Ground Source Heat Pump Efficiency in Cold Climates

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ABSTRACT

Until recently, only a few ground source heat pumps (GSHPs) have been installed in Alaska. Increasingly GSHPs are being adopted as efficient heating devices for residential and commercial buildings in Alaska; however, significant questions about their long-term efficiency in severe cold climates remain unanswered. A study of a residential-size GSHP installed in Fairbanks, Alaska began in October 2013 in order to document the long term effects of heat extraction on the ground thermal regime and any associated degradation in the efficiency of the heat pump system. Fairbanks, located in Interior Alaska, has an extremely cold climate, along with discontinuous permafrost. The ground surrounding the heat pump ground loop was thawed to a depth of approximately 30 ft (9m) at the time of the ground loop installation, which provided a narrow band for optimizing a ground loop between the zone of seasonal frost and the underlying permafrost. These are challenging conditions for the operation of a heat pump system and provide a rigorous testing environment for using GSHPs in Alaska. Depression of the soil temperatures around the ground loop is anticipated and acceptable if within design specifications. Conditions at the surface may affect the ground temperatures and ultimately the efficiency of the heat pump. This study compares three surface treatments and their effect on ground temperatures. A combination of physical monitoring and computer simulation are used to study the effects of the heat pump heat extraction and the surface treatments on the ground thermal regime. This interim report presents information on the design of the research project, predictions from the simulations, and data from November 2013 to January 2014.

INTRODUCTION

The installation and use of ground source heat pumps (GSHPs) for heating in Interior Alaska has substantially increased in recent years, raising questions about the efficiency and long-term performance of heat pump installations in areas of discontinuous permafrost and low annual temperatures. A 2011 study of GSHP technology in Alaska found that longer term (6 to 10 years) studies of heat pump performance are necessary to better gage the performance of the systems and the effects the systems have on the thermal regime of the soil (Meyer et. al., 2011).

In an effort to address the lack of studies into the long-term performance of ground source heat pumps in cold climate the Cold Climate Housing Research Center (CCHRC) has begun a ten-year study of a GSHP system at their Research and Testing Facility (RTF) in Fairbanks, Alaska. The study was designed to determine if long-term performance of a GSHP is stable in a severe cold climate and to thoroughly characterize its efficiency over multiple heating seasons by evaluating if thermal degradation of the ground loop field is a fundamental challenge for adoption of the technology in cold climates and examining the significance of practical and affordable ground surface treatments to maximize energy capture in the ground.

BACKGROUND

In 2011 the Alaska Center for Energy and Power and the Cold Climate Housing Research Center completed an extensive study of GHSPs in cold climates focusing on Alaska specifically. The economic assessment found that even with high capital costs, GSHPs with a minimum COP of 2.5 are cost effective in several parts of the state, including the cold interior Fairbanks area (Meyer et. al., 2011). Alaska-specific studies from 1976 to 1996 found COPs ranging from 2 to 3.89, depending on their geographical location and on the installation technique and equipment used (Meyer et. al., 2011).

Several studies of GSHPs were conducted in Alaska in the 1980s and 1990s. The studies spanned the state, covering climates from the temperate rainforest of Southeast Alaska to the cold arid interior. The longest of the interior Alaska studies lasted for 1.5 years and concluded that the soil temperatures with extraction loops at 4 ft (1.2 m) of depth recovered early in the summer season (Nielsen and Zarling, 1983). A one year study of a heat pump installation in the Southcentral Alaska found that deeper (9 ft, 2.7m) heat extraction coils did not recover temperature completely in the summer months whereas the shallower (5 ft, 1.5 m) coils recovered well (Mueller and Zarling, 1996).

