monthly basis and for simplicity it was assumed that everyday of the year experienced twelve hours of sunshine and twelve hours of night.

The set point temperature inside the shelter, T_2 , was fixed at 80°F [2] (27°C), while T_1 was varied as the ambient air temperature. In order to provide conservative results, the ambient air temperature (T_1) during 12 hours of daytime operation was assumed to be the average high for the month (Appendix B) under analysis within the specific climate zone. Similarly, the ambient air temperature during 12 hours of night was assumed to be the average low for the month (Appendix C) under analysis within the specific climate zone. The thermal kilowatts of cooling provided by the air economizer was then calculated by the addition of the cooling provided by the two different twelve hour time periods. This cooling load provided by the economizer was then converted to kWh by simply multiplying by the respective number of hours in the month under analysis. This value was then subtracted from the cooling demand inside the shelter for the month assuming a

[2] The current shelter set point is 72°F, however, efforts are being made to increase the set point to 80°F

continuous 8.1kWt heat output from the network equipment. This then provided the amount of additional cooling capacity the alternate cooling unit (GHP or A/C) was required to meet.

2.4 Geothermal Heat Pump/Air Economizer Design

Four different ground loop exchanger designs were examined with the load reduction provided by the implementation of air economizers:

Design 1: The base case design, featuring a single vertical well with a single U tube exchanger, simulated in "Average Rock" conditions with standard conductivity grout (0.43 BTU/hr*ft*°F).

Design 2: The same as Design 1, above, with a double U tube exchanger and enhanced conductivity grout (1.0 BTU/hr*ft*°F).

Design 3: The same base case design with a HORIZONTAL well field in a 6.6 feet deep trench, 12 inches wide with two exchanger pipes, placed in soil with a thermal conductivity of 0.60 BTU/hr*ft*°F.

Design 4:The same as Design 3 above with three exchanger pipes in a 24 inch wide trench.

The horizontal well field was examined because it was possible that the air economizer could reduce the cooling load such that it could be installed within the limits of the site location, which could significantly reduce capital costs. Horizontal wells require no grout and can be installed with common excavation equipment. A medium sized excavator can be contracted for roughly $100 per hour. Conservatively, it is possible to excavate 300 linear feet of a 6'x2' trench in 8 hours. The costs for heat pump equipment were the same as the costs used in Section 1.7.

Results are also provided for the capital and operating costs of an air conditioning/economizer hybrid system. The air conditioning unit must offset the same cooling load as geothermal heat pumps in each respective zone, but do so at a lower EER, increasing operating costs. However, capital requirements are much lower for air conditioners. Section 2.5 provides a detailed life cycle cost analysis.

2.4.1 Zone 1 and 2

The southern most climate zones provide the biggest challenge for air economizers due to the low temperature delta in reference to the shelter set point and ambient conditions. Despite these poor conditions, improvements were still made in loop reduction.

Table 2-1 Temperature Extremes and Supplied Kilowatt-hours by Equipment Type

Zone 1 & 2	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg High (°F)	69	71	76	81	86	90	92	91	89	83	76	71
Avg Low (°F)	50	52	57	62	68	73	75	75	73	66	58	52
Air Economizer (kWh)	7451	6080	4901	3217	2074	1269	878	921	1326	2506	4515	6678
Geothermal HP (kWh)	0	69	1125	2615	3953	4563	5148	5105	4506	3521	1317	164

The red values in Table 2-1 (and similar, subsequent tables) indicate the months in which the average high temperature does not provide enough of a temperature differential in order to cool the shelter during the 12 hour daytime period. Consequently, the kilowatt-hours in these months are only a function of the 12 hour nighttime cooling period. The blue values represent months in which the average monthly high and low provide enough temperature differential to cool the shelter 24/7.

Design 1 from above provided a vertical well depth of 1200 feet and a capital investment of $22,200 and Design 2 yielded 960 feet of vertical borehole and $21,000. The same designs with no air economizer resulted in well depths of 1570 feet and upfront expenses of $26,300 and 1280 feet and $25,000, respectively, saving about $4,000 in each case.

Table 2-2. Horizontal Design Results in Zone 1 & 2

Zone 1 & 2	Trench Length (ft)	Pipe Length (ft)	Area (ft^2)
Design 3	1130	2270	1130
Design 4	910	2740	1820

The capital required for Design 3 is $11,200 and Design 4 is $10,700. The additional piping in the ground reduces the amount of excavation needed, which outweighs the extra cost of the pipe. The capital of the horizontal system is less than half that of a vertical system meeting the same cooling load, but requires a much larger area.

Section 1.8 showed that the conventional air conditioning units operated for approximately 3700 hours per year and cost $1150 (at $0.10/kWh). When this operating factor (approximately 10 hours per day) was applied to a standalone geothermal heat pump whose EER was equal to 26, the yearly operating cost was about $400. If we apply the same operating factor to a hybrid geothermal/air economizer system, the yearly operating costs are estimated to be $220, a difference of $930 when compared to air conditioning. When this figure is applied over a 15 year period, the savings in energy use is nearly $14,000. The additional cost of the economizer can pay for itself in less than one year while reducing the total cost of a vertical system around $5,500, while a horizontal system can save over $20,000. Table 2-3 provides a summary of capital and operating expenses, as well as savings and payback periods.

Table 2-3 Summary of Expenses: Zone 1 & 2

Zone 1 & 2	Capital ($)	Operating ($/yr)	Savings ($/yr)	Payback (yrs)
Air Conditioner	3000	1150	-	-
GHP Vertical Well Design 1	26300	400	750	31
GHP Vertical Well Design 2	25000	400	750	29
GHP/Econ Vertical Well Design 1	22100	220	930	20
GHP/Econ Vertical Well Design 2	20900	220	930	19
GHP/Econ Horizontal Design 3	11200	220	930	9
GHP/Econ Horizontal Design 4	10700	220	930	8
Air Conditioner/Economizer	3300	556	594	< 1

Savings and Payback period calculated in reference to operation of Air Conditioning unit ONLY

2.4.2 Zone 3

Climate Zone 3 provides more suitable conditions for the use of the air economizers as a means of cooling. Table 2-4 shows that the geothermal heat pump is only required to operate 5 months of the year, and during that time it supplements what the economizer is unable to provide.

Table 2-4 Temperature Extremes and Supplied Kilowatt-hours by Equipment Type

Zone 3	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg High (°F)	53	58	65	73	80	86	89	88	83	75	65	56
Avg Low (°F)	32	36	43	50	58	65	68	68	63	52	43	35
Air Economizer (kWh)	13209	10713	9276	6400	4176	2799	2081	2262	3149	6007	9066	12253
Geothermal HP (kWh)	0	0	0	0	1850	3033	3945	3765	2683	19	0	0

Design 1 resulted in a single vertical well of 600 feet while Design 2 required 460 feet of borehole. Capital required for Design 1 is estimated to be $14,800 and Design 2 is $14,000. The capital of Design 1 with no air economizer is $20,400 (1080 feet) and Design 2 is $19,500 (880 feet).

Table 2-5 Horizontal Design Results in Zone 3

Zone 3	Trench Length (ft)	Pipe Length (ft)	Area (ft^2)
Design 3	710	1420	710
Design 4	560	1690	1120

The capital required for Design 3 is $9,900 and Design 4 is $9,700, which is roughly $5,100 less expensive than installing the same capacity as Design 1.

Applying the same operating factor from Section 1.8 and assuming the same price of electricity, the hybrid system designed for Zone 3 would cost $135 per year to operate. In comparison to the conventional air conditioner, this saves $1,015 per year, or nearly $15,000 over 15 years. Table 2-6 provides a summary of estimated expenses in Zone 3.

Table 2-6 Summary of Expenses: Zone 3

Zone 3	Capital ($)	Operating ($/yr)	Savings ($/yr)	Payback (yrs)
Air Conditioner	3000	1150	-	-
GHP Vertical Well Design 1	20400	400	750	23
GHP Vertical Well Design 2	19500	400	750	22
GHP/Econ Vertical Well Design 1	14900	135	1015	12
GHP/Econ Vertical Well Design 2	14100	135	1015	11
GHP/Econ Horizontal Design 4	9900	135	1015	7
GHP/Econ Horizontal Design 4	9600	135	1015	6
Air Conditioner/Economizer	3300	295	855	< 1

Savings and Payback period calculated in reference to operation of Air Conditioning unit ONLY

2.4.3 Zone 4

The temperature differential provided by the ambient air conditions found in Zone 4 more than justify the use of air economizers. Table 2-7 shows that the geothermal system is only needed 5 months of the year and that the air economizer can provide 24 hour cooling for all but 3 months.

Table 2-7 Temperature Extremes and Supplied Kilowatt-hours by Equipment Type

Zone 4	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg High (°F)	44	48	57	67	75	83	87	86	79	69	57	47
Avg Low (°F)	25	28	36	44	53	61	66	64	58	46	37	28
Air Economizer (kWh)	16173	13415	11852	8458	5784	3317	2630	2849	4111	8061	11267	14944
Geothermal HP (kWh)	0	0	0	0	242	2515	3396	3177	1721	0	0	0

Design 1 in Zone 4 produced a vertical borehole of 400 feet while Design 2 yielded 310 feet of borehole. The capital required for Design 1 is $12,500 and Design 2 is $12,000. The borehole depth required for Design 1 with no economizer is 860 feet, which gives a capital cost of $17,800. Design 2 with no economizer necessitates 700 of borehole at $17,100.

Table 2-8 Horizontal Design Results in Zone 4

Zone 4	Trench Length (ft)	Pipe Length (ft)	Area (ft^2)
Design 3	550	1100	550
Design 4	430	1280	860

In Zone 4, the capital needed for Design 3 is $9,399 and Design 4 is $9,117. The amount of land required to install a horizontal system continues to decrease, with Design 4 requiring slightly more than twice the perimeter of the standard cell tower location for a well field.

Continuing to use the operating factor in Section 1.8, the operating cost of a hybrid geothermal/air economizer system is calculated at $120 per year, saving $1,030 versus operating an air conditioner. Taken over 15 years, this saves about $15,500. Table 2-9 summarizes the expenses of each system in Zone 4.

