Experimental and Numerical Results on the Performance of a Heat Pump

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Abstract*:*A 21 kW ground source heat pump (GSHP) operating since 2013 in Alaska is described in this paper. Six years of successful operation in an extreme climate and measured performance data from 2013 to 2017 prove the viability of heat pumps for extreme cold regions. Summary of performance evaluation data such as monthly electric energy use and cost, savings of the heat pump system compared to the cost of heating oil, energy extracted from the ground, heat delivered to building are tabulated by months. The coefficient of performance (COP) of the heat pump is calculated from the experimental data, which show the COP to vary from a maximum value of 4.15 to a minimum value of 2.34 depending on the heating load of the month and the ground temperature. Cost comparison shows savings by heat pump over regular heating oil boilers of 80% efficiency. In cold regions it is of concern that GSHP can create frozen ground or permafrost around the ground heat exchanger coil by extracting too much heat from the ground. A finite element heat conduction simulation performed over the ground heat exchanger coil spanning over a 30-year period shows that small volumes of frozen ground form around the coil each season, but they melt away during the summer by the recharge of heat from the solar heat gain. The mechanical system of the heat pump, sensors for measurements and cost of the system components are presented, which would be valuable to designers implementing heat pumps in various locations of the world.

Index Terms*: *COP,Experimental Performance, Heat pump

I. INTRODUCTION

A. Ground Source Heat Pumps In Cold Regions

Ground source heat pumps (GSHPs) are used around the world for space conditioning. They rely on a large energy sink (usually soil or a large water body) for heat rejection or extraction. In climates with balanced heating and cooling demand GHSPs work well because energy is rejected to and collected from the ground sink in more or less similar amounts. In colder climates that do not have cooling demands GHSPs extract much more energy from the ground than is returned. This unbalanced energy extraction lowers the temperature of the ground and thus the efficiency of the heat pump. There has been questions as to whether the ground has enough thermal energy to heat buildings in extreme cold climates like the Arctic and subarctic regions. This study proves that there is enough thermal energy in the ground and it is possible to gainfully employ heat pump in Fairbanks, Alaska, USA, which is located at northern latitude of about 65 degree. This result will be helpful in circumpolar nations such as the northern part of the USA, Canada, Russia, Norway, Sweden, Finland and many countries in the cold regions.

Another benefit of this study is addressing the mitigation of global climate change. In circumpolar regions the global warming and climate change are melting glaciers and permafrost, which have devastating effect on the society. Therefore, reduction of greenhouse gases is critical to minimize this effect by minimizing the combustion of fossil fuel. In cold regions, like Fairbanks, Alaska the buildings need to be heated for about 8 months of the year. The common method of heating by utilizing the thermal energy derived from the combustion of oil and natural gas in building heating furnaces. However, GSHPs use green energy for more than half of the energy supplied, the energy stored in the earth by solar radiation. Thus development of GSHP technology is extremely valuable of circumpolar regions. Analysis of GSHPs performance in cold climates over multiple heating seasons had not been studied prior to the beginning of this research. In 2013 a GSHP was installed at the Cold Climate Housing Research Center (CCHRC) in Fairbanks, Alaska with the intent to collect data on its performance and effects on the soil for at least 10 years.

The demonstration GSHP at CCHRC described in the thesis of Garber-Slaght [1] provides a wealth of data on a system that is at the edge of the recommended range for heat pumps and in a marginal location. The unfrozen ground temperature in this location is approximately 1°C and there is frozen soil (near 0°C) at approximately 9.5 m below the surface. The results of this GSHP project have been presented by Garber-Slaght et al [2]. in American Society of Heating, Refrigerating and Air- Conditioning Engineers (ASHRAE) journal, Garber-Slaght and Peterson [3] in International Ground Source Heat Pump Association (IGSHPA) conference proceedings and Garber-Slaght and Spitler [4] in Cold Climate Heating Ventilating and Air Conditioning (HVAC) conference proceedings.

B. Previous Work on Cold Climate Ground Source Heat Pumps

The CCHRC has conducted research since 2014 to evaluate the viability of GSHP in cold climates. The effectiveness depends on system performance, the price of oil and any rebates. It has been found that GSHPs can be cost effective in many areas of Alaska although the capital cost is high. Therefore, more GSHPs are being installed in colder climates due to the improvement in the technology. However, there is a lack of information on long-term performance in cold climates.

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There is unbalanced heat extraction from the soil surrounding the ground heat exchanger (GHE) and the potential degradation in the efficiency of the heat pump. If the winter heat extraction is higher than the summer heat recharge by space cooling through the GSHP and solar radiation it has the effect of lowering the ground temperature, making the GSHP less efficient and increasing permafrost (frozen ground). The results presented in the present paper answers these questions. These results can also be applied to gain knowledge for warm countries like India in a cooling dominated situation, where the ground temperature may increase steadily making the heat pump less efficient after several years of operation. A good approach would be to cool the soil by keeping the heat pump loop operational and cool the soil in winter months by rejecting heat to air.

A limited amount of work has appeared in the literature on GSHP performance, where heating is the dominant demand. Wu, et al. [5] note that the soil temperatures around a GHE in a heating dominated climate can degrade over time, which reduces the efficiency of the GSHP. They suggest several approaches to overcoming this problem: increasing the GHE size, installing a secondary heating source, and using thermal storage. You, et al. [6] recommend several ways to improve GHE performance. They conclude, increasing the size of the GHE or changing the layout of boreholes can mitigate thermal imbalance slightly, but is not effective for a larger thermal imbalance. Modifying the heat pump system to include auxiliary heating sources or restricting the use to certain times of the day when other heating options are not available are effective ways to help the GHE maintain higher temperature and improve efficiency [6].

Yang, et al. [7] explored about the phase change process in the soil surrounding the GHE. They discovered that freezing the soil surrounding the GHE coil can enhance the heat transfer performance and can help in downsizing the heat exchanger. The higher thermal diffusivity of the frozen soil has a significant effect on the improvement of heat transfer to the heat exchanger under phase change condition [7].

