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Permafrost Ecosystem Warming Prototype

Installation, Operation, and Initial Site Characterization

Anna M. Wagner, Marc C. Beede, and Jon E. Zufelt

November 2013



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Permafrost Ecosystem Warming Prototype

Installation and Operation Report

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Abstract

A soil warming prototype was developed, installed, and tested to simulate increased soil temperature scenarios due to climate change using an automatically controlled heater array. The prototype was installed in a 30 × 30 m plot at a disturbed permafrost location at the US Army Cold Regions Research and Engineering Laboratory (CRREL), Fairbanks Permafrost Experiment Station, Alaska. The warming system consisted of a hexagonal array of 127 vertically installed heating elements. Three heat zones within the array could be adjusted to a set point above the current ambient ground temperature. Using integrated feedback loops, the system was able to monitor real-time temperature data and automatically adjust the output of six separate heater circuits to maintain the desired set point. Scenarios of 2, 4, 6, and 8 °C set points above ambient soil temperatures were successfully tested, and data indicated that temperatures could be tightly controlled. The report discusses the geophysical characteristics of the plot as well as installation and performance of the system.

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Preface

This study was conducted at Fort Wainwright, AK, for the Department of Energy's Oak Ridge National Laboratory under a CRREL-DOE Interagency Agreement #4400000365, *Ecosystem Warming Prototype Project*.

The work was performed by Anna M. Wagner at the Biogeochemical Sciences Branch, Marc C. Beede at the Engineering Resources Branch, and Jon E. Zufelt at the Terrestrial and Cryospheric Sciences Branch of the Research and Engineering Division, US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Terrence Sobecki was Chief, Biogeochemical Sciences Branch, CRREL, and Dr. Justin Berman was Chief, Research and Engineering Division, CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance D. Hansen, and the Director was Dr. Robert E. Davis.

COL Jeffrey R. Eckstein was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters

1 Introduction

1.1 Background

Climate change will result in increased soil temperatures, greater active layer thickness, and changes in permafrost dynamics in arctic ecosystems. One method to understand how increased soil temperatures will affect arctic ecosystems is to induce a step increase in soil temperature in a controlled area. Advanced approaches to aboveground and belowground warming will improve understanding of the biotic and abiotic processes that govern plant and soil responses to climatic change in these important ecosystems.

Prototype concepts that increase air and soil temperatures in large outdoor plots have been developed at Oak Ridge National Laboratory (ORNL) (Hanson et al. 2010). The performance of these systems has been simulated for experimental plots ranging from 3 to 20 m in diameter and field-tested in 3 m diameter plots in a temperate deciduous forest. To further develop the prototype for an arctic climate, a similar test system was installed at US Army Cold Regions Research and Engineering Laboratory (CRREL), Fairbanks Permafrost Experiment Station, Alaska.

1.2 Objectives

The objectives of this project were to

1. investigate whether the in-ground warming prototype, developed by ORNL, could be installed in an arctic environment;
2. simulate soil-warming scenarios of 2, 4, 6, and 8 °C above ambient soil temperatures;
3. observe system performance and analyze data to see if the system operates as designed; and
4. identify any operational and design issues that may need to be considered for future installations of similar prototypes in the arctic.

1.3 Approach

This report provides technical details of the installation of a soil warming prototype system developed to facilitate multi-factor climate change experiments in the arctic tundra. CRREL worked with ORNL to identify a

suitable location for prototype installation and testing. The chosen plot was a permafrost tract within a previously disturbed area that consisted of second-growth trees and shrubs. The site was chosen because of its permafrost characteristics, ease of access, and its close proximity to the CRREL Fairbanks office and supporting infrastructure of Fairbanks. System installation, troubleshooting, operation, and maintenance were provided by CRREL.

The prototype was installed in the summer 2010 and consisted of an automatically controlled array of heaters that were installed in the ground to warm a targeted volume of soil. The heaters maintained soil temperatures at a desired set point above ambient soil temperatures, simulating increased soil temperatures at some future timeframe.

Geophysical data was collected with surface resistivity prior to installing the warming system. Holes for the placement of the heating elements were drilled along with additional holes for temperature monitoring sensors. Core samples were collected to obtain initial soil and permafrost characteristics. Temperature and electrical-use data were recorded to observe the performance of the system.

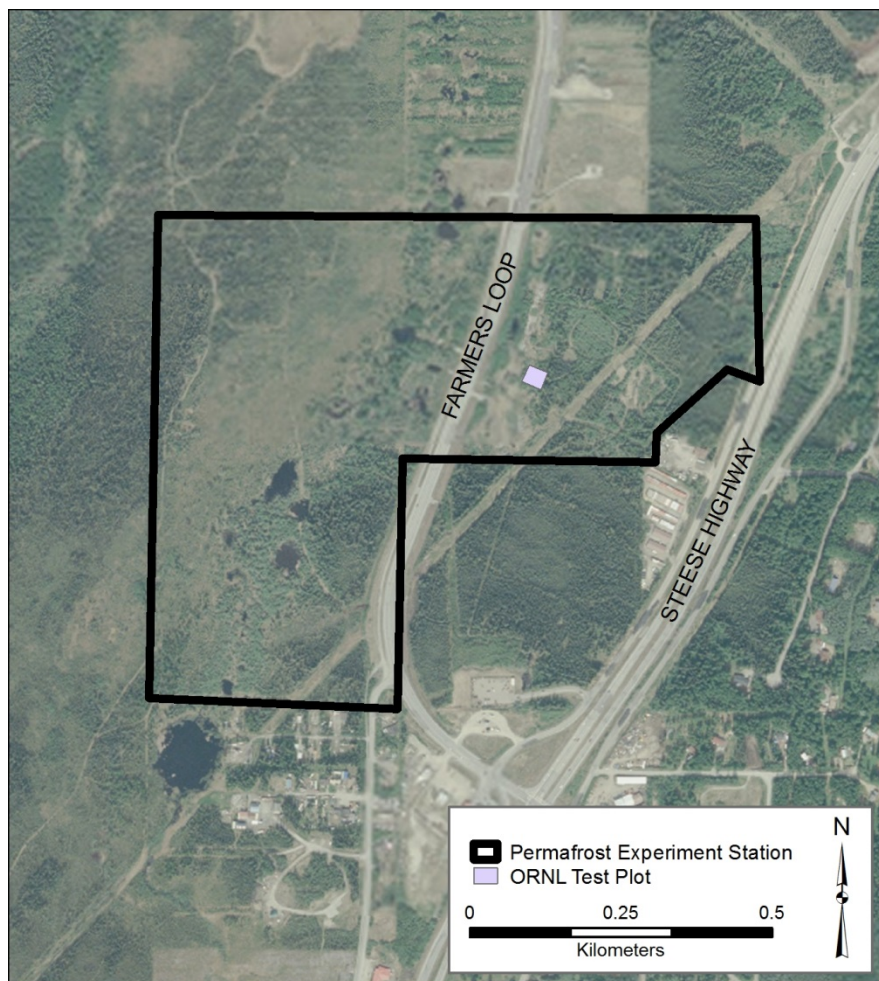
The report has five sections. Section 1 is the introduction; Section 2 describes the installation of the system; Section 3 provides information about the geological and geophysical characterization of the site; Section 4 summarizes the performance and operation of the soil warming system; and Section 5 presents results and discussion.