Table 2-9 Summary of Expenses: Zone 4

Zone 4	Capital ($)	Operating ($/yr)	Savings ($/yr)	Payback (yrs)
Air Conditioner	3000	1150	-	-
GHP Vertical Well Design 1	17800	400	750	20
GHP Vertical Well Design 2	17100	400	750	19
GHP/Econ Vertical Well Design 1	12500	120	1030	9
GHP/Econ Vertical Well Design 2	12000	120	1030	8
GHP/Econ Horizontal Design 3	9400	120	1030	6
GHP/Econ Horizontal Design 4	9100	120	1030	6
Air Conditioner/Economizer	3300	235	915	< 1

Savings and Payback period calculated in reference to operation of Air Conditioning unit ONLY

2.4.4 Zone 5

Spanning the north-central portion of the country, the temperatures in Zone 5 provide more than enough temperature differential to rationalize the use of air economizers. Table 2-10 shows that the heat pump only operates 3 months of the year and the air economizer is capable of continuous cooling all but for 2 months of the year.

Table 2-10 Temperature Extremes and Supplied Kilowatt-hours by Equipment Type

Zone 5	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg High (°F)	34	38	48	59	70	79	86	83	75	63	49	37
Avg Low (°F)	16	20	28	37	46	55	60	59	51	40	31	21
Air Economizer (kWh)	19386	16216	14776	10955	7870	4531	3523	3800	5961	10092	13698	18046
Geothermal HP (kWh)	0	0	0	0	0	1301	2503	2227	0	0	0	0

Design 1 in Zone 5 yielded a vertical borehole depth of 250 feet requiring $10,700 of capital. The borehole depth for Design 2 was 190 feet costing $10,300. The borehole depth and capital cost for Design 1 with no air economizer was 750 feet and $16,400. Installing Design 2 with no air economizer resulted in 610 feet of borehole depth and $15,800.

Table 2-11 Horizontal Design Results in Zone 5

Zone 5	Trench Length (ft)	Pipe Length (ft)	Area (ft^2)
Design 3	420	830	420
Design 4	320	970	640

Capital costs for Design 3 and 4 within Zone 5 are $9,000 and $8,800, respectively. Instinctively, the area required for the horizontal ground loop exchanger continues to decrease as the temperature differentials increase, making their use all the more appealing.

The operating factor applied to the load required in Zone 5 resulted in yearly operating costs of the hybrid geothermal/air economizer system to be $95, saving $1,055 when compared to stand alone air conditioning. When carried over a 15 year period, the energy savings amount to nearly $16,000. Table 2-12 summarizes estimated expenses in Zone 5.

Table 2-12 Summary of Expenses in Zone 5

Zone 5	Capital ($)	Operating ($/yr)	Savings ($/yr)	Payback (yrs)
Air Conditioner	3000	1150	-	-
GHP Vertical Well Design 1	16400	400	750	17
GHP Vertical Well Design 2	15800	400	750	17
GHP/Econ Vertical Well Design 1	10700	95	1055	7
GHP/Econ Vertical Well Design 2	10300	95	1055	7
GHP/Econ Horizontal Design 3	9000	95	1055	6
GHP/Econ Horizontal Design 4	8700	95	1055	5
Air Conditioner/Economizer	3300	158	992	< 1

Savings and Payback period calculated in reference to operation of Air Conditioning unit ONLY

2.4.5 Zone 6 and 7

It is quite obvious that Zone 6 and 7 will provide the best ambient conditions to cool the shelters. Even during the summer months, the temperatures remain moderate and significantly reduce the amount of ground loop required by the geothermal heat pump to offset the load. Table 2-13 demonstrates the reduction in demand required from the geothermal heat pump, operating only three months per year, two of which are at low kWh consumption. The air economizer is able to supply cooling 24 hours a day for 11 months.

Table 2-13 Temperature Extremes and Supplied Kilowatt-hours by Equipment Type

Zone 6 & 7	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg High (°F)	23	28	39	53	65	74	80	78	68	56	39	26
Avg Low (°F)	4	8	20	32	42	51	56	54	45	34	22	9
Air Economizer (kWh)	23485	19644	17937	12950	9394	6063	4455	5093	8198	12413	16880	21939
Geothermal HP (kWh)	0	0	0	0	0	40	1571	933	0	0	0	0

From this information, Design 1 resulted in 130 feet of vertical borehole and Design 2 required 90 feet. The capital investment for Design 1 is $9,200 and Design 2 is $9,000. Designs 1 and 2 with no air economizer would call for 640 feet and 520 feet, and the required capital of $15,000 and $14,500, respectively. The addition of an air economizer could save as much as $6,000.

Table 2-14 Horizontal Design Results in Zone 6 & 7

Zone 6 & 7	Trench Length (ft)	Pipe Length (ft)	Area (ft^2)
Design 3	310	630	310
Design 4	230	700	460

The capital investment for Design 3 is $8,700 and Design 4 is $8,500. It should be noted that the trench length of Design 4 is nearly that of the perimeter of the cell tower location.

When the operating factor is applied to the proposed hybrid system in Zone 6 & 7, the yearly operating cost is $75, saving $1,075 versus conventional air conditioning. Taken over 15 years the savings potential is $16,100. Table 2-15 summarizes expenses in Zone 6 & 7.

Table 2-15 Summary of Expenses: Zone 6 & 7

Zone 6 & 7	Capital ($)	Operating ($/yr)	Savings ($/yr)	Payback (yrs)
Air Conditioner	3000	1150	-	-
GHP Vertical Well Design 1	15100	400	750	16
GHP Vertical Well Design 2	14500	400	750	15
GHP/Econ Vertical Well Design 1	9200	75	1075	6
GHP/Econ Vertical Well Design 2	9000	75	1075	6
GHP/Econ Horizontal Design 3	8670	75	1075	5
GHP/Econ Horizontal Design 4	8470	75	1075	5
Air Conditioner/Economizer	3300	102	1048	< 1

Savings and Payback period calculated in reference to operation of Air Conditioning unit ONLY

2.5 Life Cycle Cost Analysis

In order to develop a true understanding of the long term costs associated with any system, it is important to not only consider capital, operating costs and installation costs, but maintenance and CO_2 costs as well. The maintenance costs used were based upon data within Gaia Geothermal, which was gathered from industry case studies and available ASHRAE data. Maintenance costs for geothermal heat pumps is approximately $0.10/ft^2/yr and $0.50/ft^2/yr for air conditioning units. While there are no current fees associated with carbon dioxide, it appears as if it will be an inevitable expense in the future. Again, data from Gaia Geothermal dictates that current carbon dioxide rates in the United States are based on an emission rate of 1.34 lb/kWh, priced at $30/ton.

2.5.1 Geothermal Heat Pumps versus Air Conditioning

The yearly cost of a geothermal heat pump system, based on an 8.1 kWt cooling load and a ten hour per day operating factor will not vary by installed location, provided the price of electricity and carbon dioxide remains constant. The life cycle total will vary due to the introduction of the capital requirements for each system, which is not constant across the country. The capital costs for the geothermal system was based upon the design criteria of a double U tube exchanger with enhanced grout, installed in dense rock. Table 2-16 details the life cycle costs of a standard air conditioner and geothermal heat pump systems for each zone, designed as previously noted.

Table 2-16 Geothermal Heat Pump vs. Air Conditioning Lifecycle Costs

Annual Costs	A/C	GHP Zone 1&2	GHP Zone 3	GHP Zone 4	GHP Zone 5	GHP Zone 6&7
Energy ($)	1150	400	400	400	400	400
CO2 ($)	230	80	80	80	80	80
Maintenance ($)	120	20	20	20	20	20
TOTAL ($)	1500	500	500	500	500	500
20 Year Cost						
Energy ($)	23100	8000	8000	8000	8000	8000
CO2 ($)	4600	1600	1600	1600	1600	1600
Maintenance ($)	2400	500	500	500	500	500
Capital ($)	3000	24000	18700	16400	15218	14000
Lifecycle Total ($)	33100	34100	28800	2650	25300	24100

The results from Table 2-16 show that geothermal heat pumps are less expensive to operate over time, except in Zone 1 & 2. Regardless of the thermal ground conditions, a geothermal system designed with a double U tube heat exchanger and enhanced grout (costs as defined in Section 1.7) would require the borehole depth to be no greater than 900 feet in order to be less expensive than air conditioning.

2.5.2 Hybridizing with Air Economizers

Including an air economizer with either cooling system can significantly reduce capital and operating costs. Geothermal heat pumps receive the most benefit in the reduction of capital expenses, because the air economizer carries a significant percentage of the cooling load requirement, which allows for the ground loop exchanger to be scaled down.

By designing either technology (A/C or GHP) to incorporate an economizer, the energy use for each system will vary by climate zone due to each zone having a different percent reduction in kWh from the economizer (a function of ambient air temperature). The life cycle costs for the geothermal system were based upon the criteria defined by Design 4 in Section 2.4 and expenditures from Section 1.7. Table 2-17 outlines the results.

Table 2-17 Hybrid System Life Cycle Costs: Horizontal GHP & Air Conditioning

Annual Costs	GHP Zone 1&2	AC Zone 1&2	GHP Zone 3	AC Zone 3	GHP Zone 4	AC Zone 4	GHP Zone 5	AC Zone 5	GHP Zone 6&7	AC Zone 6&7
Energy ($)	220	560	140	300	120	240	100	160	80	100
CO2 ($)	40	110	30	60	20	50	20	30	20	20
Maintenance ($)	20	120	20	120	20	120	20	120	20	120
TOTAL ($)	280	790	190	480	160	410	140	310	120	240
20 Year Cost										
Energy ($)	4400	11100	2700	5900	2400	4700	1900	3200	1500	2000
CO2 ($)	890	2200	540	1200	480	900	380	630	300	400
Maintenance ($)	480	2400	480	2400	480	2400	480	2400	480	2400
Capital ($)	10800	3300	9600	3300	9100	3300	8800	3300	8500	3300
Lifecycle Total ($)	16570	19000	13320	12800	12460	11300	11560	9530	10780	8100

Surprisingly, Table 2-17 demonstrates that in all but Zone 1 & 2, a hybrid air conditioner/economizer design is less expensive than a system composed of a geothermal heat pump and air economizer. The difference in operating expense between hybridized air conditioners and hybridized geothermal heat pumps is so small that the amount of time necessary for the heat pump to make up the large capital expenditures in energy savings is beyond the life of the equipment. Bear in mind that the geothermal heat pump values in Table 2-17 are calculated for the most economical ground loop system in this study (horizontal well). Life cycle costs for hybrid A/C vs. hybrid GHP systems with a vertical well, double U ground loop exchanger and enhanced grout can be found in Appendix G.