Rezaei, et al. [8] investigated the effects of providing different types of surface conditions above the GHE and how it affected the soil temperatures. A layer of tire-derived aggregate (shredded tires) affected soil temperatures down to 4 m with a layer of material that is 0.2 m thick [8]. They determined the surface layer of aggregate had the potential to increase the energy absorbed by the GHE by 17% over no surface treatment and the aggregate performed better in cold climates [8].

Zhihua et al. [9] studied a long-running vertical GHE heat pump in Tianjin, China to evaluate the thermal imbalance on the soil temperatures. Tianjin is a cooling dominated climate but their analysis of the thermal imbalance is instructive to both heating and cooling dominated climates. The cooling load was approximately twice the heating load in this study. They found the imbalance led to a gradual increase in soil temperature and at 30 years expect an auxiliary cooling unit will be required [9] due to the loss of cooling capacity in the soil. Bakirci [10] evaluated an experimental vertical GHE heat pump in Erzurum, Turkey. While warmer than Fairbanks, Alaska, Erzurum is one of the colder climates where heat pumps have been evaluated, the average January temperature is -10.8 °C and the annual minimum temperature is -16.9°C while the annual maximum is 17.3°C. Bakirici's study was only over one winter and he found the system was effective with a COP of 3.0 to 2.6 in the coldest months [10].

C. Objectives

This paper presents a complete description of the CCHRC GSHP system and the experimental data collected from the demonstration project. The analysis of data from the first four heating seasons is conducted to compare the performance of the heat pump. This analysis and performance evaluation proves the heat pump in extreme cold climate is viable. The second objective is to perform numerical analysis by finite element software in geotechnical engineering to determine soil temperature regime and the extent of the ground freezing that may occur due to cooling and the heat extraction from ground in the GHE of the GHSP.

II. THE CCHRC HEAT PUMP DEMONSTRATION PROJECT

There are very limited long term studies of GSHPs in a heating dominated climate where the soil temperature is low, say around 1°C. The GSHP demonstration project at the Cold Climate Housing Research Center (CCHRC) was designed to install and evaluate the performance of a GSHP in a cold climate for at least 10 years. The following topics were researched. (i) Determine if long-term performance of a GSHP is consistent in a severe cold climate, and does its efficiency vary over multiple heating seasons. (ii) Evaluate whether the thermal degradation of the ground loop is a challenge for adoption of the technology in cold climates. (iii) Examine, to what extent affordable ground surface treatments by different materials can enhance energy capture in the ground. (iv) Compare the primary energy consumption and savings of fossil fuel (oil) at the GSHP installation relative to conventional heating systems. (v) Demonstrate the viability of a GSHP at its most northern (coldest) limit of operation.

D. Location and Heating Information

The system was installed in 2013 and only runs in heating mode (September to April). It has been operating for 6 years; however, this paper only evaluates performance for the first 4 years.

The Research and Testing Facility (RTF) of the CCHRC is located on the campus of the University of Alaska Fairbanks. Fairbanks has 7,509°C heating degree-days$_{18}$ and 40°C cooling degree-days$_{18}$ the 99.6% design temperature is -41.9°C [11]. Fairbanks is in a zone of discontinuous and warm permafrost (0°C). The RTF is 2,044 m^2 with 3 different heating sections. The heat pump was selected to heat the 464 m^2 office space with a design heat load of 17.6 kW. Heat is distributed to the area via an in-floor hydronic tubing system embedded in the concrete floor. There are nine thermostatically controlled zone valves in the office space. The heat pump system replaced a 22.3 kW oil fired condensing boiler. There is a masonry stove used as supplemental heating for this space.