Studies of cold weather GHSP installations question the long term effect of the thermal balance in the ground loop heat exchanger. The heat extracted from the soil during the heating season is generally greater than the heat rejected during the cooling season in colder climates. Soil temperatures can decrease over time, which leads to a decrease in GSHP performance (Wu et. al., 2013). Very few studies look into the long term performance of GSHPs in cold regions (Wu et. al., 2013). Andrushuk and Merkel (2009) studied 10 GSHP installations in Manitoba for one year and found that the system COP averaged 2.8, but were unable to produce any definitive findings on the longer term performance of the systems and their effects on the ground due to the short nature of the study and the relatively recent installation of the systems.

In cold climates, engineers often attempt to balance the heat extraction from the ground with hybrid systems that supplement summer heat with other heat sources (Harsem et. al., 2012). Several studies in cold climates have concentrated on the use of solar thermal heat recovery systems in conjunction with GSHP systems. A Yukon study in 2006 found that a hybrid GHSP/solar thermal system was effective at heating a well-insulated residential building in Whitehorse, Canada (Lessoway Moir Partners, 2006). Wu et. al. (2013) suggest that using a ground source absorption heat pump rather than a ground source electrical heat pump will aid in preserving the thermal balance of the soil. Using simulations Eslami-nejad and Bernier (2012) found that using saturated soil in the borehole and allowing it to freeze adds the energy from phase change to the circulating fluid. In addition, if a solar thermal loop is added to the system the borehole lengths can be reduced by 38% (Eslami-nejad and Bernier, 2012).

There have been a few international studies that assess the performance of cold climate heat pump installations; several studies found the COP of the systems range from 2.6 to 5.72 during the heating season (Bakirci 2010; Takeda-Kindaichi et. al., 2008). However, the minimum temperature of the coldest region of Turkey was 27°F (-2.8°C) (Bakirci, 2010) and in the Japan study the minimum winter temperature was 20°F (-6.8°C) (Takeda-Kindaichi et. al., 2008), both are much warmer than the minimum temperatures found in Fairbanks, Alaska. Both of these studies found GHSPs viable in their climate but did not study the systems beyond one year.

Most of the long-term studies of heat pumps in cold climates have to do with GSHP systems that are used to cool foundations over ice-rich permafrost. Several buildings in Svalbard, Norway have on-grade foundations with heat pump cooling tubes embedded in them (Instanes and Instanes, 2008). These systems were designed to keep the temperature under the foundation at 23°F (-5°C). A similar system was used to retrofit a Fairbanks home in 1993 (McFadden, 2000); the structure had to be leveled and heat extraction tubes were installed below the unfinished basement floor. The surface temperature of the soil dropped from 54°F (12°C) in 1993 to 32°F (0°C) by 1996. The heat extraction tubes attached to a heat pump were able to maintain the soil under the house around 32°F (0°C) until 2000, except for a brief time in 1999 when the heat pump failed. In 2001 frost heaving was discovered under the house caused by excessive cooling from the heat pump system, at which time a failure in the system controls was discovered and repaired. A final report on the project in 2007 found the system still functioning to maintain the permafrost below the structure (the heat pump itself had been replaced once) 14 years after its initial installation (McFadden, 2007). Neither of these studies comments on the performance of the heat pump as a space heating system.

SITE CONDITIONS

The CCHRC RTF is located on the campus of the University of Alaska Fairbanks. Fairbanks has 13,517°F heating degree-days$_{65}$ (7,509°C HDD$_{18}$) and 72 °F cooling degree-days$_{65}$ (40°C CDD$_{18}$); the 99.6% design temperature is -43.5°F (-41.9°C) (ASHRAE, 2013). The heat pump system was designed to heat a 5000 ft^2 (464 m^2) portion of the building that already has in-floor hydronic heat. The design heat load for the portion of the building is 60,000 BTU/hr (17.6 kW). Prior to the installation of the heat pump this portion of the building was heated with a 76,000 BTU/hr (22.3 kW) oil fired condensing boiler and a wood fired masonry heater. The heat pump system was designed to replace the oil boiler as the main source of heat for this portion of the building; the masonry heater will remain in use for supplemental space heating.