However, hybridized geothermal heat pumps still have the potential to be more cost effective than hybridized air conditioning. Verizon Wireless has the capacity to install a large number of systems nationwide. It is within the realm of possibility to negotiate lower prices not on just the units from a single manufacturer, but from regional installers as well. As previously mentioned in Section 1.7, a price point of $3000 per geothermal unit could hypothetically be achieved. Table 2-18 estimates lifecycle costs based upon this assumption. Appendix H provides life cycle costs for hybrid A/C vs. hybrid GHP systems with a vertical well, double U ground loop exchanger and enhanced grout with this discounted rate.

Table 2-18 Hybridized Lifecycle Costs with Discounted GHP's

Annual Costs	GHP Zone 1&2	AC Zone 1&2	GHP Zone 3	AC Zone 3	GHP Zone 4	AC Zone 4	GHP Zone 5	AC Zone 5	GHP Zone 6&7	AC Zone 6&7
Energy ($)	220	560	140	300	120	240	100	160	80	100
CO2 ($)	40	110	30	60	20	50	20	30	20	20
Maintenance ($)	20	120	20	120	20	120	20	120	20	120
TOTAL ($)	280	790	190	480	160	410	140	310	120	240
20 Year Cost										
Energy ($)	4400	11100	2700	5900	2400	4700	1900	3200	1500	2000
CO2 ($)	890	2200	540	1200	480	950	380	630	300	410
Maintenance ($)	480	2400	480	2400	480	2400	480	2400	480	2400
Capital ($)	6300	3300	5200	3300	4700	3300	4400	3300	4100	3300
Lifecycle Total ($)	12070	19000	8920	12800	8060	11350	7160	9530	6380	8110

Table 2-18 indicates that if a lower price can be negotiated for just the heat pump unit, the lifecycle cost favors geothermal energy. The life cycle costs can be even further reduced if discounts can be attained for the necessary subsurface equipment.

Part 3: Endorsements and Closing Thoughts

3.1 Recommendations

Designing a geothermal heat pump system that is applicable to geologic and atmospheric conditions found across the entire Unites States is not a simple task. The range of variables that would need to be taken into consideration for a detailed tower by tower or even state by state analysis are simply too great. Simplifications and generalizations were needed in order to make the project realistic, while still covering a representative range of characteristics necessary to satisfy the scope of the study.

Using the worst case scenario for conditions found in the U.S, namely ground surface temperature (23°C) and an average ground thermal conductivity (0.50 BTU/hr*ft*°F) and applying it across the entire country would be a severe mistake. While the system would certainly operate in nearly every situation, it would not only be grossly oversized, but unreasonably expensive for the majority of the country. For example, a system installed in Zone 6 and 7 in dense rock with enhanced grout and a double U tube exchanger should require 380 feet of borehole. The worst case design calls for 3,450 feet of borehole, nearly nine times more than what is needed, causing nearly $36,000 extra dollars to be spent. It is for this reason designing a system for the specific location where it is to be installed is imperative.

By examining the results presented in this report, all effort should be made to avoid the installation of a unit in low conductivity geology. Even in Zone 6 and 7, the vertical borehole depth required for a solitary system is still rather high and searching for suitable rock formations can save a significant amount of money. Identifying new locations for cell tower construction already requires some geological research to determine the foundation in which the tower will be located. It would require very little additional work to establish locations that are suitable for geothermal heat pumps. Local water well drilling records can provide an excellent source for the type of geology that can be encountered.

In order to ensure proper system performance, each system should be individually designed for the specific location to take into account all appropriate variables. Discussing options with local, certified installers who are familiar with the regional geological conditions will yield more accurate designs. Furthermore, not all materials are used or are available to every installer. Differences in brand, pricing and performance characteristics could vary depending upon the region. As mentioned in the report, purchasing equipment and negotiating multiple installations with a single contractor in a localized geography will almost certainly lead to lowering costs.

Based upon the results presented in Section 2, it is the author's recommendation that the cooling of cell tower equipment shelters be installed as systems hybridized with air economizers. Their low energy expenditure (0.18 kWe) supplies the shelter with significant quantities of cooling, which allows the geothermal heat pump (1.1 kWe) and air conditioner (3.1 kWe) to operate less frequently, thus saving money. If the geothermal heat pump equipment is to be purchased at retail value, the lifecycle costs indicate that air conditioners actually provide a more cost effective solution when each is coupled with an air economizer. However, the large number of units that Verizon Wireless has the capacity to install can reduce the cost of the geothermal heat pump equipment immensely. As discussed in Section 2.5.2, a realistic volume price for the heat pump unit of $3000 would shift the lifecycle cost analysis in favor of geothermal heat pumps, assuming Design 4 with horizontal wells. Appendix H shows the life cycle cost analysis using vertical wells with enhanced grout and double U ground loop exchangers at the same discounted rate; where in only Zone 1 & 2 and Zone 3 that the hybrid air conditioning systems are less expensive than hybrid geothermal systems.

Minimizing the amount of land occupied by cell tower installations is a high priority issue; hence the reason for designing vertical ground loops; having said that, dismissing the application of horizontal ground loops would be unfortunate. Air economizer's possess the ability to reduce the length of the ground loop such that horizontal systems could be implemented. Depending upon the costs associated with leasing the available land, it may be feasible to lease slightly more land to satisfy the loop requirements and save money by not having to install a vertical system. It is for that reason that horizontal loops should not be disregarded.

3.1.1 Zone 1 & 2

The climatic and ambient conditions found in Zone 1 & 2 do not lend themselves very well to geothermal cooling applications, but it is these regions where cooling demand potentially is the highest. Assuming retail pricing for equipment, the best solution for cooling shelters within Zone 1 & 2 is the use of a hybrid air conditioner/economizer. The lifecycle cost analysis suggests that a hybrid geothermal/economizer system would be superior, but the design is based on the predication that a horizontal ground loop would be installed, requiring 910 linear feet of trench. It is very likely that this is beyond what Verizon Wireless is willing to undertake. Should Verizon Wireless choose to install a solitary system (no economizer), then generally speaking, air conditioning units should continue to be used. The high average ground surface temperature in this zone requires that the vertical borehole be too deep to recover the costs in a timely manner. It may be possible for locations to exist within this zone that lend themselves to geothermal heat pumps, be it from a higher conductivity geology, lower ground surface temperature or enhanced cooling effects from aquifers.

3.1.2 Zone 3 through Zone 6 & 7

Each zone lends itself to individual designs based on different ground and ambient temperature conditions and varying cooling loads (when air economizers are introduced). Yet, the end result in selecting a method to cool the shelter remains the same from Zone 3 to Zone 6 & 7. In the case for installing individual systems with no economizer, geothermal heat pumps provide a better cooling solution than air conditioning. When considering hybridized systems purchased at retail, air conditioners coupled with air economizers are more cost effective than hybrid geothermal systems. Discounted costs will lend themselves to geothermal heat pumps, again using Design 4.

3.2 Concluding remarks

Geothermal heat pumps can provide an excellent opportunity to reduce costs and electricity consumption for heating and cooling applications compared with traditional cooling methods. Taking advantage of the natural energy storage capacity beneath the surface of the earth presents a fantastic opportunity to employ geothermal energy as a fully deployable and reliable renewable energy source for the widespread application of cell tower power and energy management

The addition of air economizers presents an interesting complexity. The reduction in cooling load required to be met by the alternate system (geothermal heat pumps or air conditioners) is reduced drastically, particularly in northern climates. While both hybrid systems will reduce costs and energy consumption when compared to conventional cooling methods, analyzing the hybrid systems against one another makes the choice less clear and requiring corporate goals to be defined and used in the decision making process. If saving money in the short term is the primary goal, the hybrid air conditioning/air economizer system is the system of preference. If saving energy for the long term is the principal concern, then geothermal heat pumps are vastly superior. It may be entirely feasible to meet both goals if geothermal heat pump equipment can be purchased at volume discounted rates.

It is indisputable that energy savings can be made by employing alternate cooling methods to cell tower equipment shelters. Saving energy is not only beneficial from the economic standpoint of Verizon Wireless, but as a sustainability measure it has value for the general community as well. All of the options presented in this report can provide substantial energy savings when compared to the cooling method currently in place. No matter what options are selected, decisions that decrease energy use are the right choice for the long term when facing uncertainty with respect to future electricity prices and in anticipation of possible regulations on performance.

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APPENDIXES

Appendix A: Average Monthly Temperatures by Climate Zone (°F)

ZONE 1	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Key West	69.9	70.5	73.8	77.1	83.1	84.4	84.3	83.3	80	75.6	71.5	77.8
Miami	67.2	68.5	71.7	75.2	78.7	81.4	82.6	82.8	81.9	78.3	73.6	69.1
Fort Myers	63.8	64.8	69.1	73.1	78.3	81.7	82.8	83	82	77.2	70.8	65.6
Average	67	67	71	75	80	82	83	83	81	77	72	70

ZONE 2	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Orlando	59.7	61.2	66.7	71.2	76.9	81.1	82.3	82.5	81	75.2	68	62.1
Jacksonville	52.4	55.2	61.1	67	73.4	79.1	81.6	81.2	78.1	69.8	61.9	55.1
Tallahassee	50.5	53.2	60.2	66.3	73.6	79.6	81.3	81	78.3	68.7	59.7	53.2
Pensacola	50.6	53.6	60.4	67.6	74.5	80.3	82.1	81.5	78.4	69.3	60.6	53.7
Savannah	48.9	51.8	59.2	66	73.5	79.1	81.8	81	76.6	67.3	59.1	51.7
Mobile	49.9	53.2	60.5	67.8	74.5	80.4	82.3	81.8	77.9	68.4	59.8	53
New Orleans	51.3	54.3	61.6	68.5	74.8	80	81.9	81.5	78.1	69.1	61.1	54.5
Waco	45.2	49.4	58.2	67.1	74.3	81.5	85.6	85.6	78.6	68.5	57.7	48.3
San Antonio	49.3	53.5	61.7	69.3	75.5	82.2	85	84.9	79.3	70.2	60.4	52.2
Corpus Christi	55.1	58.5	65.6	72.5	77.9	81.9	84.1	84.2	81	73.9	65.7	58.3
Phoenix	53.6	57.7	62.2	69.9	78.8	88.2	93.5	91.5	85.6	74.5	61.9	54.1
Average	51	54	61	68	75	81	83	83	79	70	61	54