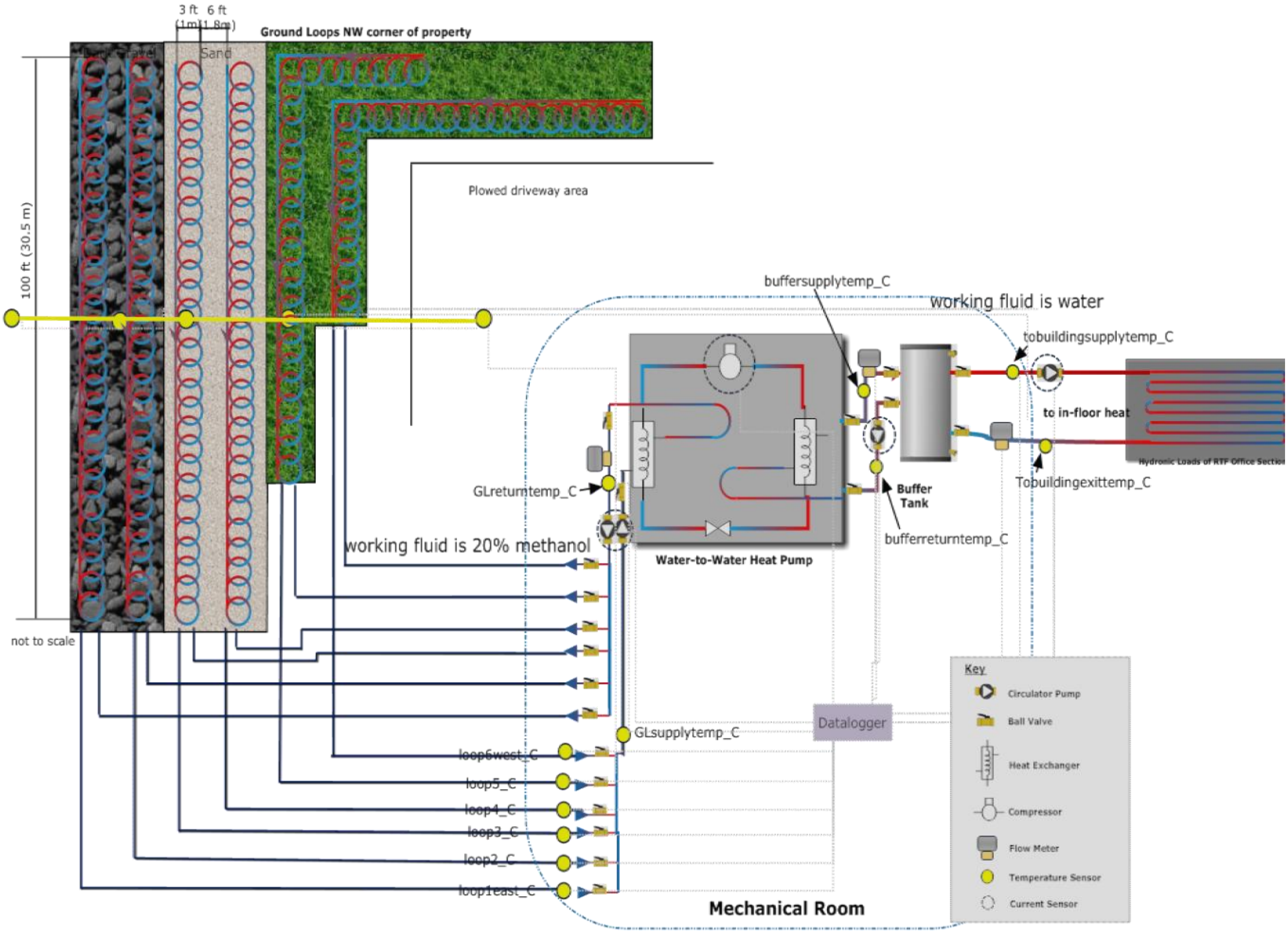

Figure 1. Schematic of the heat pump layout with the GHE, heat pump unit, buffer tank and the in-floor heating coil [1]. Circulating pumps, valves, flow meters, temperature sensors, voltage and current sensors are also shown.

E. Design and Installation

Prior to the installation of the heat pump, in October 2012, a soil thermal conductivity test was conducted at the test site. A 34 m long horizontal loop at 2.7 m of depth was installed. A 20:80 methanol/water solution was run through the loop. Heat was added to the fluid circulating in the loop via an electric heating coil. The temperature change in fluid and the energy input into the system were recorded. Geothermal Resource Technologies, Inc., which has specialty in measuring soil thermal conductivity and thermal diffusivity, performed this test. Upon analyzing the data they determined the soil thermal conductivity to be 1.42 W/m·K and the thermal diffusivity to be 0.055 m^2/day. This data was later used in numerical modeling of heat conduction in soil.

Initially, both deep wells and horizontally trenched GHEs were under consideration. However, past test bores had found frozen schist bedrock from 19.5 m down to 45.7 m, which would be the bottom of the boreholes. The frozen schist was at -0.2 °C. This large layer of frozen bedrock is a poor conductor of heat. Therefore, a horizontal GHE was selected over the vertical configuration. Horizontal "slinky" coils were adopted, which was the standard and economic design, since directional drilling was not an option in Fairbanks in those days. Six 30.5 m long by 1 m wide slinky coils with a 0.5 m pitch were installed 1.8 m apart. Please see the left side of Fig. 1 for the lay out of the six slinky coils forming the GHE.

The total length of the heat exchanger tubing is 1,463 m. It is made from high density polyethylene (HDPE) with a nominal diameter 1.9 cm, which was installed at 2.7 m depth to create the GHE. The GHE size and depth were determined by knowledge of past installations in the area, in conjunction with ground thermal conductivity test data, and information from a finite element model. Additionally, IGSHPA (International Ground Source Heat Pump Association) guidelines for flow path (one 30 m slinky coil per ton of capacity) and turbulent flow were used to further guide the design of the ground heat exchanger [12]. The depth was chosen to be below the line of seasonal frost (about 1.2 m) and above the top of the permafrost (nearly 9.1 m). In addition, the 2.7 m depth is the typical installation depth for residential horizontal GHE in the Fairbanks area.

In Fig. 1, notice that three different ground surface coverings over slinky coils are being evaluated: dark rocks (left), sand (center), and grass (right). Each surface treatment covers 2 slinky loops. This evaluated the effects of different surface treatments. To establish, which are more advantageous for energy recharge, the soil temperatures under the coverings were monitored as were the temperatures of the fluid returning from the slinky coils.

III. HEAT PUMP COST AND COP ANALYSIS

F. The Heat Pump Unit

Based on previous installation of heat pumps in Fairbanks, a residential water-to-water unit of 21 kW capacity was selected. The unit is a GeoSource Hydronic RGS-W072 with a single stage compressor. The working fluid of the heat pump is refrigerant R-410a. It is rated to have a COP of 3.4 at 0°C entering water temperature and 68 l/min of flow from the GHE to the buffer tank. The GHE actual installed flow is 63 l/min and the flow to the buffer tank is 65 l/min. It is clear from Figure 1 that the GHE absorbs heat from the ground, which is transferred by the heat pump unit to the buffer tank. The heat from the buffer tank is supplied to the in-floor heating coil, which heats the building.

The buffer tank contains 303 liter of water, which is heated by the heat pump to a temperature determined by the outdoor set point curve. The minimum temperature set point for the buffer tank is 26.7°C and the maximum is 42.8° C. Originally, the set point curve had a maximum of 41.7°C ; however the in-floor heating tubes were configured in a way that required a higher temperature so the set point curve was slightly elevated. This higher set point lowers the efficiency of the heat pump slightly. The GHE side of the heat pump is charged with a 20% methanol/80% water mixture by mass. The building hydronic side of the heat pump is charged with water.

G. Data Acquisition

Temperatures, fluid mass flow rates, thermal energy rates and electrical energy consumptions are recorded by an automated data acquisition system. The instruments taking part in the data collection are listed in Table 1 and shown in Fig. 1 on the system layout.

Table 1. Instruments for Data Acquisition [1].