The RTF is in a zone of discontinuous permafrost, the surrounding area is an open field that has been cleared of native vegetation for more than 60 years and consists of mostly moist silt (Shannon & Wilson, Inc., 2002). Clearing an area of natural trees and brush allows the underlying permafrost to degrade (Department of the Army, 1954); as a result the permafrost underlying the field surrounding the RTF continues to degrade. When the building was constructed in 2006 there was a permafrost layer approximately 15 ft (4.6 m) below the southern side of the building. The top of the permafrost layer on the site ranged from 15 to 24 ft (4.6 to 7.3 m). A test drill in 2012 prior to installing the ground loop did not find permafrost within 30 ft (9.4 m) of the surface. Other test drilling in the area located frozen schist bedrock (20°F, -6.7°C) from 64 ft (19.5 m) down to 150 ft (45.7 m) (the bottom of the boreholes). A thermal conductivity test at 9 ft (2.7 m) of depth found the thermal conductivity to be 0.82 Btu/hr·ft·°F (1.42 W/m·K).

GSHP DESIGN

Originally, CCHRC wanted to test horizontal versus vertical ground heat exchangers, however, there was a concern that frozen bedrock would not have the necessary heat transfer in an area that is already marginal. In the end a horizontal ground loop heat exchanger was designed. At the time of installation, directional drilling was not available in the Fairbanks area, so slinky coils were installed. Six 100 ft (30.5 m) long by 3 ft (1 m) wide slinky coils with an 18 in (0.5 m) pitch were installed 6 ft (1.8 m) apart (a plan view is shown in Figure 1). Overall, 4,800 lineal ft (1,463 m) of 3/4 in (1.9 cm) HDPE was installed at 9 ft (2.7 m) depth to create the in-ground heat exchanger. The ground loop size was determined by knowledge of past installations in the area, in conjunction with ground thermal conductivity test data, and information from the model. Additionally, IGSHPA (International Ground Source Heat Pump Association) guidelines for flow path (one per ton of capacity) and turbulent flow were used to further guide the design of the ground heat exchanger (IGSHPA, 2009).

The depth of the ground loop is more than was recommended by the Mueller and Zarling (1960) and Nielsen and Zarling (1983) Alaskan studies. However, the depth was chosen to be below the line of seasonal frost and above the top of the permafrost. In addition, the 9 ft (2.7 m) depth is the typical installation depth for residential horizontal ground loops in the Fairbanks area.

In order to develop suggestions for the optimization of the summer recharge of the ground heat exchanger, three different surface treatments were applied over the ground loop. The loop field is broken into three sets of two loops and each set of loops has a different surface treatment: dark rocks, light colored sand, and grass. The temperatures within the soil are monitored across the differing treatments. The temperature of each loop as it returns to the building is also monitored.

A residential 6 ton (21 kW) water-to-water heat pump was installed based on previous experience with the model in Fairbanks, it was connected to the existing in-floor hydronic heat delivery system. The heat pump has an outdoor set point which maintains a buffer tank at temperature based on the external ambient temperature, with a maximum temperature of

109°F (42.8 °C). The ground loop side of the heat pump is charged with a 20% methanol, 80% water mixture. The in-floor hydronic side of the heat pump is charged with water.