Zone 3	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Charlotte	39.3	42.5	50.9	59.4	67.4	75.7	79.3	78.3	72.4	61.3	52.1	42.6
Charleston	48.4	51	57.9	65.4	72.8	78.8	81.8	81	76.8	67.9	59.7	52.2
Atlanta	41	44.8	53.5	61.5	69.2	76	78.8	78.1	72.7	62.3	53.1	44.5
Birmingham	41.5	45.7	54.2	62	69.4	76.3	79.8	79	73.4	62.5	53.1	45.2
Huntsville	38.8	43.1	51.9	60.8	68.4	75.8	79	78.3	72.2	61.2	51.5	42.9
Meridian	45	48.9	56.6	64.1	71.3	78.1	81	80.6	75.4	64.1	55.5	48.4
Little Rock	39.1	43.6	53.1	62.1	70.2	78.4	81.9	80.6	74.1	63	52.1	42.8
Dallas	43.4	47.9	56.7	65.5	72.8	81	85.3	84.9	77.4	67.2	56.2	46.9
Amarillo	35.1	39.2	47.1	56.8	65.4	74.1	78.6	76.5	69.1	58.5	46	36.9
San Angelo	43.7	48.4	58.1	67	74.2	79.5	82.7	81.9	75.4	66.2	55.4	46
Oklahoma City	35.9	40.9	50.3	60.4	68.4	76.7	82	81.1	73	62	49.6	39.3
Roswell	39.5	44.5	52.1	61	69.7	77.9	80.7	78.4	72.6	62.2	50.6	40.8
Los Angeles	58.3	60.1	60.7	62.2	65.8	69.7	74.3	75.1	73.7	69.7	63	58.2
San Francisco	48.7	52.2	53.3	55.6	58.1	61.5	62.7	63.7	64.5	61	54.8	49.4
Average	43	47	54	62	69	76	79	78	73	64	54	45

Zone 4	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Greensboro	36.7	40	48.8	57.6	65.9	73.1	76.9	75.7	69.7	58.6	49.5	40.5
Nashville	36.2	40.4	50.2	59.2	67.7	75.6	79.3	78.1	71.8	60.4	50	40.5
Richmond	35.7	38.7	48	57.3	66	73.9	78	76.8	70	58.6	49.6	40.1
Roanoke	34.5	37.3	46.8	55.6	64.1	71.5	75.6	74.6	67.7	56.5	47.5	38.3
Washington DC	34.6	37.5	47.2	56.5	66.4	75.6	80	78	71.3	59.7	49.8	39.4
Baltimore	31.8	34.8	44.1	53.4	63.4	72.5	77	75.6	68.5	56.6	46.8	36.7
Wilmington	44.9	47.3	54.4	62.3	70.1	76.5	80.1	79.4	75.3	65.3	57	48.5
Lexington	30.8	34.5	45.3	54.8	64	72.2	75.8	74.7	68.2	56.7	46	35.9
Cincinnati	28.1	31.8	43	53.2	62.9	71	75.1	73.5	67.3	55.1	44.3	33.5
Evansville	30.1	34.4	45.8	56.2	65.5	74.8	78.4	76.1	69.2	57.2	46.2	35.2
Springfield	31.1	35.7	46	56	64.6	73.2	78.1	76.8	69	57.8	46	35.2
Kansas City	25.7	31.2	42.7	54.5	64.1	73.2	78.5	76.1	67.5	56.6	43.1	30.4
Wichita	29.5	34.8	45.4	56.4	65.6	75.7	81.4	79.3	70.3	58.6	44.7	33
Amarillo	35.1	39.2	47.1	56.8	65.4	74.1	78.6	76.5	69.1	58.5	46	36.9
Eugene	40.8	44.2	47.4	50.6	55.8	62	67.3	67.6	62.8	54.1	46.1	41.1
Seattle	40.1	43.5	45.6	49.2	55.1	60.9	65.2	65.5	60.6	52.8	45.3	40.5
Average	34	38	47	56	64	72	77	75	69	58	47	38

Zone 5	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Boston	28.6	30.3	38.6	48.1	58.2	67.7	73.5	71.9	64.8	54.8	45.3	33.6
Hartford	24.6	27.5	37.5	48.7	59.6	68.5	73.7	71.6	63.3	52.2	41.9	29.5
Harrisburg	28.6	31.3	41.2	51.6	61.8	70.9	75.7	74.1	66.4	54.7	44.4	33.6
Pittsburgh	26.1	28.7	39.4	49.6	59.5	67.9	72.1	70.5	63.9	52.4	42.3	31.5
Syracuse	22.4	24	33.9	45.7	57.1	65.3	70.4	68.4	61.5	50.7	40.5	28.3
Cleveland	24.8	27.2	37.3	47.6	58	67.6	71.9	70.4	63.9	52.8	42.6	30.9
Detroit	22.9	25.4	35.7	47.3	58.4	67.6	72.3	70.5	63.2	51.2	40.2	28.3
South Bend	23.3	26.4	37.4	48.7	59.4	69.1	72.9	70.9	63.9	52.6	40.9	28.9
Chicago	21	25.4	37.2	48.6	58.9	68.6	73.2	71.7	64.4	52.8	40	26.6
Des Moines	19.4	24.7	37.3	50.9	62.3	71.8	76.6	73.9	65.1	53.5	39	24.4
Lincoln	21.3	36.6	38.6	51.7	62.1	72.5	78.2	75	65.3	53.6	38.8	25.6
Denver	29.7	33.4	39	48.2	57.2	66.9	73.5	71.4	62.3	51.4	39	31
Elko	25.1	31.5	37.6	44.3	53.1	62.4	70.7	68.7	58.7	47.7	35.8	25.7
Salt Lake City	27.9	34.1	41.8	49.7	58.8	69.1	77.9	75.6	65.2	53.2	40.8	29.7
Boise	29	35.9	42.4	49.1	57.5	66.5	74	72.5	62.6	51.8	39.9	30.1
Burns	23.3	29.4	36.3	42.8	50.8	58	66.2	64.2	55	45	33.6	25.1
Spokane	27.1	33.3	38.7	45.9	53.9	62	68.8	68.4	58.9	47.3	35.1	27.8
Average	25	30	38	48	58	67	73	71	63	52	40	29

Zone 6	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Portland	39.6	43.6	47.3	51	57.1	63.5	68.2	68.6	63.3	54.5	46.1	40.2
Concord	18.6	21.8	32.4	43.9	55.2	64.2	69.5	67.3	58.8	47.8	37.1	24.3
Burlington	16.3	18.2	30.7	43.9	56.3	65.2	70.5	67.9	58.9	47.8	36.8	23
Alpena	17.6	18.3	28	40.9	52	61.3	67.1	64.8	57.3	46.9	35.7	23.7
Green Bay	14.3	18.3	30	44	55.5	64.5	69.7	67.1	50	48	34.4	20.2
Minneapolis	11.8	17.9	31	46.4	58.5	68.2	73.6	70.5	60.5	48.8	33.2	17.9
Aberdeen	10.1	16.7	29.8	45.2	57.1	66.6	72.8	70.6	59.6	47.3	30.3	15.3
Bismarck	9.2	15.7	28.2	43	55	64.4	70.4	68.3	57	45.7	28.6	14
Sheridan	20.8	26.4	33.9	43.8	52.7	62.1	69.6	68.4	57.1	46.7	32.5	22.6
Billings	22.8	29	35.5.	45.6	55	64.8	72.5	70.7	59.1	49.1	35.1	25.5
Missoula	22.7	29.2	35.8	44.2	51.8	60	66.8	65.8	55.7	44.2	32.4	23.4
Average	19	23	33	45	55	64	70	68	58	48	35	23

Zone 7	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Caribou	8.9	11.9	24.6	37.9	50.9	60.5	65.5	62.8	53.7	43.2	30.7	14.8
Int'l Falls	1	7.7	22.1	39	52.1	61.4	66.7	63.7	53.4	42.4	24.9	7.2
Fargo	5.9	12	25.9	43	56.2	65.5	71.1	68.8	57.7	45.7	28.1	11.6
Williston	8.9	16.1	28.4	43.2	55.3	64.7	70.7	68.7	56.3	44.8	27.2	13.2
Anchorage	14.9	18.7	25.7	35.8	46.6	54.4	58.4	56.3	48.4	34.6	21.2	16.3
Average	8	13	25	40	52	61	66	64	54	42	26	13

Appendix B: Average Monthly High Temperature by Climate Zone (°F)

Zone 1	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Key West	74.8	75.4	78.6	81.7	85.1	87.6	89.1	89.2	88	84.4	80	76.1
Miami	75.2	76.5	79.1	82.4	85.3	87.6	89	89	87.8	84.5	80.4	76.7
Fort Myers	74.3	75.4	79.7	84.2	88.7	90.3	91.1	91.3	89.8	85.8	80.7	76
Average	75	76	79	83	86	89	90	90	89	85	80	76

Zone 2	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Orlando	70.8	72.7	78	83	87.8	90.5	91.5	91.5	89.7	84.6	78.5	72.9
Jacksonville	64.2	67	73	79.1	84.7	89.3	91.4	90.7	87.2	80.2	72.6	66.8
Tallahassee	62.9	66.3	73.5	80.4	86.3	90.8	91.3	91	88.5	81.5	73	65.9
Pensacola	59.8	62.9	69.4	76.6	83.2	88.7	89.9	89.2	86.4	79.1	70.1	62.9
Savannah	59.7	62.4	70.1	77.5	84	88.8	91.1	89.7	85.2	77.5	70	62.3
Mobile	59.7	63.6	70.9	78.5	84.6	90	91.3	90.5	86.9	79.5	70.3	62.9
New Orleans	60.8	64.1	71.6	78.5	84.4	89.2	90.6	90.2	86.6	79.4	71.1	64.3
Waco	56.1	60.8	69.6	78	84.4	92	96.8	97.2	89.6	80.3	68.8	59.3
San Antonio	60.8	65.7	73.5	80.3	85.3	91.8	95	95.3	89.3	81.7	71.9	63.5
Corpus Christi	65	69	75.7	81.7	86.2	90.4	93.3	93.4	89.7	83.9	75.8	68.3
Phoenix	65.9	70.7	75.5	84.5	93.6	104	106	104	98.3	88.1	74.9	66.2
Average	62	66	73	80	86	91	93	93	89	81	72	65