2 Soil Warming System Description

2.1 Site Description

The prototype was installed at the Fairbanks Permafrost Experiment Station at Farmers Loop (Figure 1). Fairbanks has a continental climate as it is sheltered from maritime influences by the surrounding mountains. The mean annual air temperature is -3°C , ranging from average monthly temperatures of -28°C in the winter to 23°C in the summer (Shulski and Wendler 2007). The mean annual precipitation is 287 mm and falls mainly as snow during the months of September through April.

Figure 1. Fairbanks Permafrost Experiment Station and location of the ORNL test plot.



Fairbanks Permafrost Experiment Station at Farmers Loop Road was established in 1945 and consists of 135 acres of ice-rich permafrost soils generally present to a depth of 60 m (Linell 1973). In undisturbed areas, the active layer thickness varies from 55 to 85 cm. The site has a comparatively smooth, gentle slope to the west, providing good surface drainage except at the lowest elevations where saturated conditions can exist. Soils consist of tan silt and wind-blown loess near the surface and grey silt at depths below 1.4 m (Linell 1973). Permafrost moisture contents range from 26% to 41% by mass for the frozen silts, which represents relatively low moisture content permafrost. Vegetation is typical of the Alaskan Interior—subarctic taiga forest with white spruce and black spruce interspersed with lowbush cranberry and Labrador tea. Feather moss and sphagnum moss are present in the understory.

The site selected for the installation of the prototype system measured approximately 30×30 m and is shown prior to clearing in Figure 2. Vegetation consisted mainly of spruce (as indicated above) and white birch trees ranging from 0.025 to 0.15 m in diameter at the ground surface with additional small willows and other low brush. The site was cleared of trees and brush in order to make room for the prototype installation (Figure 3). In this figure, the access road to the plot is evident in the foreground. A simple x, y grid was developed with the origin (0,0) located in the northwest corner of the plot. The x-axis is left to right (north to south), parallel to the tree line at the back of the plot. The y-axis is perpendicular to the x-axis and travels front to back (west to east) in this figure. Figure 4 shows the general layout of the prototype heating system in the plot.

2.2 Heaters

The prototype soil warming system consisted of a hexagonal array of 127 vertically installed heating elements arranged in a 25×29 m area (Figure 4). Heaters rated at 60 Watts were spaced at a distance of 2.4 m and extended to a depth of 4 m with the effective heating applied only at the bottom 0.6 m of each heater (Figure 5). This design of the heater element was selected to achieve uniform heating at depth in a permafrost environment. The heater casings were installed by first pushing a 5.7 cm solid-stem drill pipe into the soil using a GeoProbe 7822 track-mounted, direct-push drill rig (Figure 6a). The drill pipe was removed, and the heater casings were then placed in the resulting holes (Figure 6b) and pushed to the required depth (Figure 6c), leaving 0.15 m exposed above the ground surface (Figure 6d). The annulus between the native soil and the heater casings was backfilled with silica sand. Figure 6e shows a line of installed heater casings.

Figure 2. Prototype plot prior to vegetation clearing.