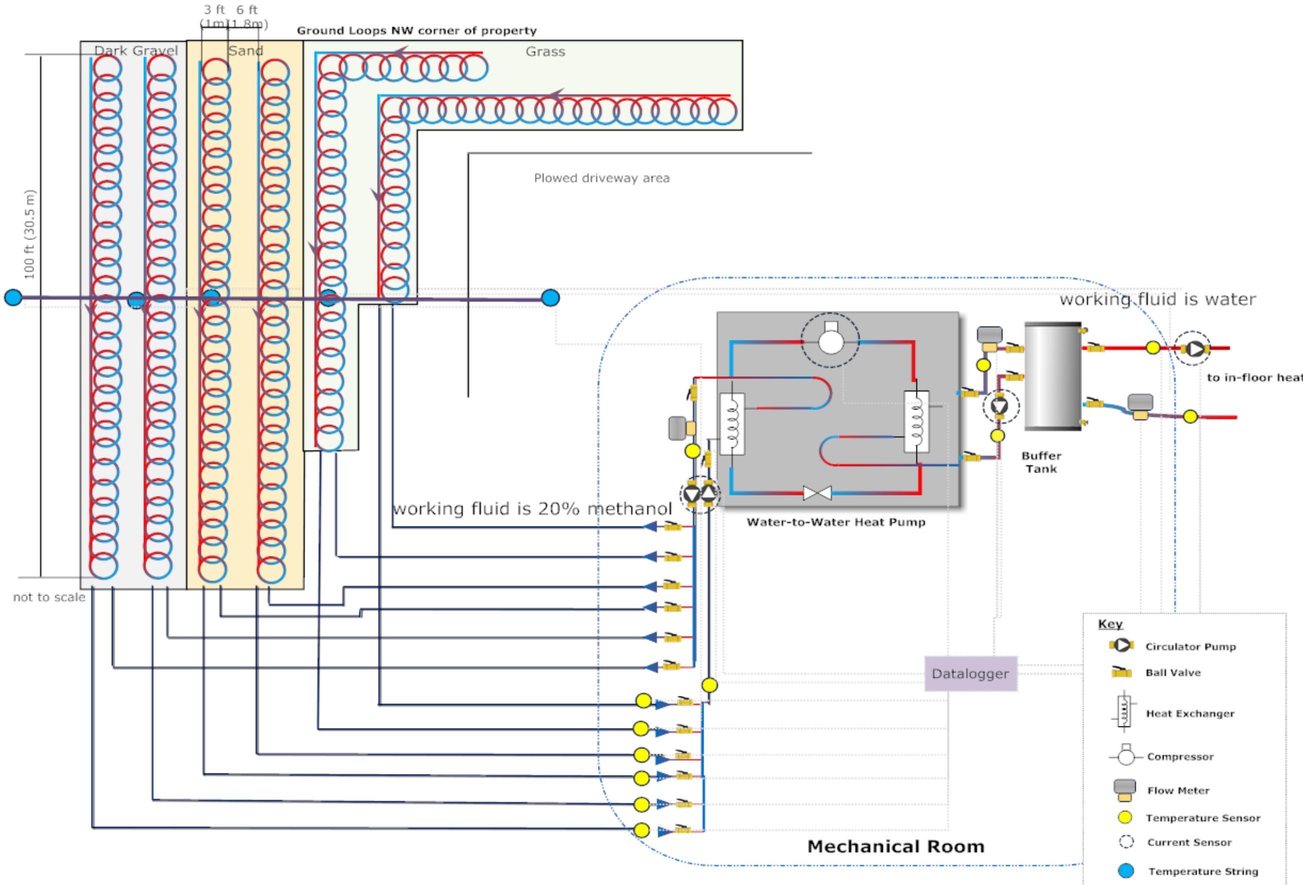

Figure 1. Schematic of the GSHP system. Locations of the data collection sensors are included in the schematic.

SIMULATION DISCUSSION

In order to inform the design of the ground heat exchanger loop for the heat pump a 2-D finite element model of the ground and ground loops was prepared. The geometry was simulated using 22,636 elements for heat transfer with phase change. A slice from a long loop field with more loops on either side of it was selected for the 2-D geometry. The slice was modeled as a tall box with a width of 2.7 m (9ft) and depth of 29 m (95ft). The loop itself was simulated as a rectangle, 1m (3ft) wide and 0.1 m (0.3 ft) high, 2.7 m (9ft) below the top (ground surface) of the tall box. Equation 3 was applied to the loop rectangle as a heat sink.