Data	Instruments and Locations	Range and Accuracy
Ground Temperatures	Thermistors within and around the GHE	-20°C to 80°C ±0.1°C
Manifold Temperatures	Thermistors in the manifold returning from the GHE	-20°C to 80°C ±0.1°C
Ground Loop Energy	Energy (BTU) meters in the piping to and from the GHE	0 to 75.6 l/min ±2% -12°C to 21.1± 0.15°F
Heat Pump Energy	Flow meters and Thermistors in the piping to and from the buffer tank and to and from the building	0 to 56.8 l/min ±2% 4.4°C to 60°C± 0.15°F
Heat Pump Electrical Use	Power Meters at heat pump compressor and the circulating pumps	0 to 100 amp ±1% 115 to 230 VAC ±1%

H. Ground Heat Exchanger

The automated data acquisition system is recording soil temperature data from 7 thermistor strings in and around the GHE (Fig. 1). Furthermore, the temperatures of the fluid entering the building at the manifold from each heat extraction slinky coil are recorded.

The GHE soil temperatures are used to determine if the ground heat extraction coils are cooling the soil more than the solar recharge in the summer can recover. The temperatures are taken across the surface of the GHE loop field, as shown by the yellow line across the loop field in Figure 1. They are also taken down into the GHE field, as far down as 4.1 m in the center of the GHE field. Two of the vertical temperature strings are located in the middle of the slinky coils, while the third is between two sets of coils. The ground heat extraction coils cross the vertical temperature strings at approximately 2.7 m from the surface. Two other vertical temperature strings are 4 m to the west and east sides of the GHE field.

The thermistors in the manifold record the temperature of the fluid as it comes back from the GHE. These temperatures were intended to verify whether or not the surface treatments are creating any differences in temperature from each slinky coil loop.

The temperatures around the GHE help to monitor the change in soil temperature over time at certain depths. A 0°C temperature in the ground does not necessarily indicate frozen soil, because all the latent heat must be removed to make it fully frozen. Therefore, it is more of an indication that phase change is occurring. As energy is extracted from the GHE the temperature drops to 0°C quickly, and once the freezing temperature is reached the energy that is extracted changes the phase of the water in the soil to ice. This phase change takes much longer to complete and the soil is not necessarily frozen at the freezing temperature. Locations that stay below the freezing temperature for more than 2 years are considered permafrost.

I. Coefficient of Performance

The data acquisition system is also collecting data on the thermal and electrical energy rates of the heat pump. There are two pumps that send fluid in and out of the GHE coil to the heat pump. A third pump draws water to the heat pump from the buffer tank. A fourth pump delivers hot water from the buffer tank to the in-floor heating coils in the building. See Figure 1. The electrical energy consumption rates of each pump are recorded individually by the power meters. Additionally, the electrical consumption of the compressor of the heat pump is monitored as shown in Figure 1.

The thermal energy rates are determined using mass flow rate and temperatures at 3 locations: (i) the energy delivered to the heat pump from the GHE, (ii) the energy from the heat pump to the buffer tank and (iii) the energy from the buffer tank to the floor heating coil in building.

The thermal energy rate is determined from the equation;

$$\dot{Q} = \dot{m}(C_p)(T_{out} - T_{in}) \quad \textbf{(1)}$$

The mass flow rate and the temperatures are measured by flow meters and thermistors shown in Figure 1. A BTU meter referred to in Table 1 combines the readings of mass flow and temperatures and generates thermal energy rate.

The electrical energy rate is derived from the equation;

$$\dot{W} = VIcos(\Phi) \quad \textbf{(2)}$$

The voltage, current and the power factor are measured by power meters connected to the compressor, and each pump shown in Figure 1.

The oil-fired condensing boiler replaced by the heat pump is kept active. It can be used as a backup system should the heat pump ever fail. The energy output of the condensing boiler is monitored to verify if the boiler is augmenting the heat pump. A masonry stove is also available to heat the same area of the building as the heat pump. The amount of wood added to the stove is manually recorded to verify how much the heat pump is offset by the stove.

The efficiency of a heat pump or the Coefficient of Performance (COP) is calculated using Equation (3).

$$COP = \frac{Heat\ Energy\ to\ the\ Building}{Electricity\ \ for\ the\ Heat\ Pump} \quad (3)$$

"Electricity for the heat pump" includes the electricity powering the heat pump compressor and the 3 circulation pumps (2 in the GHE loop and 1 between the buffer tank and the heat pump) that are controlled by the heat pump. Data is collected on an hourly basis but the COP is calculated as an average for each month.

J. Installation Costs

The costs for the overall heat pump installation are presented in Table 2. This is a research project with additional features such as manifolds inside the building for instrumentation and monitoring capabilities and emphasis on precision. These features make this installation more expensive than a typical residential installation, which in the Fairbanks area generally cost between $20,000 and $35,000.

Table 2.Cost breakdown for the project [1].

Materials and Labor	Cost
Engineering Design	$1,162
GHE Installation	$30,305
Heat Pump Installation	$22,546
Total	$54,013

K. The Cost of Operation

Over the course of the first four operating years the system used 26,517 kWh of electricity. The total comes to $6,364 in heating costs using a constant rate of $0.24 per kWh. Table 3 lists the electricity use and cost for each month. When the heat pump is not running (May, June, July and August) it has a small electrical load of as low as 5 W. This load runs the thermostat that maintains the buffer tank water temperature at a set point based on the outdoor temperature. Each summer, except for 2015, CCHRC turned off the heat pump when the heating season was over in late May and kept it off into early September. This off time is indicated by a '0' in Table 3. The summer of 2015 provides the data of how much the heat pump costs in idle mode, since it was not turned off that summer.

L. Heat Pump Savings Over Oil-Fired Boiler

Savings due to the use of heat pump over an oil-fired boiler is a function of the cost of oil per gallon and the efficiency of the boiler. Oil prices have been variable since the beginning of this project. More savings are realized when the oil prices have remained high. Heat pump savings over the first 4 years of operation are presented in Table 4. The comparison is based upon using the real cost of fuel over that time period. In order to determine an oil-fired thermal energy equivalent to the amount of heat delivered by the heat pump, a 96% efficient oil-fired condensing boiler has been used in the calculation. This is a top quality high cost boiler, which is similar to the one the heat pump replaced. However, the high efficiency of this model is not typical of most boilers, which is around 80% in most residences in Fairbanks.