Zone 3	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Charlotte	49	53	62.3	71.2	78.3	85.8	88.9	87.7	81.9	72	62.6	52.3
Charleston	57.8	61	68.6	75.8	82.7	87.6	90.2	89	84.9	77.2	69.5	61.6
Atlanta	50.4	55	64.3	72.7	79.6	85.8	88	87.1	81.8	72.7	63.4	54
Birmingham	51.7	56.9	66.1	74.6	81	87.4	89.9	89.1	83.9	74.7	64.6	55.7
Huntsville	48.2	53.5	62.8	72.5	79.3	86.6	89	88.8	82.8	73	62.4	52.6
Meridian	56.4	61.2	69.6	77.4	83.6	90	92.1	91.8	86.9	77.7	68.6	60.1
Little Rock	49	53.9	64	73.4	81.3	89.3	92.4	91.4	84.6	75.1	62.7	52.5
Dallas	54.1	58.9	67.8	76.3	82.9	91.9	96.5	96.2	87.8	78.5	66.8	57.5
Amarillo	49	52.8	61.6	71.5	79.1	87.6	91.7	89.1	81.8	72.5	59.7	50.1
San Angelo	56.8	62	72.6	81.2	87.4	92.7	96.2	95.3	86.8	78.8	68.2	59
Oklahoma City	46.7	52.1	62	71.9	79.1	87.3	93.4	92.5	83.8	73.6	60.4	49.9
Roswell	54.3	59.9	67.8	76.7	84.7	93.6	94.6	91.9	86	77.3	66	56
Los Angeles	65.7	65.9	65.6	67.4	69	71.9	75.3	76.6	76.6	74.4	70.3	65.9
San Francisco	55.6	59.4	60.8	63.9	66.5	70.3	71.6	72.3	73.6	70.1	62.4	56.1
Average	53	58	65	73	80	86	89	88	83	75	65	56

Zone 4	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Greensboro	46.7	50.7	60.2	69.6	77	83.6	86.9	85.5	79.9	69.9	60.5	50.5
Nashville	45.9	50.8	61.2	70.8	78.8	86.5	89.5	88.4	82.5	72.5	60.4	50.2
Richmond	45.7	49.2	59.5	70	77.8	85.1	88.4	87.1	80.9	70.7	61.3	50.2
Roanoke	43.8	47.3	57.8	67.3	75.7	82.9	86.4	85.3	78.5	68.1	58	47.6
Washington DC	42.3	45.9	56.5	66.7	76.2	84.7	88.5	86.9	80.1	69.1	58.3	47
Baltimore	40.2	43.7	54	64.3	74.2	83.2	87.2	85.4	78.5	67.3	56.5	45.2
Wilmington	55.3	58.1	65.7	74	80.8	85.4	88.5	87.6	85.2	76.9	69.1	59.4
Lexington	39.1	43.6	55.3	65.5.	74.3	82.7	85.8	84.9	78.3	67.2	54.9	44.2
Cincinnati	36.6.	40.8	53	64.2	74	82	85.5	84.1	77.9	66	53.3	41.5
Evansville	38.9	43.7	55.9	67.4	76.9	86.2	89.1	87.2	80.7	69.6	55.9	43.6
Springfield	41.8	46.3	57.4	67.9	76	84.4	89.6	88.6	80.3	69.8	56.6	45.3
Kansas City	34.7	40.6	52.8	65.1	74.3	83.3	88.7	86.4	78.1	67.5	52.6	38.8
Wichita	39.8	45.9	57.2	68.3	76.9	86.8	92.8	90.7	81.4	70.6	55.3	43
Amarillo	49	52.8	61.6	71.5	79.1	87.6	91.7	89.1	81.8	72.5	59.7	50.1
Eugene	46.4	51.4	55.9	60.5	67.1	74.2	81.7	81.8	76.2	64.6	52.4	46.2
Seattle	46.1	50.6	53.7	58.1	64.2	69.6	74.1	74.1	68.8	60	51.5	46.2
Average	44	48	57	67	75	83	87	86	79	69	57	47

Zone 5	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Boston	35.7	37.5	45.8	55.9	66.6	76.3	81.8	79.8	72.8	62.7	52.2	40.4
Hartford	33.2	36.4	46.8	59.9	71.6	80	85	82.7	74.8	63.7	51	37.5
Harrisburg	35.9	39.2	50.3	62	72.5	81.2	85.8	83.8	76.3	64.7	52.6	40.6
Pittsburgh	33.7	36.9	49	60.3	70.6	78.9	82.6	80.8	74.3	62.5	50.4	38.6
Syracuse	30.6	32.5	42.7	56	68.3	76.7	81.7	79	71,6	60.3	48	35.4
Cleveland	31.9	35	46.3	57.9	68.6	78.3	82.4	80.5	73.6	62.1	50	37.4
Detroit	30.3	33.3	44.4	57.7	69.6	78.9	83.3	81.3	73.9	62.5	48.1	35.2
South Bend	30.4	34.1	45.6	58.7	70	79.5	82.9	80.7	74.1	62.3	48.5	35.4
Chicago	29	33.5	45.8	58.6	70.1	79.6	83.7	81.8	74.8	63.3	48.4	34
Des Moines	28.1	33.7	46.9	61.8	73	82.2	86,7	84.2	75.6	64.3	48	32.6
Lincoln	32.4	37.9	50.3	64.4	74.2	84.7	90	86.6	77.2	66.7	50.2	35.8
Denver	43.2	46.6	52.2	61.8	70.8	81.4	88.2	85.8	76.9	66.3	52.5	44.5
Elko	36.7	43	50.2	59.1	69.4	80.2	91	88.6	78.3	65.9	49.1	37.4
Salt Lake City	36.4	43.6	52.2	61.3	71.9	82.8	92.2	89.4	79.2	66.1	50.8	37.8
Boise	36.4	44.2	52.9	61.4	71	80.9	90.2	88.1	77	64.6	48.7	37.7
Burns	33.6	39.5	47.7	56.5	65.6	74.4	85.1	83.3	73.6	61.8	45.2	35.2
Spokane	33.2	40.6	47.7	57	65.8	74.4	83.1	82.5	72	58.6	41.4	33.8
Average	34	38	48	59	70	79	86	83	75	63	49	37

Zone 6	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Portland	45.5	51	56	60.6	67.1	74	79.9	80.3	74.6	64	52.6	45.6
Concord	29.8	33	42.8	56.3	68.9	77.3	82.4	79.8	71.6	60.7	47.1	34.2
Burlington	25.1	27.5	39.3	53.6	67.2	75.8	81.2	77.9	69	57	44	30.4
Alpena	26.4	28.2	37.9	51.6	64.8	74.5	80.2	76.9	68.3	56.8	43	30.9
Green Bay	22.8	27.1	38.5	54	67.2	75.5	80.5	77.5	69.1	57.4	42	27.7
Minneapolis	20.7	26.6	39.2	56.6	69.4	78.8	84	80.7	70.7	58.8	41	25.5
Aberdeen	20.9	26.9	39.8	57.3	69.7	78,8	85.9	84.4	72.9	60.4	40.5	25.4
Bismarck	20.2	26.4	38.5	54.9	67.8	77.1	84.4	82.7	70.8	58.7	39.3	24.5
Sheridan	33	38.3	46.2	57.1	66.3	76.9	86.1	85.2	72.8	61.7	45.3	35
Billings	31.8	38.6	45.8	57.1	66.7	77.6	86.7	84.7	71.6	60.6	44.5	34.4
Missoula	30	37.4	46.6	57.5	65.7	73.9	83.4	82.2	70.9	57	40.6	30.2
Average	28	33	43	56	67	76	83	81	71	59	44	31

Zone 7	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Caribou	19.4	23	34.3	46.7	61.7	71.9	76.5	73.6	64	52	37.6	24
Int'l Falls	11.9	19.3	32.8	50.1	64.6	73.4	78.8	75.6	64.3	51.8	32.8	16.6
Fargo	15.4	21.1	34.6	53.8	68.5	77.4	83.4	81.3	69.4	56.7	36.8	20.1
Williston	19.6	26.8	39.4	55.8	68.3	78	84.8	83.3	70.1	58.1	38	23.6
Anchorage	21.4	25.8	33.1	42.8	54.4	61.6	65.2	63	55.2	40.5	27.2	22.5
Average	18	23	35	50	64	72	78	75	65	52	34	21

Appendix C: Average Monthly Low Temperature by Climate Zone (°F)

Zone 1	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Key West	65.0	65.6	69.0	72.2	76.1	78.5	79.6	79.3	78.5	75.5	71.2	66.8
Miami	59.2	60.4	64.2	67.8	72.1	75.1	76.2	76.7	75.9	72.1	66.7	61.5
Fort Myers	53.2	54.2	58.6	62.0	67.9	73.1	74.5	74.7	74.2	68.6	60.9	55.1
Average	59.1	60.1	63.9	67.3	72.0	75.6	76.8	76.9	76.2	72.1	66.3	61.1

Zone 2	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Orlando	48.6	49.7	55.2	59.4	65.9	71.8	73.1	73.4	72.4	65.8	57.5	51.3
Jacksonville	40.5	43.3	49.2	54.9	62.1	69.1	71.9	71.8	69.0	59.3	50.2	43.4
Tallahassee	38.1	40.1	46.8	52.2	60.8	68.5	71.1	71.4	68.0	55.9	46.3	40.3
Pensacola	41.4	44.1	51.3	58.5	65.7	71.8	74.2	73.8	70.3	59.4	51.0	44.4
Savannah	38.1	41.1	48.3	54.5	62.9	69.2	72.4	72.2	67.8	56.9	48.1	41.0
Mobile	40.0	42.7	50.1	57.1	64.4	70.7	73.2	72.9	68.7	57.3	49.1	43.1
New Orleans	41.8	44.4	51.6	58.4	65.2	70.8	73.1	72.8	69.5	58.7	51.0	44.8
Waco	34.2	38.0	46.8	56.2	64.2	70.9	74.4	74.0	67.6	56.8	46.6	37.3
San Antonio	37.9	41.3	49.7	58.4	65.7	72.6	75.0	74.5	69.2	58.8	48.8	40.8
Corpus Christi	45.3	48.0	55.3	63.2	69.5	73.4	74.8	75.0	72.3	63.9	55.6	48.4
Phoenix	41.2	44.7	48.8	55.3	63.9	72.9	81.0	79.2	72.8	60.8	48.9	41.8
Average	40.6	43.4	50.3	57.1	64.6	71.1	74.0	73.7	69.8	59.4	50.3	43.3
Avg 1&2	49.9	51.7	57.1	62.2	68.3	73.3	75.4	75.3	73.0	65.7	58.3	52.2