Phase change is simulated using an unfrozen water content curve based on Van Genuchten's (1980) equation for the estimation of the relative saturation, S_E:

$$S_E = \left(\frac{1}{1+(a \cdot |f \cdot T_s|)^n}\right)^m \text{ for } T_s \leq 0°\text{C}; \quad S_E = 1 \text{ for } T_s > 0°\text{C} \qquad (1)$$

Where S_E is the relative fraction of liquid water of the total soil moisture; *n*, *m*, and *a* are the van-Genuchten-Parameters (for this project, *n=1.6*, *m=0.375* and *a=0.1)* as used in the Richards equation; T_s is the soil temperature in °C; and *f* is the solution of the Clapeyron-equation assuming zero ice pressure (333 kJ/(Kg·K) (143 Btu/lbf) at 273.15 K (32°F) at or near 0°C f =1.22 KJ/(Kg·K) (0.52 Btu/lbf·°F)) (Van Genuchten, 1980). For temperatures above 32°F (0°C), S_E is always 1, whereas for temperatures below 14°F (-10°C) the value of S_E is assumed to be 0. Actual water content fractions (θ_w) also depend on porosity and residual water content:

$$\theta_w = S_E(\theta_s - \theta_r) + \theta_r \quad (2)$$

Where s=porosity and r=residual water content. Using these equations, the amount of ice forming in the soil depends on the changing temperature alone and can therefore be used, in the nonlinear heat transfer equation, to modify the temperature dependent heat capacity. The liquid water saturation is also used to scale the thermal conductivity between thawed and frozen soil.

The air temperature drives the freezing and thawing rate from the surface, it is approximated using a sinusoidal function, which was fitted to measured data from a nearby climate station:

$$T_a = -5 - 25.525 * \cos((2 * \text{pi} * (\text{t} - 1.1\text{e}7))/31536000) \quad (3)$$

Where T_a is the air temperature in °C; and t is the time in seconds since the start of the simulation. The soil surface temperature is calculated from the air temperature multiplying it with n-factors to approximate the temperature correction for radiation in summer and snow insulation in winter. Surface n-factors used are different for each surface treatment in the loop field. Dark gravel has a winter n-factor of 0.5 and a summer n-factor of 2; sand has 0.5 and 1.75, and grass has 0.5 and 1.5 respectively.

The heat demand on the model is also calculated as a time-dependent sinusoidal function based on the heating requirement of the building; the heat demand curve was fitted as the air temperature with the greatest amount of heat subtracted during the coldest period:

$$Q_d = 2800 - 5000 * \cos((2 * \text{pi} * (\text{t} + 0.65\text{e}7))/31536000) \quad (4)$$

Where Q_d is the heat demand for values greater than 2000 W (6824 Btu/hr), values smaller than 2000 W (6824 Btu/hr) are set to zero; and t is the time in seconds since the start of the simulation.