When oil price fell below $2.45 per gallon in the third winter, the savings advantage of the heat pump disappeared. The numbers in brackets in Table 4 show losses. In the 2015-16 heating season, using the oil-fired condensing boiler would have saved $207 over using the heat pump. However, considering the annual cost of 4 years at the bottom row of the Table 4, the heat pump has saved a combined total of $707 over using the oil fired condensing boiler that is 96% efficient. Replacing an 80% efficient boiler would have increased the savings to $1,676. Had fuel prices remained near $4 per gallon, as it was for a while, the heat pump system would have saved an estimated $3,421 over the 96% efficient boiler and $4,803 over the 80% efficient boiler in 4 years.

M. Heat Delivered to the Building and Electric Energy Use

The rate of thermal energy supplied to the building was recorded along with the electrical power consumption of the heat pump. Both data is listed in Table 5. The data of heat delivered to the building and the electrical power consumption allow the calculation of the energy removed from the GHE. This was corroborated with results derived from the mass flow rate in the GHE coil and inlet and outlet fluid temperatures measurements to record the thermal energy absorbed from the ground directly.

Examining the total value at the bottom row of Table 5, notice that the higher electrical use (6946 kWh) but roughly the same amount of heat delivered (about 20,000 kWh) to the building during the third winter (Year 3), compared to Year 2. This observation indicates the loss in efficiency of the heat pump over a period. Year 1 does not include a full year of data (project started in November), so it is not effectively comparable. In addition, the masonry stove was fired on a regular basis during year one, offsetting the heat loads. The thermal energy extraction rate from the ground is presented in Table 6. It is a function of the climate plus the ambient and ground temperatures variation from year to year. It can be correlated to the heating degree days, for each year, which is described in the subsequent section. On a total basis, the maximum annual thermal energy extraction of 17,900 kWh occurred in the 4th year.

Table 3. Annual electrical costs [1].

	1st Year (2013-14)		2nd Year (2014-15)		3rd Year (2015-16)		4th Year (2016-17)	
	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost
August			0	$0.00	13	$3.12	0	$0.00
September			129	$30.96	154	$36.96	146	$35.14
October			229	$54.96	434	$104.16	803	$192.69
November	97	$23.28	885	$212.40	1332	$319.68	1370	$328.81
December	1,115	$267.60	971	$233.04	1871	$449.04	2133	$511.98
January	962	$230.88	1636	$392.64	1104	$264.96	2096	$503.13
February	908	$217.92	1272	$305.28	1129	$270.96	1471	$353.14
March	306	$73.44	740	$177.60	593	$142.32	1442	$346.12
April	297	$71.28	132	$31.68	272	$65.28	286	$68.74
May	24	$5.76	14	$3.36	39	$9.36	83	$19.94
June	0	$0.00	9	$2.16	0	$0.00	0	$0.00
July	0	$0.00	5	$1.20	0	$0.00	0	$0.00
Annual Cost	3,709	$890.16	6,022	$1,445.28	6,941	$1,665.84	9,830	$2,359.70

Table 4. Comparison of savings by the heat pump over oil-fired boiler [1].

	1st Year (2013-14 winter)	2nd Year (2014-15 winter)	3rd Year (2015-16 winter)	4th Year (2016-17 winter)
	Heat pump savings over oil	Heat pump savings over oil	Heat pump savings (or loss) over oil	Heat pump savings (or loss) over oil
August				
September		$27.78	$9.75	($10.93)
October		$113.62	($3.56)	($44.97)
November	$18.12	$146.29	($10.57)	($17.23)
December	$161.28	$135.95	($34.56)	($38.21)
January	$158.10	$93.83	($47.31)	($79.05)
February	$147.28	$42.69	($60.87)	($55.53)
March	$57.70	$53.31	($35.22)	($59.62)
April	$58.42	$21.92	($21.29)	($17.95)
May	$2.65	$3.83	($3.67)	($4.44)
June				
July				
Annual Total	$603.55	$639.22	($207.30)	($327.94)

N. COP Comparison over Four Years

As defined by Eq. (3), the COP is calculated by taking the sum of the heat delivered to the building and dividing it by the sum of the electricity consumed by the compressor and the 3 circulation pumps linked to the heat pump over that time period. Monthly COPs are presented in Table 7. The efficiency (COP) of the heat pump varied from month to month and year to year. It is generally a bit higher in the fall (September, October and part of November) when the GHE was the warmest and decreases somewhat through the winter (December, January and February). However, as the heating demand of the building lessened in the spring, the COP did not decrease, rather held steady or improved slightly as the heat pump delivered lower temperature heat to the building. Theoretically, a COP of greater than 1 proves that the heat pump system is acceptable. To be attractive, it must be much higher. This installation has achieved a COP of as high as 4.15 and as low as 2.34 for a cold climate proving the viability of GSHP in the extreme subarctic region.

Figure 2 shows a bar chart of the trend for the COP. It is observed that the COP of the heat pump is diminishing over time. On an annual basis, the year 2014 is the high COP year and the year 2017 is the low COP year. The average decline has been about 9 % between the first 2 years, again approximately 9% between the second and third winter, and dropping only about 6% between the third and fourth winters. The total decline in the annual COP over 4 years is 24%. The reduction may be weather related. A severe winter can affect the efficiency of the heat pump, with lower outdoor temperature scaling for higher delivery fluid temperature. The heating degree days (HDD) is a measure of demand for heat in a building and is dependent on outdoor temperature. The HDD equation is described elaborately in the book of Mc Quiston et al. [13].