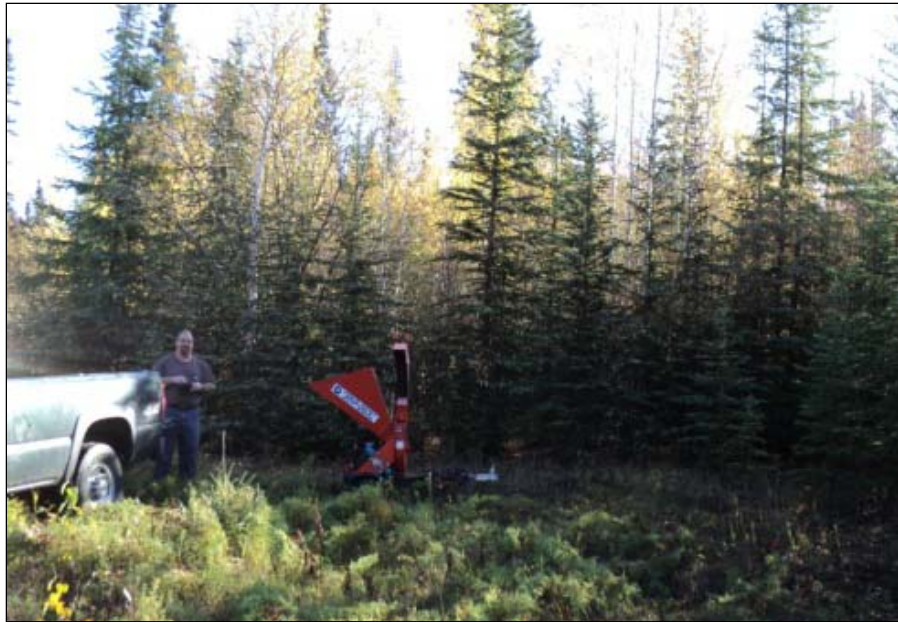
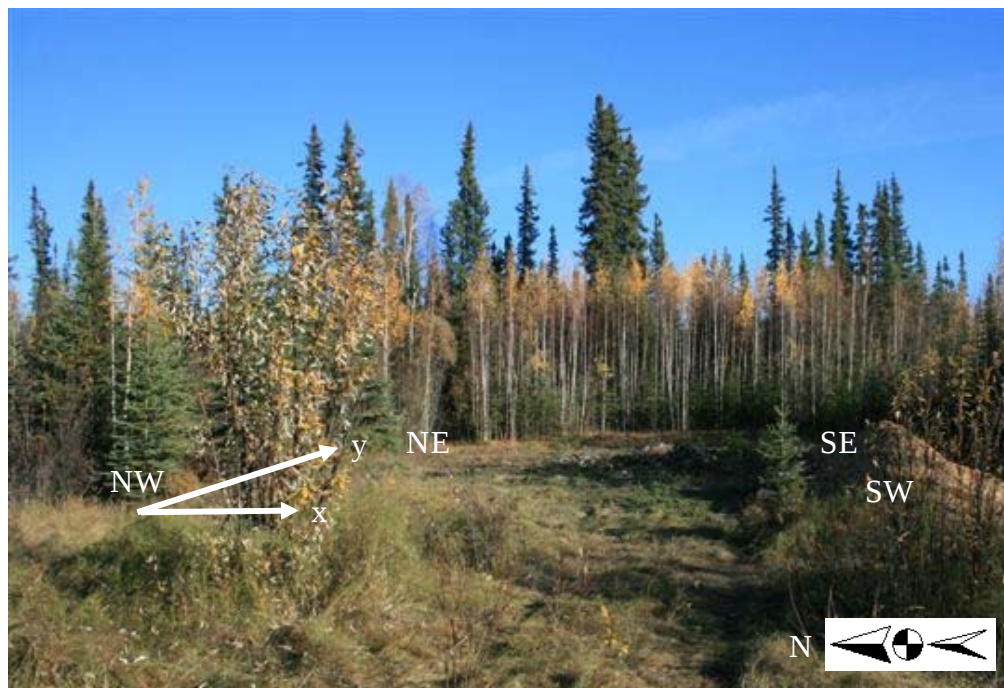
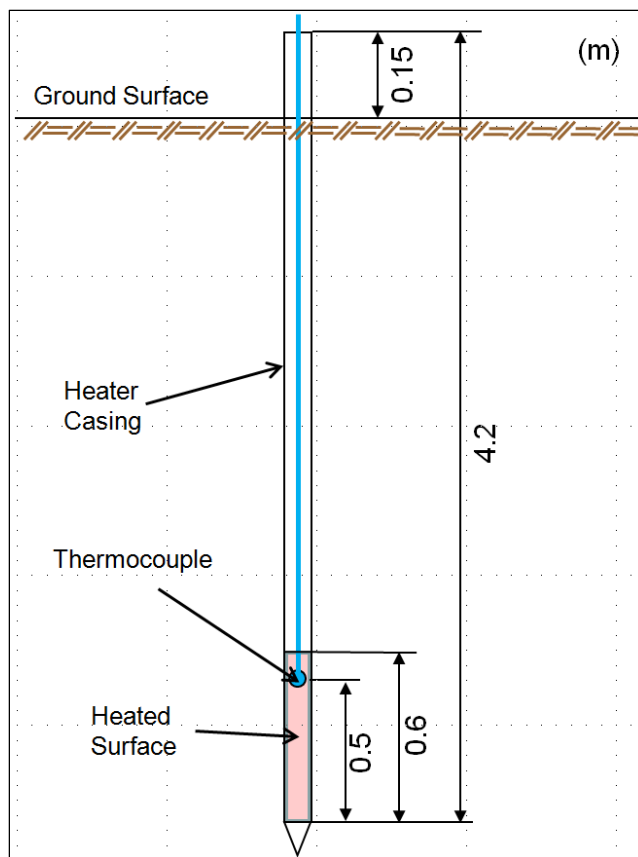


Figure 3. Prototype plot after vegetation clearing. NW indicates the origin (0,0) location of the plot grid.



The diagram illustrates the layout of the test area, which is a hexagonal structure divided into three concentric zones. The outermost zone (Zone 3) is pink, the middle zone (Zone 2) is light blue, and the innermost zone (Zone 1) is yellow. The test area is surrounded by an 'ABOVE-GROUND ENCLOSURE' and a 'BUFFER ZONE'. The layout includes various monitoring points (P1-P15, T1-T4, TCH1-TCH2, TC1-TC2, TCPH1-TCPH6) and heaters (WCL, WCT0-WCT5). The diagram also shows dimensions (11m, 14.40m, 24.96m, 15m) and a coordinate system (X, Y).

Figure 5. Diagram of the heater, heater casing, and thermocouple placement.



The heater elements were designed to slide into and screw onto a collar on the heater casings (Figure 7a-b). The heaters were wired in parallel using flexible, water-resistant conduit as depicted in Figure 7c.

2.3 Temperature Control for Heater Circuits

As shown in Figure 4, there were three heat zones within the array that could be adjusted to a set point above the current ambient ground temperature. Zone 1 consisted of three separate circuits: 1a (19 heaters), 1b (18 heaters), and 1c (24 heaters). A thermocouple, located at TCPH1, controlled the set point for zone 1. Zone 2 had a single circuit consisting of 30 heaters and a set-point thermocouple located at TCPH3. Zone 3 had two separate circuits: 3a and 3b, each consisting of 18 heaters, and a set-point control at thermocouple TCPH5. A backup thermocouple was provided for each zone in the event that there was a failure with the original. The thermocouples were located next to a heater casing, and the temperature was read at a depth of 3.5 m. Ambient soil temperature was provided by an additional thermocouple placed outside of the affected

Figure 6. Heater casing installation.



a. GeoProbe pushing solid stem drill pipe.



b. Heater casing being placed into hole.