Zone 3	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Charlotte	29.6	31.9	39.4	47.5	56.4	65.6	69.6	68.9	62.9	50.6	41.5	32.8
Charleston	37.7	40.0	47.5	53.9	62.9	69.1	72.7	72.2	67.9	56.3	47.2	40.7
Atlanta	31.5	34.5	42.5	50.2	58.7	66.2	69.5	69.0	63.5	51.9	42.8	35.0
Birmingham	31.3	34.5	42.3	49.2	57.7	65.2	69.5	68.8	62.9	50.2	41.6	34.8
Huntsville	29.2	32.6	40.9	49.0	57.3	64.9	68.9	67.9	61.6	49.3	40.5	33.1
Meridian	33.4	36.6	43.5	50.9	58.9	66.1	69.9	69.2	63.9	50.5	42.4	36.6
Little Rock	29.1	33.2	42.2	50.7	59.0	67.4	71.5	69.8	63.5	50.9	41.5	33.1
Dallas	32.7	36.9	45.6	54.7	62.6	70.0	74.1	73.6	66.9	55.8	45.4	36.3
Amarillo	21.2	25.5	32.7	42.1	51.6	60.7	65.5	63.8	56.4	44.5	32.3	23.7
San Angelo	30.6	34.7	43.5	52.7	61.1	66.4	69.1	68.4	64.0	53.6	42.6	33.0
Oklahoma City	25.2	29.6	38.5	48.8	57.7	66.1	70.6	69.9	62.2	50.4	38.6	28.6
Roswell	24.7	29.1	36.3	45.3	54.7	62.1	66.7	64.9	59.2	47.1	35.1	25.6
Los Angeles	48.9	50.6	51.8	54.2	57.7	61.1	64.5	65.7	64.6	60.3	53.5	48.8
San Francisco	45.8	48.7	49.0	49.8	50.5	52.6	53.5	54.6	55.9	55.2	51.6	47.0
Average	32.2	35.6	42.6	49.9	57.6	64.5	68.3	67.6	62.5	51.9	42.6	34.9

Zone 4	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Greensboro	26.6	29.3	37.4	45.6	54.7	62.6	66.9	65.6	59.5	47.2	38.5	30.5
Nashville	26.5	29.9	39.1	47.5	56.6	64.7	68.9	67.7	61.1	48.3	39.6	30.9
Richmond	25.7	28.1	36.3	44.6	54.2	62.7	67.5	66.4	59.0	46.5	37.9	29.9
Roanoke	25.0	27.2	35.7	43.8	52.5	60.2	64.8	63.8	56.8	44.8	37.0	28.9
Washington DC	21.0	23.3	31.8	40.3	50.0	59.2	64.1	62.8	55.4	42.4	34.2	25.8
Baltimore	23.4	25.9	34.1	42.5	52.6	61.8	66.8	65.7	58.4	45.9	37.1	28.2
Wilmington	34.4	36.4	43.1	50.5	59.3	65.7	71.7	71.0	65.3	53.7	44.8	37.5
Lexington	22.4	25.3	35.3	44.2	53.5	61.5	65.7	64.4	58.0	46.0	37.0	27.6
Cincinnati	19.5	22.7	33.1	42.2	51.8	60.0	64.8	62.9	56.6	44.2	35.3	25.3
Evansville	21.2	25.0	35.7	45.0	54.2	63.3	67.5	64.9	57.6	44.7	36.5	26.7
Springfield	20.4	35.0	34.4	44.1	53.2	61.9	66.6	65.0	57.7	45.9	35.5	25.3
Kansas City	16.7	21.8	32.6	43.8	53.9	63.1	68.2	65.7	56.9	45.7	33.6	21.9
Wichita	19.2	23.7	33.6	44.5	54.3	64.6	69.9	67.9	59.2	46.6	33.9	23.0
Amarillo	21.2	25.5	32.7	42.1	51.6	60.7	65.5	63.8	56.4	44.5	32.3	23.7
Eugene	35.2	37.0	38.9	40.6	44.5	49.7	52.8	53.2	49.3	43.5	39.7	35.9
Seattle	36.4	38.0	39.5	42.7	47.9	53.2	56.4	57.2	52.9	46.9	41.0	37.0
Average	24.7	28.4	35.8	44.0	52.8	60.9	65.5	64.3	57.5	46.1	37.1	28.6

Zone 5	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Boston	21.6	23.0	31.3	40.2	49.8	59.1	65.1	64.0	56.8	46.9	38.3	26.7
Hartford	15.8	18.6	28.1	37.5	47.6	56.9	62.2	60.4	51.8	40.7	32.8	21.3
Harrisburg	21.2	23.3	32.0	41.2	51.1	60.6	65.6	64.3	56.5	44.6	36.1	26.1
Pittsburgh	18.5	20.3	29.8	38.8	48.4	56.9	61.6	60.2	53.5	42.3	34.1	24.4
Syracuse	14.2	15.4	25.1	35.5	46.0	53.8	59.0	57.7	51.4	41.1	33.0	21.1
Cleveland	17.6	19.3	28.2	37.3	47.3	56.8	61.4	60.3	54.2	43.5	35.0	24.5
Detroit	15.6	17.6	27.0	36.8	47.1	56.3	61.3	59.6	52.5	40.9	32.2	21.4
South Bend	16.1	18.7	29.1	38.7	48.8	58.6	63.0	61.1	53.7	42.8	33.4	22.3
Chicago	12.9	17.2	28.5	38.6	47.7	57.5	62.6	61.6	53.9	42.2	31.6	19.1
Des Moines	10.7	15.6	27.6	40.0	51.5	61.2	66.5	63.6	54.5	42.7	29.9	16.1
Lincoln	10.1	15.1	26.8	38.9	50.0	60.2	66.3	63.3	53.2	40.5	27.3	15.4
Denver	16.1	20.2	25.8	34.5	43.6	52.4	58.6	56.9	47.6	36.4	25.4	17.4
Elko	13.4	19.9	25.0	29.5	36.8	44.6	50.3	48.6	38.9	29.6	22.5	14.0
Salt Lake City	19.3	24.6	31.4	37.9	45.6	55.4	63.7	61.8	51.0	40.2	30.9	21.6
Boise	21.6	27.5	31.9	36.7	43.9	52.1	57.7	56.8	48.2	39.0	31.1	22.5
Burns	13.0	19.3	24.9	29.0	35.9	41.6	47.2	45.0	36.3	28.1	22.0	15.0
Spokane	20.8	25.9	29.6	34.7	41.9	49.2	54.4	54.3	45.8	36.0	28.8	21.7
Average	16.4	20.1	28.4	36.8	46.1	54.9	60.4	58.8	50.6	39.9	30.8	20.6

Zone 6	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Portland	33.7	36.1	38.6	41.3	47.0	52.9	56.5	56.9	52.0	44.9	39.5	34.8
Concord	7.4	10.4	22.1	31.5	41.4	51.2	56.5	54.7	46.0	34.9	27.0	14.4
Burlington	7.5	8.9	22.0	34.2	45.4	54.6	59.7	57.9	48.8	38.6	29.6	15.5
Alpena	8.8	8.3	18.0	30.1	39.2	48.0	54.0	52.6	46.3	37.0	28.4	16.5
Green Bay	5.8	9.5	21.4	33.9	43.7	53.5	58.9	56.8	48.8	38.5	26.8	12.5
Minneapolis	2.8	9.2	22.7	36.2	47.6	57.6	63.1	60.3	50.3	38.8	25.2	10.2
Aberdeen	-0.6	6.5	19.8	33.0	44.5	54.3	59.6	56.8	46.1	34.1	19.9	5.3
Bismarck	-1.7	5.1	17.8	31.0	42.2	51.6	56.4	53.9	43.1	32.5	17.8	3.3
Sheridan	8.5	14.5	21.5	30.4	39.0	47.3	53.0	51.7	41.4	31.7	19.8	10.2
Billings	13.7	19.4	25.2	34.0	43.3	52.0	58.3	56.7	46.5	37.5	25.6	16.5
Missoula	15.4	20.9	24.9	30.9	37.9	46.1	50.1	49.2	40.4	31.3	24.2	16.4
Average	9.2	13.5	23.1	33.3	42.8	51.7	56.9	55.2	46.3	36.3	25.8	14.1

Zone 7	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Caribou	-1.6	0.7	14.9	29.0	40.1	49.1	54.5	52.1	43.2	34.4	23.7	5.5
Int'l Falls	-10.0	-4.0	11.4	27.8	39.6	49.5	54.6	51.7	42.5	32.9	17.0	-2.2
Fargo	-3.6	2.7	17.3	32.1	43.8	53.6	58.8	56.4	45.9	34.6	19.4	3.1
Williston	-1.8	5.3	17.4	30.5	42.2	51.4	56.5	54.1	42.4	31.4	16.3	2.8
Anchorage	8.4	11.5	18.1	28.6	38.8	47.2	51.7	49.5	41.6	28.7	15.1	10.0
Average	-1.7	3.2	15.8	29.6	40.9	50.2	55.2	52.8	43.1	32.4	18.3	3.8
Average 6&7	3.7	8.4	19.5	31.5	41.9	50.9	56.1	54.0	44.7	34.4	22.1	9.0

Appendix D: Additional GLHEPRO Simulations and Sample Output

Base Case with Double U Exchanger and Enhanced Grout

	Grout k = **1.0 BTU/hr*ft*°F**			**Grout k = 1.4 BTU/hr*ft*°F**		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3170	1300	1060	3140	1280	960
3	2190	900	670	2170	880	650
4	1750	710	530	1740	700	520
5	1520	620	460	1510	610	450
6 and 7	1300	530	390	1290	520	380

Base Case Design with 2 Boreholes (depth per borehole)

	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	1940*	890	690	1750*	760	710
3	1340	610	470	1280	550	420
4	1070	480	380	1020	440	330
5	930	420	320	890	380	290
6 and 7	790	350	270	760	320	240

*Borehole depth to spacing ratio lower than smallest data point for G-function. Results may not be indicative of actual system performance with 30' spacing, therefore 50' spacing was used to achieve accurate an simulation