Table 5. Heat delivery rate and electric energy use [1]

	Year 1 (2013-14 winter)		Year 2 (2014-15 winter)		Year 3 (2015-16 winter)		Year 4 (2016-17 winter)	
	Electric power use (kWh)	Energy delivery rate (kWh)	Electric power use (kWh)	Energy delivery rate (kWh)	Electric power use (kWh)	Energy delivery rate (kWh)	Electric power use (kWh)	Energy delivery rate (kWh)
Aug.	-	-	-	-	13	46	-	-
Sept.	-	-	129	537	154	543	146	342
Oct.	-	-	229	892	433	1,451	803	2051
Nov.	97	379	885	3,216	1,332	4,123	1,370	4479
Dec.	1,115	3,870	971	3,479	1,871	5,517	2,133	6593
Jan.	962	3,405	1,636	5,210	1,104	3,250	2,096	5589
Feb.	908	3,167	1,272	3,966	1,129	3,368	1,471	3932
Mar.	306	1,145	740	2,347	593	1,677	1,442	3816
April	297	1,109	132.	419	272	758	286	699
May	24	96	14	32	39	144	83	228
June	-	-	9	0	-	-	-	-
July	-	-	5	0	-	-	-	-
Total	3,709	13,171	6,022	20,098	6,946	20,877	9,832	27,729

Table 6. Energy rate extracted from the ground [1]

	1st Year (2013-14 winter)	2nd Year (2014-15 winter)	3rd Year (2015-16 winter)	4th Year (2016-17 winter)
	Energy from ground (kWh)	Energy from ground (kWh)	Energy from ground (kWh)	Energy from ground (kWh)
Aug.	-	-	33	-
Sept.	-	408	389	196
Oct.	-	663	1,018	1,248
Nov.	282	2,331	2,791	3,109
Dec.	2,755	2,508	3,646	4,460
Jan.	2,443	3,574	2,146	3,493
Feb.	2,259	2,694	2,239	2,461
Mar.	839	1,607	1,084	2,374
April	812	287	486	413
May	72	18	105	145
June	-	-	-	-
July	-	-	-	-
Total	9,462	14,090	13,937	17,899

Table 7. Comparison of the COP of the heat pump [1]

	1st Year (2013-14 winter)	2nd Year (2014-15 winter)	3rd Year (2015-16 winter)	4th Year (2016-17 winter)
September		4.15	3.52	2.34
October		3.9	3.34	2.55
November	3.9	3.63	3.09	3.27
December	3. 47	3.58	2.95	3.09
January	3.54	3.18	2.94	2.67
February	3.48	3.12	2.98	2.67
March	3.73	3.17	2.82	2.65
April	3.73	3.17	2.78	2.44
Annual	3.69	3.34	3.01	2.82

Table 8. Heating degree days in Fairbanks [1]

	1st Year 1 (2013-14 winter)	2nd Year (2014-15 winter)	3rd Year (2015-16 winter)	4th Year (2016-2017 winter)
°C HDD_{18}	6,921	6,769	6,487	7,535

$$HDD = \frac{(T - T_a)N}{24} \quad (4)$$

where T is 18° C and T_a is the outdoor ambient air temperature, N is the number of hours for which T_a remained below 18° C during the heating season of a year. The concept is that below an outdoor ambient temperature of 18 ˚C heating of building becomes necessary. The HDD is a good criterion to compare how much colder one winter is in comparison to another. Table 8 presents a comparison of the HDD for Fairbanks for 4 years of study. The HDD of the first 3 years are comparable, but the 4th year was the most severe winter with almost 1,000 more HDD than Year 3. This additional heating demand is a major factor in the cooling of the soil temperature, more severe operating condition and in lowering the annual COP to 2.82.

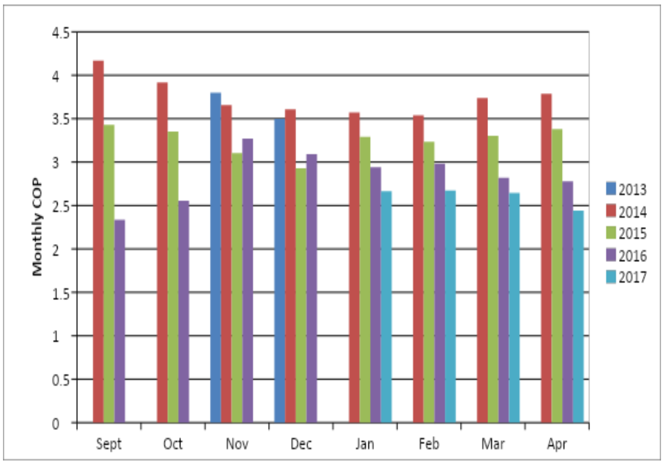

Figure 2. Heat Pump COP over time [1]

O. Ground Surface Treatments

The temperature sensors in the manifold yielded results as to whether the surface treatments were having any effect on the GHE. The temperature data revealed that the fluid returning from the dark gravel loop was slightly warmer than the other two surface treatment loops. Therefore, out of the three types of surface coverings tested in this project, the dark gravel performed better than the sand or the grass. The grass produced the coolest temperature among the three treatments. The differences in the surface treatments was noticeable in the fall of 2015, with the gravel 0.5°C warmer than the sand loops and 1°C warmer than the grass loops. According to the manufacturer's information on this heat pump model, a 0.6C° change in the incoming temperature for the heat pump creates a 0.044 change in the COP of the heat pump. The 1C° increase in the fluid temperature returning from the ground loop could improve the COP by 0.08.

IV. NUMERICAL ANALYSIS

P. Soil Model

The ground source heat pump (GSHP) demonstration at the Cold Climate Housing Research Center (CCHRC) has provided data on the soil interactions with the heat pump system for more than 4 seasons. This data is in the form of how much heat energy has been extracted from the ground heat exchanger (GHE), what the temperatures within the GHE have been, and the temperature of the fluid in the GHE GSHP loops. This data is useful in developing a soil heat transfer model to evaluate the impacts of the GHE on the soil several years out from the current point. The life span of a heat pump is about 20 years and GHE can last up to 30 years. Therefore, a soil heat transfer model can evaluate potential changes in the soil thermal/moisture regime and how those changes might impact the GSHP system. This model can also determine if the GHE can handle more heat extraction in the long term if CCHRC wanted to install a bigger heat pump to heat more of the building.