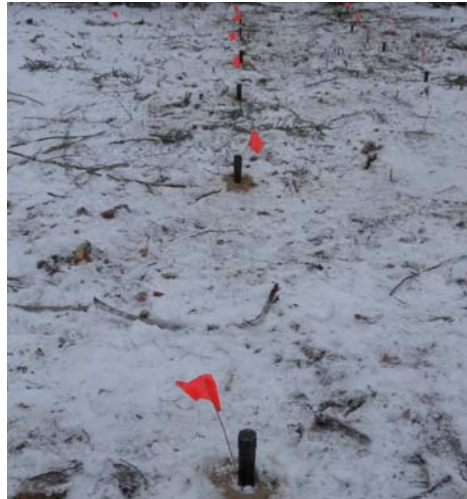


c. Heater casing being pushed down to required depth using the GeoProbe.



d. Close-up of heater casing.

Figure 6. (concluded).



e. Line of installed heater casings.

Figure 7. Heater installation and connections.



a. Heater placement.



b. Line of heaters in casing.

Figure 7. (concluded).



c. Line of connected heaters.

warming zone, also at 3.5 m depth and approximately 15 m to the north of the warming zone (TCH1; TCH2). Using integrated feedback loops, the system was able to monitor real-time temperature data and automatically adjust the output of the six separate heater circuits to maintain the desired set point. Over-temperature protection was included and would cut power to a zone in the event that the zone temperature overshoot the desired set point by a specified amount. Figure 8 shows the installation of the thermocouples by attaching to the heater casing and inserting to the required depth.

2.4 Soil Temperature Monitoring

2.4.1 Thermocouples

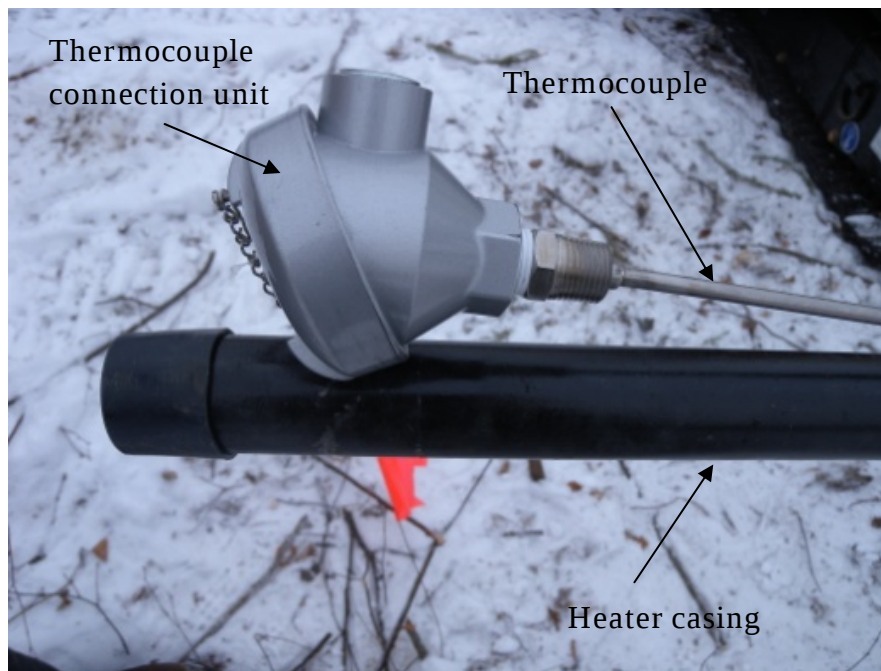
Four 2 m-long, multiple-sensor type “T” thermocouple strings (Figure 9) were installed equally spaced at a radius of approximately 5.5 m from the center of the plot (TCP1–TCP4 in Figure 4). Two additional 2 m long, multiple-sensor type “T” thermocouple strings were placed at the control location (TC1 and TC2 in Figure 4) at a distance of approximately 14–16 m from the edge of the heated plot. These thermocouple strings had sensors at depths of 0, 0.05, 0.2, 0.4, 0.8, 1.6, and 2.0 meters.

Figure 8. Thermocouple installation.



a. Thermocouple and heater casing prior to installation.

Figure 8. (concluded).



b. Close-up of the top of the thermocouple and heater casing prior to installation.



c. Installed thermocouple and heater.

Figure 9. Example of 2 m long thermocouple string housing (TCP1-TCP4).



Figure 10a shows the typical configuration of one of the thermocouple measurement stations (TCP4) and a close-up of the wiring within the box. The four permanent thermocouple measurement location cables (TCP1–TCP4) were brought together in a junction box (Figure 10b) and routed back to the instrumentation building in a single conduit (Figure 10c). Similarly, Figure 10d shows the thermocouples in the control area (TC1, TC2, TCH1, and TCH2) and gathered in a junction box and passed through a single conduit back to the instrumentation building. All wires and cables were protected from weather and animals by flexible, water-resistant, and rigid PVC conduit. TC1, TC2, and TCP1–TCP4 were wired directly into the Campbell Scientific data logger for temperature monitoring only and do not play a role in heater control.