Base Case Design with 2 Boreholes and Enhanced Grout (k=1.0 BTU/hr*ft*°F)

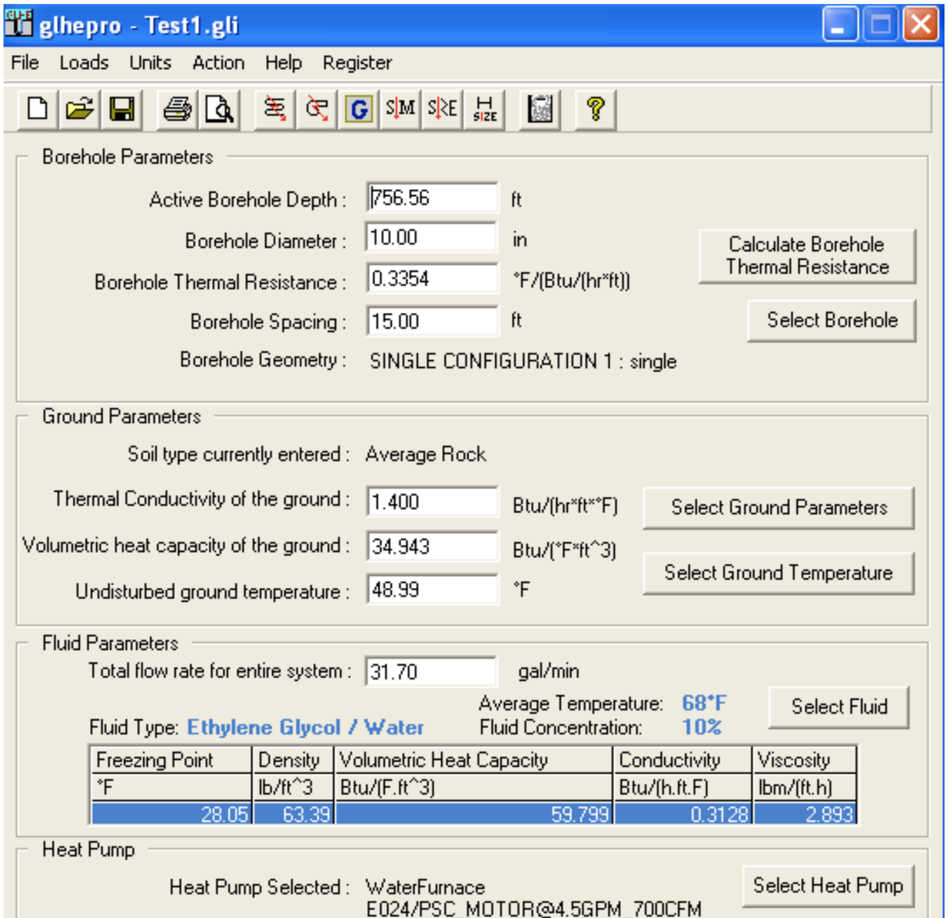
	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	1790*	900	620	1700*	760	600
3	1280	550	410	520	520	380
4	1040	440	330	990	410	300
5	880	370	280	860	350	260
6 and 7	750	320	240	730	300	220

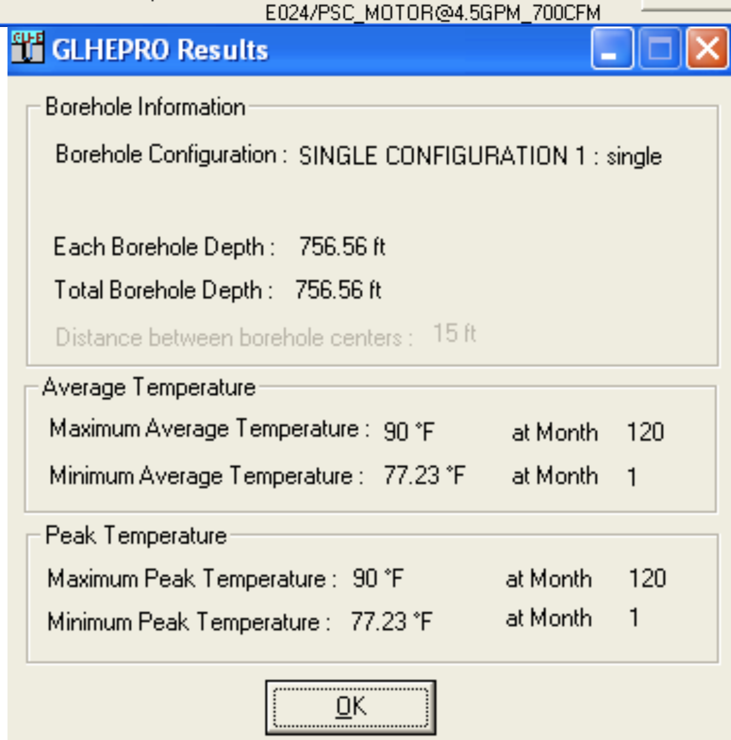
*Borehole depth to spacing ratio lower than smallest data point for G-function. Results may not be indicative of actual system performance with 30' spacing, therefore 50' spacing was used to achieve accurate an simulation

Base Case Design with 2 Boreholes and Enhanced Grout (k=1.4 BTU/hr*ft*°F)

	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	1720*	780	590	1680*	740	560
3	1250	530	400	1240	510	370
4	1010	420	310	990	400	290
5	870	360	270	860	350	250
6 and 7	740	310	220	730	300	210

*Borehole depth to spacing ratio lower than smallest data point for G-function. Results may not be indicative of actual system performance with 30' spacing, therefore 50' spacing was used to achieve accurate an simulation


glhepro - Test1.gli
File Loads Units Action Help Register
Borehole Parameters
Active Borehole Depth : 756.56 ft
Borehole Diameter : 10.00 in
Borehole Thermal Resistance : 0.3354 °F/(Btu/(hr*ft))
Borehole Spacing : 15.00 ft
Borehole Geometry : SINGLE CONFIGURATION 1 : single
Calculate Borehole Thermal Resistance
Select Borehole
Ground Parameters
Soil type currently entered : Average Rock
Thermal Conductivity of the ground : 1.400 Btu/(hr*ft*°F)
Volumetric heat capacity of the ground : 34.943 Btu/(°F*ft^3)
Undisturbed ground temperature : 48.99 °F
Select Ground Parameters
Select Ground Temperature
Fluid Parameters
Total flow rate for entire system : 31.70 gal/min
Average Temperature: 68°F
Fluid Concentration: 10%
Fluid Type: Ethylene Glycol / Water
Select Fluid
Freezing Point °F 28.05
Density lb/ft^3 63.39
Volumetric Heat Capacity Btu/(F.ft^3) 59.799
Conductivity Btu/(h.ft.F) 0.3128
Viscosity lbm/(ft.h) 2.893
Heat Pump
Heat Pump Selected : WaterFurnace E024/PSC_MOTOR@4.5GPM_700CFM
Select Heat Pump


GLHEPRO Results
Borehole Information
Borehole Configuration : SINGLE CONFIGURATION 1 : single
Each Borehole Depth : 756.56 ft
Total Borehole Depth : 756.56 ft
Distance between borehole centers : 15 ft
Average Temperature
Maximum Average Temperature : 90 °F at Month 120
Minimum Average Temperature : 77.23 °F at Month 1
Peak Temperature
Maximum Peak Temperature : 90 °F at Month 120
Minimum Peak Temperature : 77.23 °F at Month 1
OK

Appendix E: GLD 2009 Simulations and Sample Output

Base Case Design

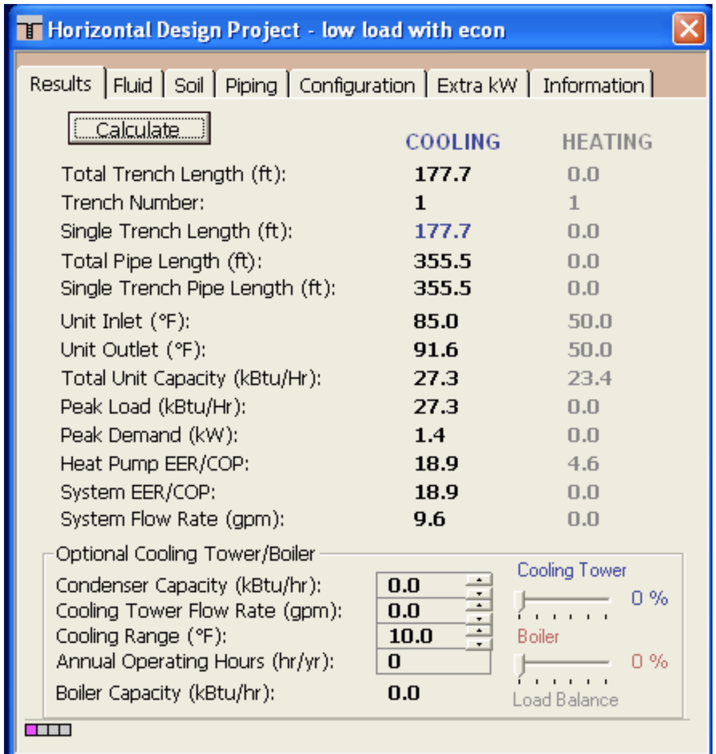
	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3630	1730	1410	3270	1600	1280
3	2350	1200	970	2260	1100	880
4	1880	960	780	1810	880	700
5	1640	830	680	1570	770	610
6 and 7	1400	710	580	1340	660	520