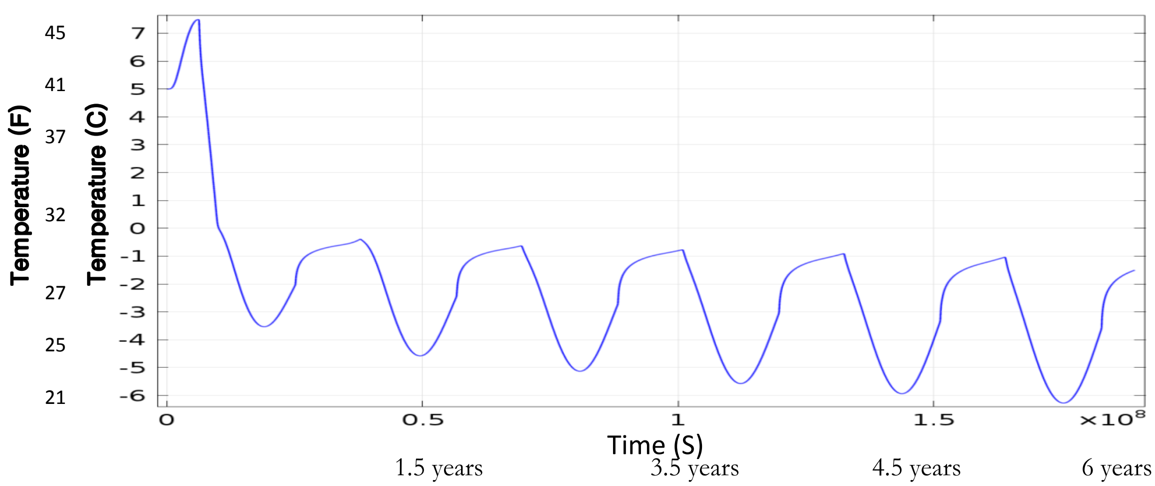

Figure 2. Results of the simulation at 10.5 ft (3.2m). This shows the temperature approximately 0.2 m (0.6ft) beneath a single loop in the loop field. The temperature is gradually dropping over time and not recovering during the summer months.

The model simulates the temperatures conservatively due to the choices made during the setup of the model. The surface conditions chosen for this simulation (grassy field) drive a large portion of the variation in soil temperatures. Results for the simulation over 6 years are summarized in Figure 2. During the demonstration project temperature data from the installed loop field will be used to correct the model for the established surface conditions. Better representation of the surface conditions will likely result in higher soil temperatures in the loop field.

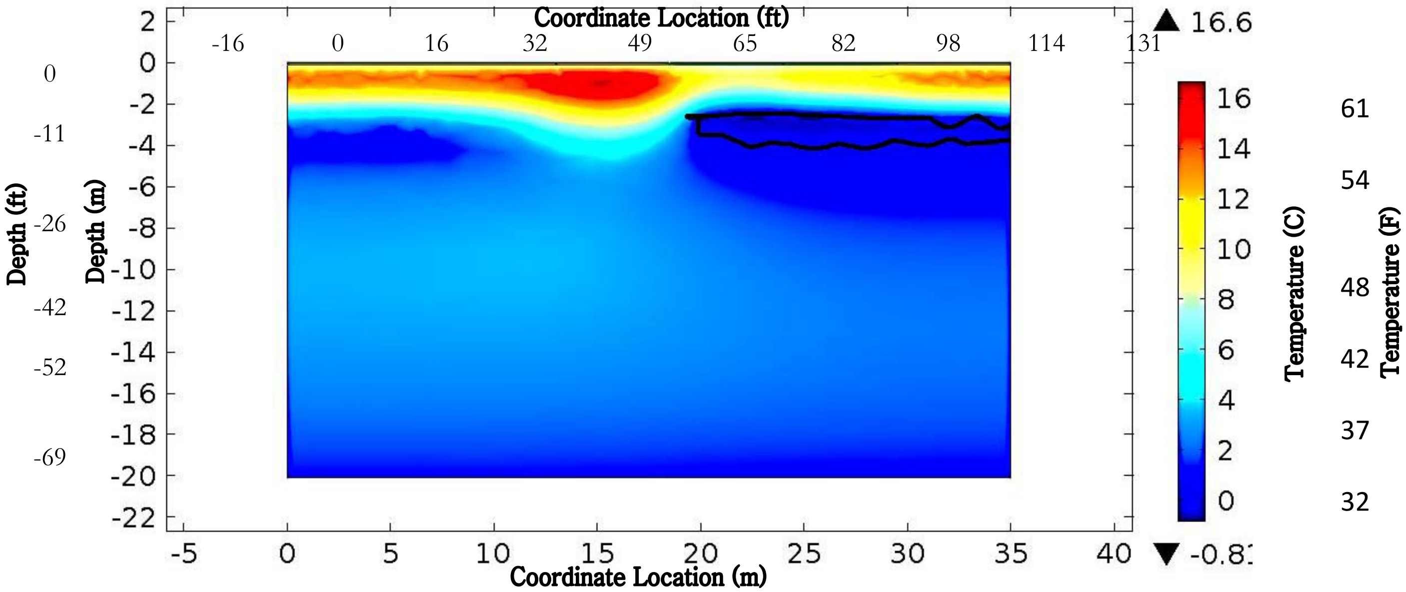

Figure 3. Profile near the center of the simulation domain from east to west and coordinate 20m (65.5 ft) at the end of a four year period. Visible is the warm area underneath the snow accumulation/gravel area lining the road around coordinate 15m (49ft). Frozen ground under the loop field (<0.0˚C (32˚F)) is outlined with a black isotherm.