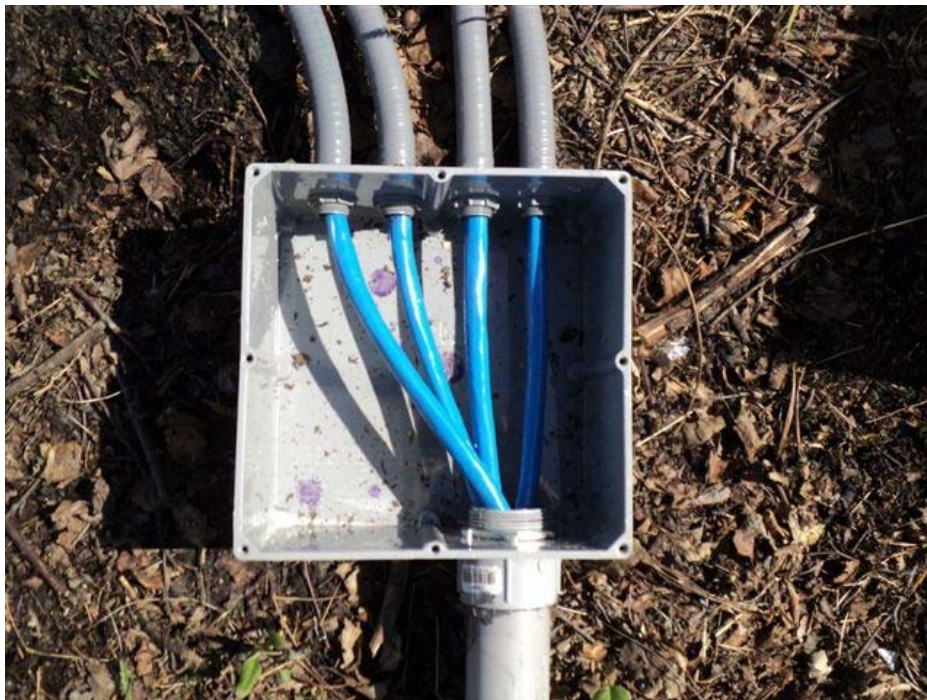
2.4.2 Thermistor Strings

During drilling operations, PVC pipe was installed to provide locations for temperature measurement by thermistor strings (Figure 11). The locations of these pipes are identified on Figure 4 as P1 through P15, WCT1, and WCL. At these locations, cores were taken to a depth of 10 m to facilitate the placement of the PVC pipes. Schedule 80 PVC pipe, with a nominal diameter of 19 mm, was used as casing to accommodate thermistor strings. The PVC pipe was strategically placed throughout the plot and provided the flexibility to monitor temperatures at many locations.

Figure 10. Thermocouple wiring and conduits.



a. Thermocouple (TCP4) box showing close-up of wiring.



b. Junction box of the four thermocouple cables (TCP1-TCP4).

Figure 10. (concluded).



c. TCP1-TCP4 conduit.



d. Control area thermocouple strings (TC1, TC2, TCH1, and TCH2).

Figure 11. Installation of thermistor string casing.



a. Placement of thermistor string casing.



b. Backfilling the thermistor casing with silica sand.

Six thermistor strings and three loggers manufactured by BeadedStream were used for temperature monitoring. One of the loggers hosted four of the thermistor strings. Two strings were placed at WCT0 and WCL (see location in Figure 4) and provided temperature measurements at undisturbed locations. WCT0 was located at an undisturbed permafrost area which was similar to the top east part of the site (P1–P5), and WCL was at a similar location to the remaining heating experiment site (TCP1–TCP4, and P6–P15). Table 1 provides information on the depth of the individual sensors at each of the thermistor locations. The BeadedStream temperature data are independent of system control.

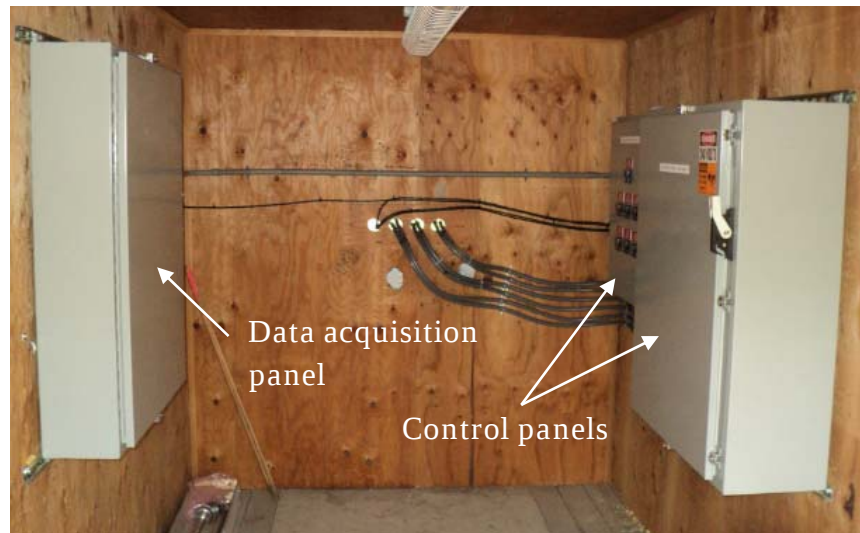
Table 1. Location and depth of thermistor sensors.

Location	Total length (m)	Depth of individual sensors (m)
WCT0	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 8.0, 10.0
WCL	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 8.0, 10.0
String 1	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0
String 2	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0
String 3	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 8.0, 10.0
String 4	10	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 8.0, 10.0

2.5 Control and Instrument Panels

The instrumentation shelter provided a heated, secure space for data acquisition and control equipment. Electrical power was extended into the plot and by a drop pole into the shelter. Three-phase capability was installed so that future additions to the system, such as an above-ground warming envelope, could be added. There were two control and two data acquisition panels within the instrumentation shelter. The four panels consisted of a temperature control panel, heater circuit control panel (SCR), electrical usage data acquisition panel (E-mon), and a temperature data acquisition panel. Wiring for the heater circuits, thermocouples, and thermistors was routed to the building. The heater circuits were wired into the SCR panel which provided 208 V single-phase power to operate the heaters. The control (ambient) and zone thermocouples were wired into the temperature control panel which utilized proportional-integral-derivative (PID) controllers to operate the heaters. The temperature control panel was powered by single-phase 110 V. Temperature and process data routed from the temperature control panel were recorded using a Campbell Scientific CR1000 datalogger. The 110 V single-phase power was supplied to the CR1000 from the electrical service panel, and it also had battery backup. Current sensors around the heater circuits monitored energy usage data which was stored in the E-mon data acquisition panel, which was also powered by 110 V. Figure 12 shows the instrumentation and control panels within the heated instrumentation shelter.

Figure 12. Instrumentation and control panels.