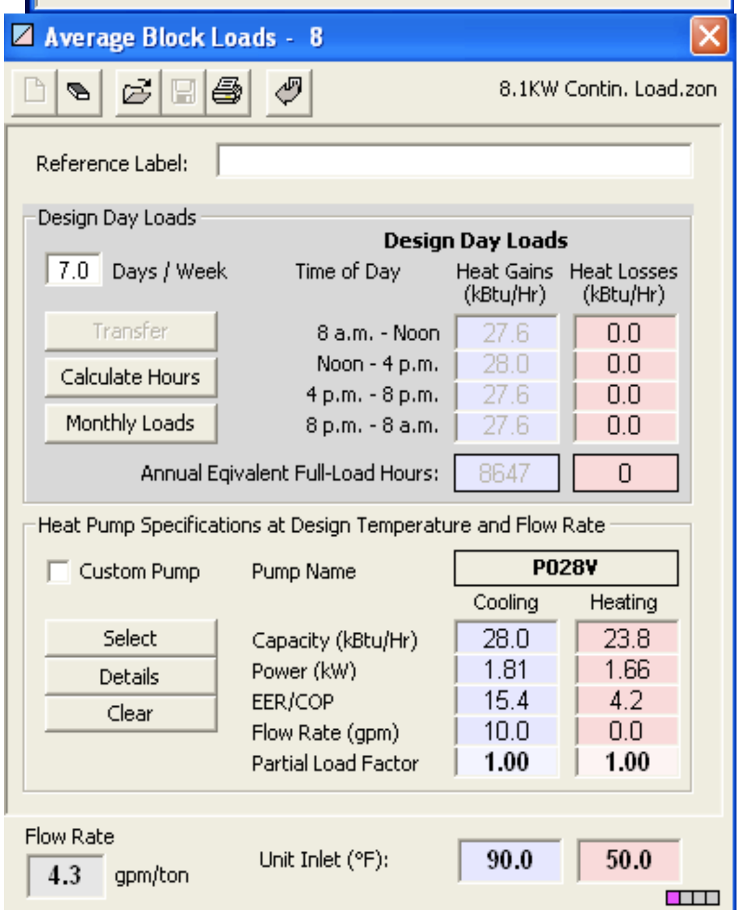
Base Case Design with Enhanced Grout (k=1.0 BTU/hr*ft*°F)

	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3150	1470	1150	3060	1390	1060
3	2170	1020	790	2110	960	730
4	1740	810	640	1690	770	590
5	1510	710	550	1470	670	510
6 and 7	1290	600	470	1260	570	440

Base Case Design with Enhanced Grout (k=1.4 BTU/hr*ft*°F)

	Single U Tube Exchanger			Double U Tube Exchanger		
Zone	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0	Depth in ft Light, Damp Soil k = 0.50	Depth in ft Average Rock k = 1.4	Depth in ft Dense Rock k = 2.0
1 and 2	3090	1420	1090	3020	1340	1020
3	2130	980	750	2080	930	700
4	1710	780	600	1670	740	560
5	1490	680	530	1450	650	490
6 and 7	1270	580	450	1240	550	420


Horizontal Design Project - low load with econ
Results | Fluid | Soil | Piping | Configuration | Extra kW | Information
Calculate
COOLING
HEATING
Total Trench Length (ft): 177.7 0.0
Trench Number: 1 1
Single Trench Length (ft): 177.7 0.0
Total Pipe Length (ft): 355.5 0.0
Single Trench Pipe Length (ft): 355.5 0.0
Unit Inlet (°F): 85.0 50.0
Unit Outlet (°F): 91.6 50.0
Total Unit Capacity (kBtu/Hr): 27.3 23.4
Peak Load (kBtu/Hr): 27.3 0.0
Peak Demand (kW): 1.4 0.0
Heat Pump EER/COP: 18.9 4.6
System EER/COP: 18.9 0.0
System Flow Rate (gpm): 9.6 0.0
Optional Cooling Tower/Boiler
Condenser Capacity (kBtu/hr): 0.0
Cooling Tower Flow Rate (gpm): 0.0
Cooling Range (°F): 10.0
Annual Operating Hours (hr/yr): 0
Boiler Capacity (kBtu/hr): 0.0
Cooling Tower
0 %
Boiler
0 %
Load Balance


Average Block Loads - 8
8.1KW Contin. Load.zon
Reference Label:
Design Day Loads
Design Day Loads
7.0 Days / Week
Time of Day
Heat Gains (kBtu/Hr)
Heat Losses (kBtu/Hr)
Transfer
Calculate Hours
Monthly Loads
8 a.m. - Noon 27.6 0.0
Noon - 4 p.m. 28.0 0.0
4 p.m. - 8 p.m. 27.6 0.0
8 p.m. - 8 a.m. 27.6 0.0
Annual Eqivalent Full-Load Hours: 8647 0
Heat Pump Specifications at Design Temperature and Flow Rate
Custom Pump
Pump Name
P028V
Cooling
Heating
Select
Details
Clear
Capacity (kBtu/Hr) 28.0 23.8
Power (kW) 1.81 1.66
EER/COP 15.4 4.2
Flow Rate (gpm) 10.0 0.0
Partial Load Factor 1.00 1.00
Flow Rate
4.3 gpm/ton
Unit Inlet (°F): 90.0 50.0

Appendix F: Energy Consumption Based Upon Operating Factor

Air Economizer Hours of Operation and Energy Use by Month (0.18 kWe)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	kWh
Zone 1&2	315	284	157	152	157	152	157	157	152	157	152	315	2310	416
Zone 3	315	284	315	305	157	152	157	157	152	157	305	315	2772	499
Zone 4	315	284	315	305	315	152	157	157	305	315	305	315	3239	583
Zone 5	315	284	315	305	315	305	157	157	305	315	305	315	3391	610
Zone 6&7	315	284	315	305	315	305	157	157	305	315	305	315	3391	610

Geothermal Heat Pump Hours of Operation and Energy Use by Month

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	TOTAL kWh
	31	28	31	30	31	30	31	31	30	31	30	31	
Zone 1&2 hours	X	284	315	305	315	305	315	315	305	315	305	315	
kWe	0	0.01	0.20	0.48	0.70	0.83	0.91	0.90	0.82	0.62	0.24	0.03	
kWe-hr	0	4	62	145	219	253	286	283	250	195	73	9	1781
Zone 3 hours	X	X	X	X	315	305	315	315	305	315	X	X	
kWe	0	0	0	0	0.33	0.55	0.70	0.66	0.49	0.00	0	0	
kWe-hr	0	0	0	0	103	168	219	209	149	1	0	0	849
Zone 4 hours	X	X	X	X	315	305	315	315	305	X	X	X	
kWe	0	0	0	0	0.04	0.46	0.60	0.56	0.31	0	0	0	
kWe-hr	0	0	0	0	13	140	189	176	96	0	0	0	614
Zone 5 hours	X	X	X	X	X	305	315	315	X	X	X	X	
kWe	0	0	0	0	0	0.24	0.44	0.39	0	0	0	0	
kWe-hr	0	0	0	0	0	72	139	124	0	0	0	0	335
Zone 6&7hours	X	X	X	X	X	305	315	315	X	X	X	X	
kWe	0	0	0	0	0	0.01	0.28	0.16	0	0	0	0	
kWe-hr	0	0	0	0	0	2	87	52	0	0	0	0	141

Air Conditioner Hours of Operation and Energy Use by Month

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	TOTAL kWh
	31	28	31	30	31	30	31	31	30	31	30	31	
Zone 1&2 hours	X	284	315	305	315	305	315	315	305	315	305	315	
kWe	0	0.04	0.57	1.38	2.01	2.40	2.62	2.60	2.37	1.79	0.69	0.08	
kWe-hr	0	11	180	419	634	732	826	819	723	565	211	26	5146
Zone 3 hours	X	X	X	X	315	305	315	315	305	315	X	X	
kWe	0	0	0	0	0.94	1.60	2.01	1.92	1.41	0.01	0	0	
kWe-hr	0	0	0	0	297	486	633	604	430	3	0	0	2453
Zone 4 hours	X	X	X	X	315	305	315	315	305	X	X	X	
kWe	0	0	0	0	0.12	1.32	1.73	1.62	0.91	0	0	0	
kWe-hr	0	0	0	0	39	403	545	510	276	0	0	0	1773
Zone 5 hours	X	X	X	X	X	305	315	315	X	X	X	X	
kWe	0	0	0	0	0	0.68	1.28	1.13	0	0	0	0	
kWe-hr	0	0	0	0	0	209	402	357	0	0	0	0	967
Zone 6&7hours	X	X	X	X	X	305	315	315	X	X	X	X	
kWe	0	0	0	0	0	0.02	0.80	0.48	0	0	0	0	
kWe-hr	0	0	0	0	0	6	252	150	0	0	0	0	408

Appendix G: Life Cycle Costs: Hybrid A/C vs. Hybrid GHP – Vertical Well, Double U, Enhanced Grout (k=1.4 BTU/hr*ft*°F)

Annual Costs	*GHP Zone 1&2*	*AC Zone 1&2*	*GHP Zone 3*	*AC Zone 3*	*GHP Zone 4*	*AC Zone 4*	*GHP Zone 5*	*AC Zone 5*	*GHP Zone 6&7*	*AC Zone 6&7*
Energy ($)	220	560	140	300	120	240	100	160	80	100
CO2 ($)	40	110	30	60	20	50	20	30	20	20
Maintenance ($)	20	120	20	120	20	120	20	120	20	120
TOTAL ($)	280	790	190	480	160	410	140	310	120	240
20 Year Cost										
Energy ($)	4400	11100	2700	5900	2400	4700	1900	3200	1500	2000
CO2 ($)	880	2200	540	1200	480	950	380	630	300	410
Maintenance ($)	480	2400	480	2400	480	2400	480	2400	480	2400
Capital ($)	20900	3300	14100	3300	11900	3300	10300	3300	9000	3300
Lifecycle Total ($)	26660	19000	17820	12800	15260	11350	13060	9530	11280	8110

Appendix H: Life Cycle Costs: Hybrid A/C vs. Hybrid GHP – Vertical Well, Double U, Enhanced Grout (k=1.4 BTU/hr*ft*°F) – Discounted GHP

Annual Costs	*GHP Zone 1&2*	*AC Zone 1&2*	*GHP Zone 3*	*AC Zone 3*	*GHP Zone 4*	*AC Zone 4*	*GHP Zone 5*	*AC Zone 5*	*GHP Zone 6&7*	*AC Zone 6&7*
Energy ($)	220	560	140	300	120	230	100	160	80	100
CO2 ($)	40	110	30	60	20	50	20	30	20	20
Maintenance ($)	20	120	20	120	20	120	20	120	20	120
TOTAL ($)	280	790	190	480	160	410	140	310	120	240
20 Year Cost										
Energy ($)	4400	11100	2700	5900	2400	4700	1900	3200	1500	2000
CO2 ($)	880	2200	540	1200	480	950	380	630	300	410
Maintenance ($)	480	2400	480	2400	480	2400	480	2400	480	2400
Capital ($)	16500	3300	9700	3300	7500	3300	5900	3300	4600	3300
Lifecycle Total ($)	22260	19000	13420	12800	10860	11350	8660	9530	6880	8110