Q. Software Package

Temp/W© 2012 by GEO-SLOPE International Ltd. [14] has been used widely in industry for geotechnical engineering to study heat conduction in soil. It is a 2-dimensional finite element modeling software. It was used in this project to focus on the thermal aspects of the soils around the GHE. It was chosen because other researchers have done some heat pump studies in Alaska using this software. Temp/W is a finite element software package that can model heat transfer through porous and solid materials while taking into account freezing and thawing actions. TEMP/W can be integrated with SEEP/W to analyze convective heat transfer in the soil, which was attractive due to the ground water movement at the site; however, SEEP/W was not integrated for this study; it is recommended for the future research.

R. Software Package

Conduction is the principal mechanism for heat flow in the Temp/W model [14]. As explained in the Temp/W manual, the model is built upon governing equations 5 to 7 summarized below. Conductive heat flow is directly dependent on thermal conductivity and the temperature gradient.

$$q = -k\frac{\partial T}{\partial x} \quad (5)$$

The following differential equation states that the change in stored heat of an elemental volume is equal to the difference in heat flux entering and leaving the volume.

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + Q = \lambda\frac{\partial T}{\partial t} \quad (6)$$

The heat storage of an element is equal to the volumetric heat capacity of the material plus the latent heat associated with phase change expressed by the equation that follows.

$$\lambda = c_v + L\frac{\partial w_u}{\partial T} \quad (7)$$

S. Domain and Grid Layout

The CCHRC heat pump is installed in a field to the northwest of the research center. The GHE is roughly a rectangular box 15 m wide by 30.5 m long and 3 m deep. For a 2-dimensional model it is assumed infinite in its long direction and symmetric in its wide direction. Since it is symmetric, half of the GHE was developed in this model. The full domain is 30 m deep and 19.5 m wide. Figure 3 shows the domain for the soil model [1]. The line at 2.8 m is the line that the heat extraction coils are on, they are visible in this graphic as the 3 thick linear zones that start at 1.5 m and proceed to the right. Each heat extraction coil is 1 m wide and 1. 8 m separates the coils.

Figure 3 also shows the grid layout for the model. The element size is 0.1m surrounding the GHE coil and near the surface; however, the further from the GHE the larger the elements. The largest size is 1.5 m at the very bottom and also to the right of the domain. There are 14,084 nodes and 14,091 elements in this mesh.

T. Boundary Conditions

The boundary conditions for the domain in this model are: (i) the geothermal gradient at the bottom, (ii) the soil temperature at the surface, (iii) zero heat flux on the left side due to symmetry, (iv) zero heat flux on the right side due to far distance and (v) temperature prescribed at the GHE pipe. The geothermal gradient is based on previous Temp/W model of the same location; it is a constant 5.2 kJ/day/m.

The surface temperature condition uses the actual surface data collected. Ground surface temperatures in 6 locations across the GHE were collected hourly for the first 4 years of the project. Those hourly temperatures were averaged for each day of the year across all four years. The recorded data provides a better estimate of temperatures at the surface because the effect of snow cover is already accounted for. The heat extraction boundary condition at the GHE pipe were obtained from the measurement of 4years of the median fluid temperature in the slinky coil and improving it considering the pipe wall resistance of high density polyethylene pipe.

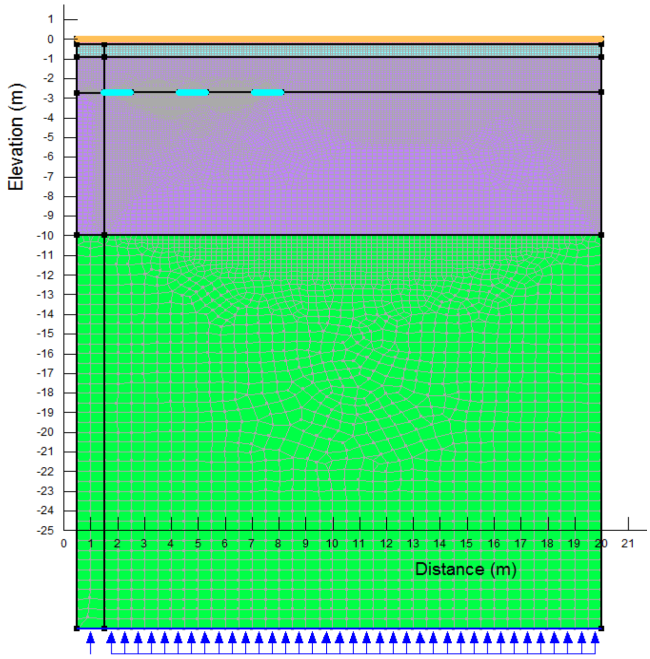

Figure 3. Domain and grid layout for the GSHP model [1]. The mesh is the most fine at the surface and around the GHE, which is depicted as the thick linear spaces at 2.8 m of depths.

U. Model Validation

A steady state parent model was created using the known temperatures and permafrost depth which produced results that existed just before the GHE was installed. Then a transient analysis was run for 12 years initially, to create a model that demonstrates the actual conditions of the soil in the subsequent four years. The first four years of the soil measured temperatures were used to evaluate if the model is close to the actual. The center of the GHE is an important location to check the agreement between the computed data and the measured data. This comparison is shown in Figure – for January, July and October of 2017. These are called whiplash curves in geotechnical engineering. The trends are correct showing high ground temperature in summer (July), moderate temperature in late fall (October) and low ground temperature in winter (January).

The model predictions shown by continuous lines are in fair agreement with the thermistor measurements represented by symbols at the ground surface (0 m) and at depths of 0.75, 1, 2.1, 2.9, 3.5 and 4.1 m.