Following the design of the system a more refined 3-D simulation was created to look at the long term effects of the varying landscape choices on the heat recovery of the ground loop. The simulation shows the development of permafrost below the loop field within four years. However, the model does not cause much concern for the heating potential of the building, because the ground does not permanently cool to less than 23 °F (-5˚C) in the simulation. A buffer of piled snow put between the road and the grassy loop field would help avoid cooler temperatures. The buffer feature was not part of the original design and has not been implemented in the demonstration project. A cross section (Figure 3) shows the distribution of frozen ground at the end of the summer near the end of the simulation.

Table 1. Data Collection System Components

Data Point	Location	Range and Accuracy
Ground temperatures	Within and around the ground loop	-20°C to 80°C ±0.1°C (-4°F to 176°F)
Manifold temperatures	In the manifold returning from the loop field	-20°C to 80°C ±0.1°C (-4°F to 176°F)
Ground loop energy	To and from the ground loop	0 to 20 gpm ±2%(0 to 75.6 l/min) 10 to 70°F ± 0.15°F (differential) (-12°C to 21.1)
Heat pump energy	To and from the building	0 to 15 gpm ±2% (0 to 56.8 l/min) 40 to 140°F ± 0.15°F (differential) (4.4°C to 60°C)
Heat pump electrical use	Heat pump and the circulating pumps	0 to 100 amp ±1% 115 to 230 VAC ±1%

DEMONSTRATION PROJECT

The demonstration project was fully engaged in November 2013. The heat pump system has a full monitoring system recording temperatures throughout the system as well as flows and electrical usage. Figure 1 shows a schematic of the heat pump system as well as the monitoring system. Table 1 provides a list of the monitoring system components.