3 Geological and Geophysical Characteristics

3.1 Resistivity Survey

Surface geophysical methods can be used to accurately and rapidly map permafrost extent over limited areas and to determine changes in permafrost extent and thickness over time. Electrical resistivity tomography is one method that is commonly used to measure and map the electrical resistivity of the soil in order to infer areas of permafrost. Those areas that exhibit high resistivity indicate areas which are likely to be frozen (permafrost) or have some variation to the surrounding ground (e.g., potentially buried debris, impervious strata, etc.). Resistivity data were collected with an AGI Supersting R8/IP multi-channel switch resistivity meter and passive cables on September 28–29, 2010. Two 2D lines were collected to characterize the plot; both passed through the center of the proposed plot with one parallel to the y-axis (Line 1) and the other parallel to the x-axis (Line 2) (Figures 13 and 14). Total length of both lines was 51 m and thus extended outside the plot. Resistivity data was also collected in a 3D grid that covered the entire 30×30 m plot (Line 3).

Figure 13. Geophysics lines.

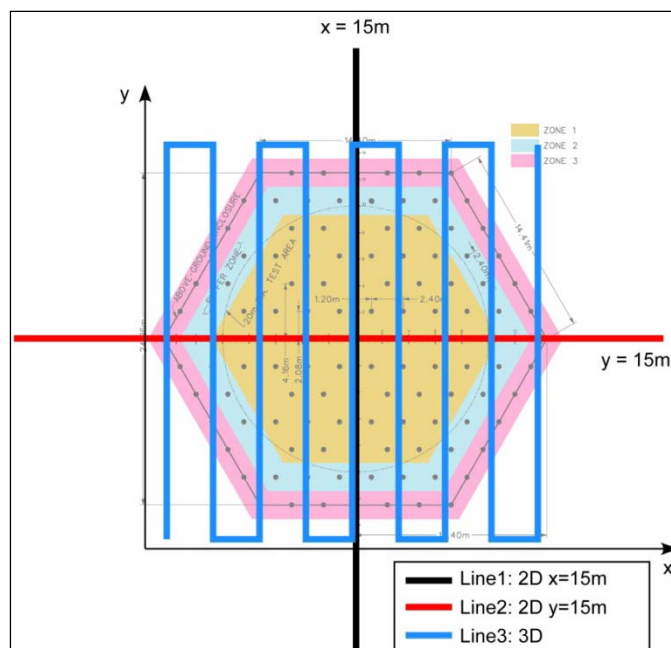


Figure 14. 2D and 3D resistivity lines (north section of the line).

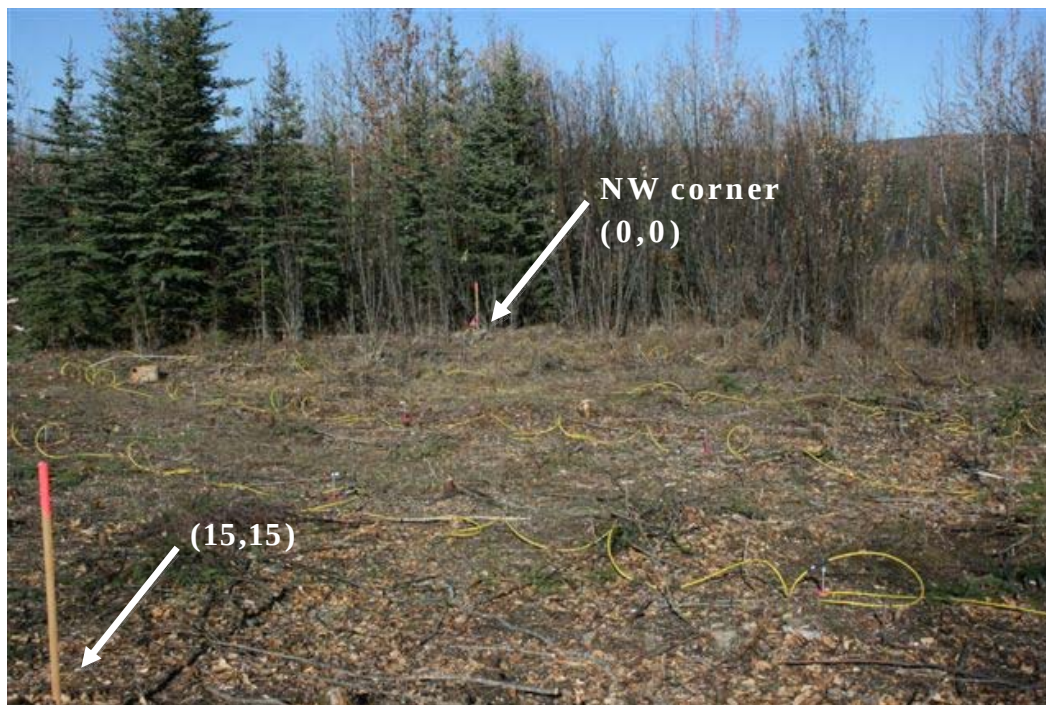


a. Resistivity Line 1 (east section of the line).



b. Resistivity Line 2.

Figure 14. (concluded).



c. Resistivity Line 3 (north part of the grid).

Figure 15 shows results from the resistivity measurements. Permafrost typically exhibits a high resistivity due to its frozen water content. The 2D measurements extended beyond the boundaries of the cleared plot, and the cleared plot was located between 0 and 30 m. The depth to permafrost was approximately 5–6 m within the west side of the experimental site (dashed line in Figure 15a), whereas the depth to permafrost was shallower (approximately 1 m) at the eastern part of the experimental site. There was also an unfrozen zone at a depth between approximately 3 and 5 m at the eastern part of the site. The red color in Figure 15a illustrates colder permafrost than what was located beneath the cleared plot (green). The red field of higher resistivity at the beginning of Line 1 is most likely buried construction debris. The lower resistivity values (dark blue) indicate higher moisture content soil.

The permafrost was located at a depth of approximately 5–6 m along Line 2 (Figure 15b). There appeared to be a slight increase in the depth to permafrost towards north which corresponded to the natural ground surface topography and could also indicate subsurface drainage.

Figure 15. 2D resistivity cross sections at a) $x=15$ m (49.2 ft) (Line 1), and b) $y=15$ m (49.2 ft) (Line 2). Dashed black line represents the unfrozen–frozen boundary.