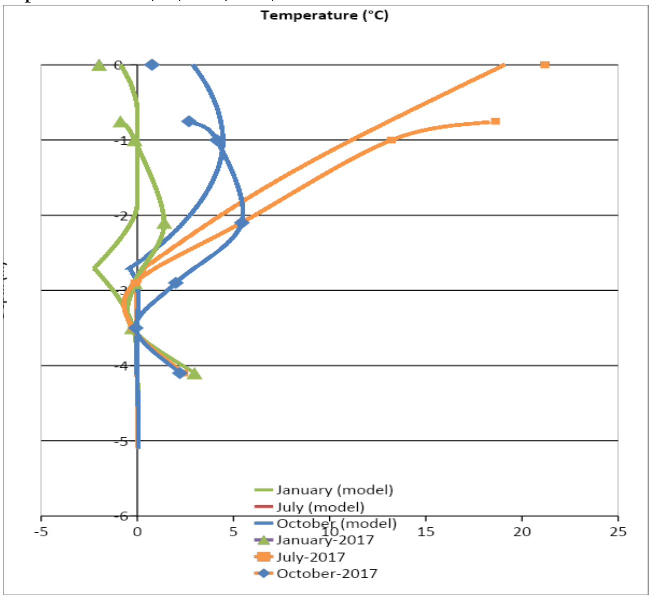

Figure 4. Comparison of numerical model data to measured data from the center of the GHE [1]

V. Long Term Performance Results

With the agreement between the model and the measured data, the model was ready to be applied to the GSHP at the CCHRC for long term performance. The main purpose of creating the numerical model was to predict how the soil regime would change due to the continuous extraction of heat for many years from ground in this subarctic region which does not possess a lot of thermal energy in the soil to begin with. Will it make the surrounding ground to turn in to permafrost? Therefore, the heat pump model was run over a 30 year period to study if the heat pump is viable in a marginal location as Fairbanks. The life of a heat pump is about 15 to 20 years but the GHE can last up to 40 to 50 years. So, 30 years seems like a feasible amount of time for a system to operate, since a replacement heat pump can utilized the same GHE.

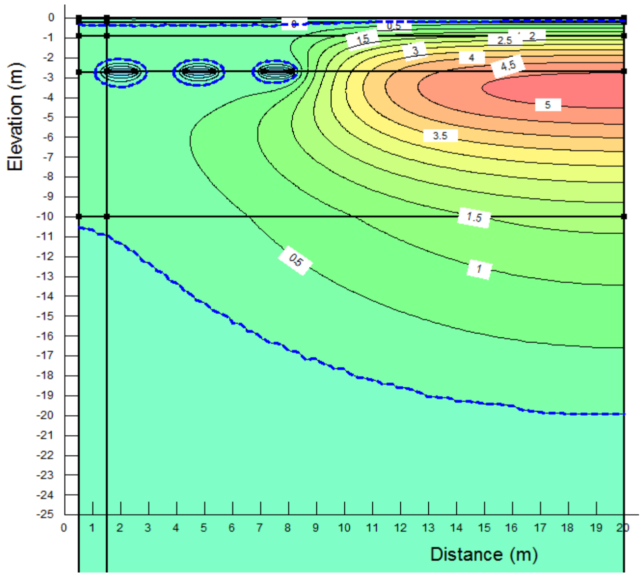

Figure 5. Soil temperatures at the end of the 30 year model (in December). The blue dashed line is the freezing line. The dots at -2.8 meters delineate three slinky coils. Frozen soil that forms around the GHE coils does not last into the next winter [1]

The results of the computation are shown in Figure – showing isotherm contours. In December, due to the cold soil temperature, the slinky coils are surrounded by 0^{o}C ground isotherm. But they melt away in summer due to the warming of the soil. To the right of the slinky coil, positive ground temperature regime occurs and as high as 5^{o}C isotherm is possible. This may be due to low extraction of heat from those regions. The permafrost exists at 10.5 m below surface underneath the slinky coil, but drops down to about 20 m, because the coil cannot extract much heat from far off region due to the increase of thermal resistance to heat flow. Therefore, this modeling proves that on a long term basis the slinky coils will remain surrounded by unfrozen soils and there would not be a cumulative buildup of permafrost around the coils due to many years of extraction of heat by the GHE.

V. CONCLUSIONS

The following conclusions have been drawn from the results of above investigations.

a) The heat pump at the Cold Climate Housing Research Center has been operating for 6 years in a climate that is far colder than most ground source heat pumps that have been discussed in the literature to date. The severe cold coupled with no summer cooling load, which could have recharged the ground, and frozen soils create an extreme test of the GSHP technology. The CCHRC heat pump is functioning well and the experimental data of first 4 years show a monthly COP of as high as 4.15 and the lowest at 2.34. Previous study [1] has found that a GSHP with a COP of 2.5 or greater would be cost effective in Fairbanks (based on $2.87 heating oil per gallon and $0.17/kWh of electricity). Therefore, it is concluded from this study that GSHPs have the potential to be a viable source of space heating for cold regions like Interior Alaska.

b) The COP for the heat pump showed a gradual reduction over time; possibly due to colder winter (higher degree days) in some years and may be due to the cooling of the ground. The ground could be potentially recharged in the summer by installing solar thermal collectors on the roof.

c) The cost of operating the GSHP is lower than running even a condensing high efficiency (96%) and high cost boiler for the first 2 years. But in next two years it is higher, mainly due to variation in the price of oil. Secondly, if a normal household boiler of 80% efficiency that is used in many homes is compared, the heat pump would save money.

d) Three surface treatments on the ground above the buried coils showed that the dark color gravel absorbs and retains more heat compared to sand or grass covering and is preferable.

e) The numerical analysis of the ground temperature regime covering the GHE slinky coil for a thirty year simulation shows that there is not going to be formation of frozen ground or permafrost around the coil.

The summer recharge of heat will thaw the small volume of frozen soil caused due to extraction of heat.

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Nomenclature

T Temperature
x Distance
t Time
k Thermal conductivity
L Latent heat of water
w Volumetric water content
q Heat flux
c_v Volumetric heat capacity
Q Applied boundary flux
˚C HDD_{18} Heating degree days based on 18 ℃

Greek Symbols

λ Capacity for heat storage

Subscripts

x in the x-direction
y in the y-direction
u unfrozen