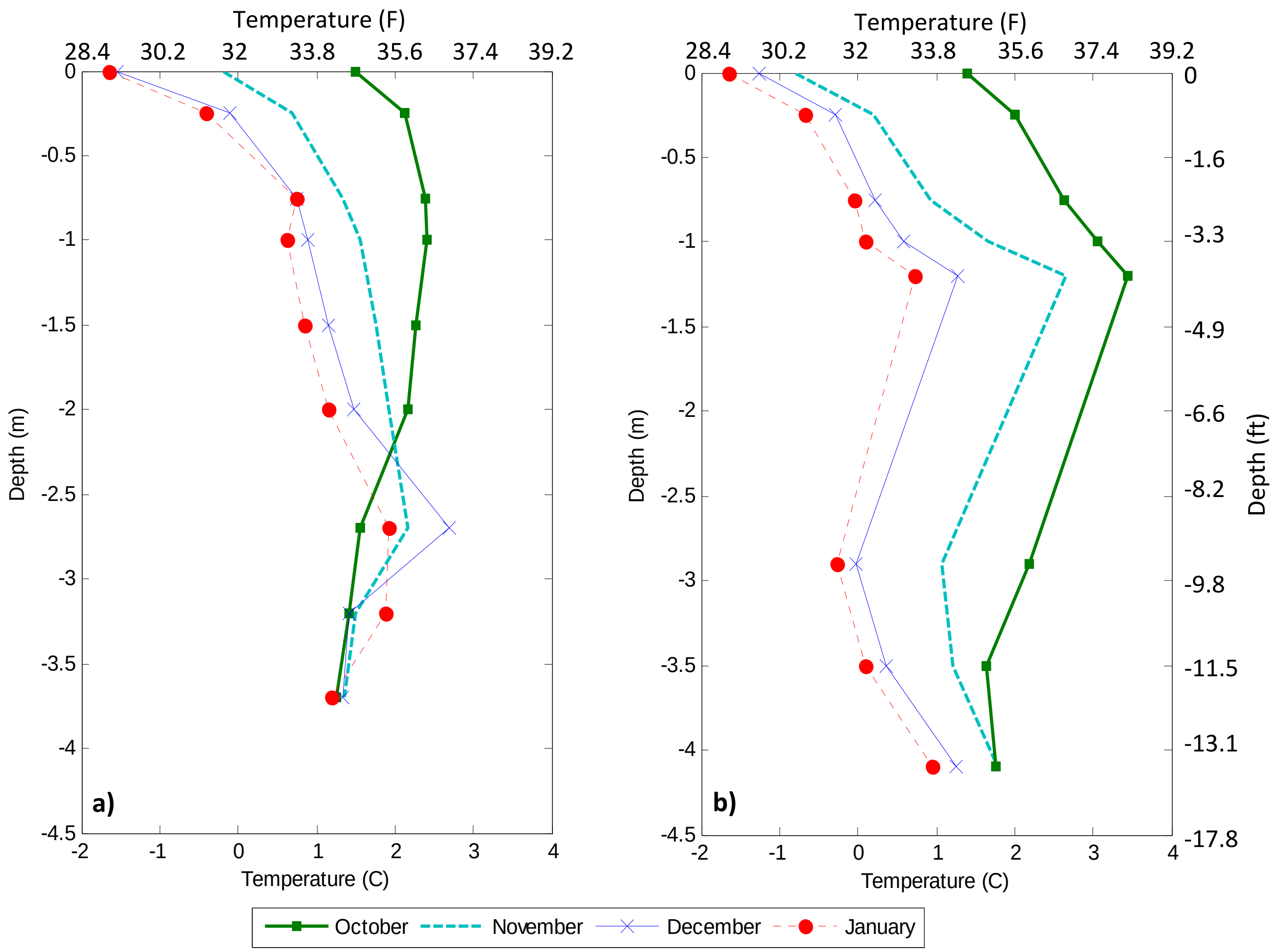

Figure 4. Preliminary soil temperature data. a) This graph is from an area to the west portion of the ground exchanger under a grassy field that is not plowed in the winter. b) This is from a temperature string under the center of the ground loop heat exchanger which is also not plowed. Data comes from 0.25m (0.8ft), 0.75m (2.5ft), 1m (3.3ft), 1.5m (5ft), 2m (6.5ft), 2.7m (9ft), 3.2m (10.5ft), and 3.7 m (12ft) depths.

Data collection started in the ground loop a month before the heat pump was enabled. Data for the first three months of collection show that the temperature in the vicinity of the ground loop is already cooler than the surrounding soil. Figure 4 demonstrates the changes that the heat pump is already creating in the soil temperatures. Figure 5a shows the temperatures under a field that is well outside the effects of the ground loop heat exchanger. Figure 5b shows the temperatures in the ground near the center of the heat exchanger loops, it is under the sand landscape covering. However, since the landscape treatments were not in place for longer than a month prior to snow covering the temperatures in the center loop are representative of all the landscaped areas for this data period. The average COP of the heat pump and the circulation pumps for the first two months of service was 3.3.

CONCLUSIONS

The demonstration project is just beginning. As data is collected it will be used to enhance the information for the model and in turn create better estimates of the effects on the soil. The data from the demonstration project will also be used to inform a life cycle assessment of the system. In the next ten years the heat pump demonstration will also be analyzed for life cycle costs. The model results and the demonstration information will be used to inform suggestions for installing GSHPs in extreme cold climates.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Alaska Energy Authority, the Alaska Housing Finance Corporation, and the Denali Commission for funding this project.

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