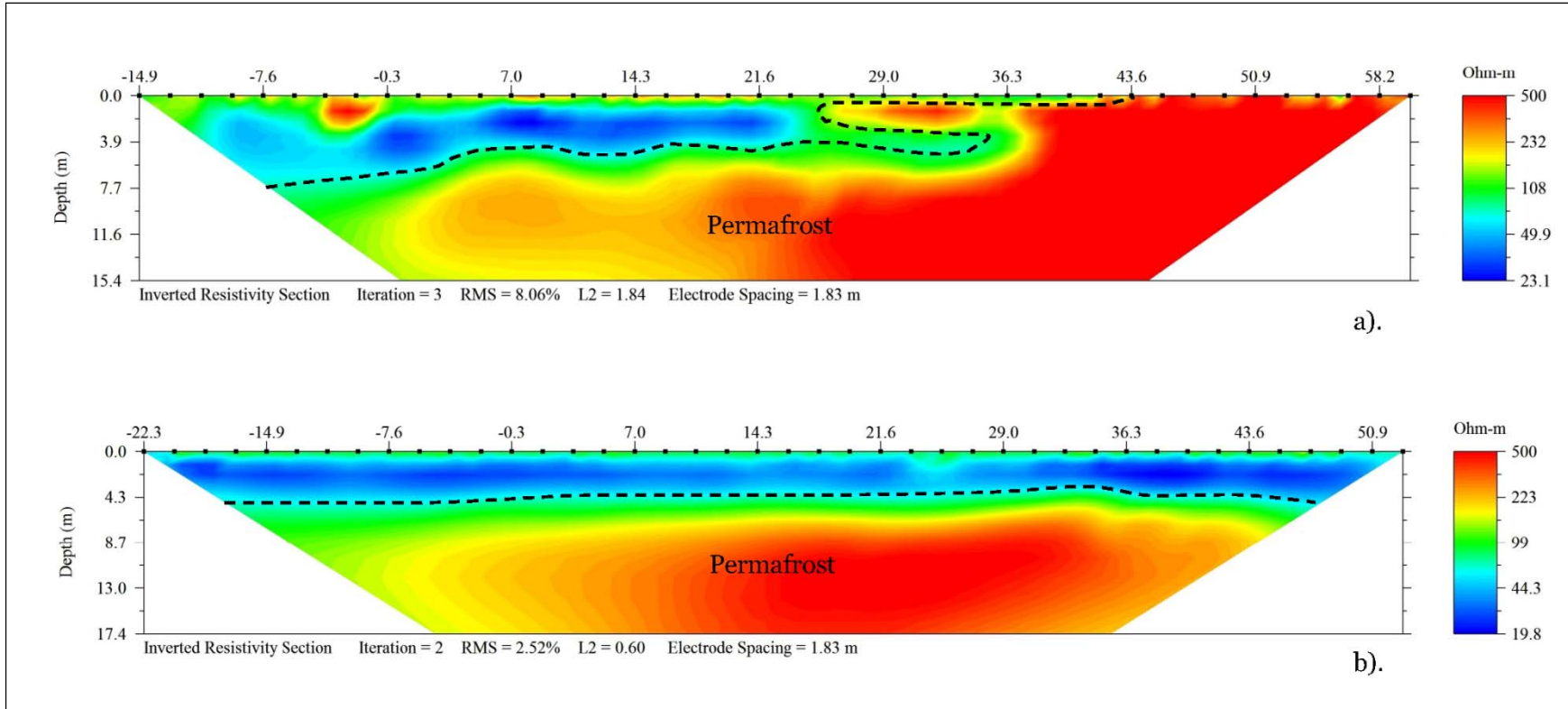
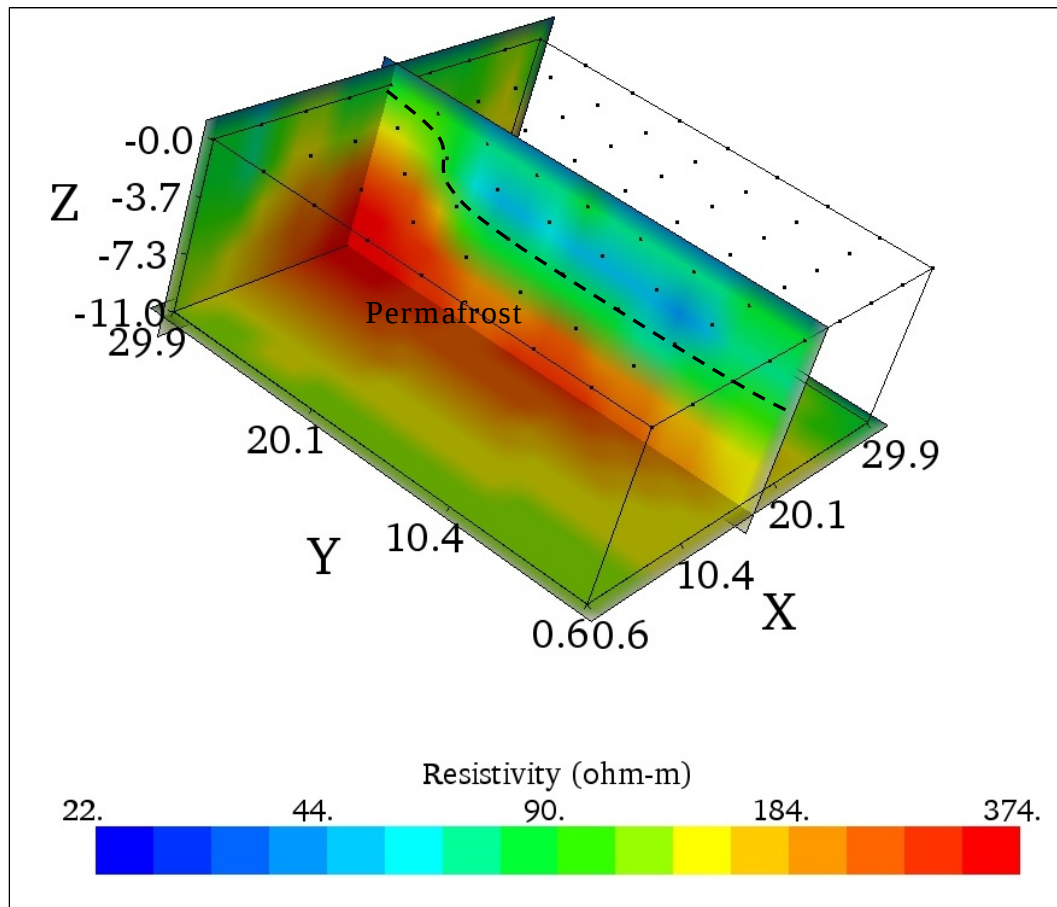


Figure 16 shows slices of the 3D grid. The 3D image re-affirms depth of permafrost with the 2D images on the previous page and also indicates that permafrost is closer to the ground surface at the upper edge ($y=30$) of the plot.

Figure 16. 3D resistivity plot with slices located at $y=30$ m, $x=15$ m, and $z=-11$ m.



3.2 Ground Truth of Depth to Permafrost

Soil core samples were collected at most locations where PVC pipes were installed in order to ground-truth the depth to permafrost estimated from the geophysical measurements. Cores were sampled in 1.5 m sections using the Geoprobe Macro-Core MC5 Soil Sampler with a diameter of 0.03 m. The core liners were cut open to physically identify the unfrozen-frozen transition (Figure 17). Visual inspection of the cores showed that soil moisture content and depth to permafrost was quite variable throughout the plot area.

Figure 17. Sample cores from a depth of approximately 5 m (16.4 ft) at a) P1 (frozen), b) P5 (frozen), and c) at P6 (unfrozen and very wet).



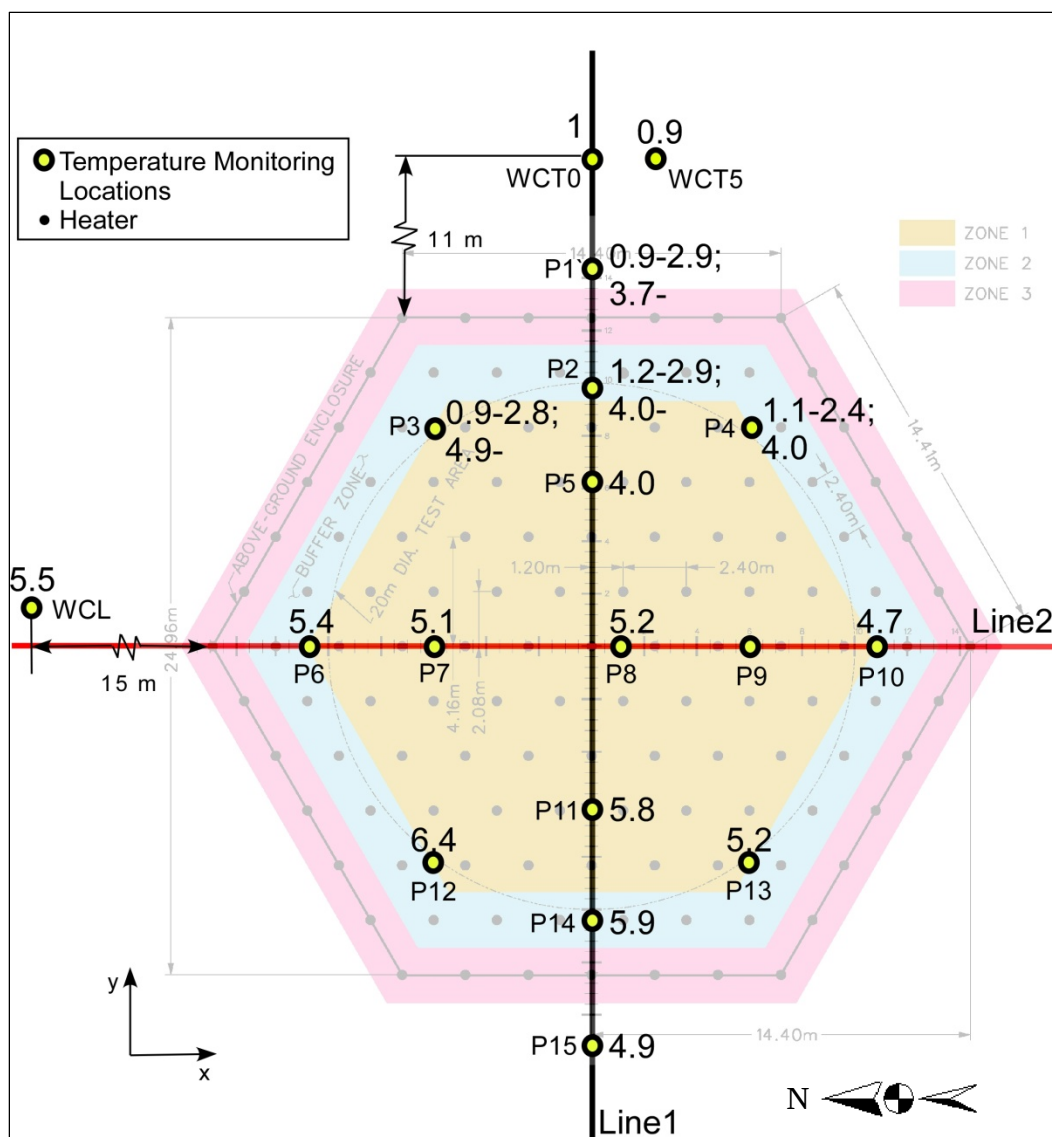
3.2.1 Depth to Permafrost

It was evident from the geophysical measurements that depth to permafrost was shallower in the east section of the plot than the west. This was confirmed with the ground-truth borings where the depth to permafrost on the west side was between 4 and 6 m and approximately 1 m on the east side. It was also found that the upper part of the site had a 1–2 m unfrozen layer (see P1–P4 in Figure 18). The ground-truth borings also confirmed that the depth to permafrost increased slightly in the south-to-north direction (4.7–5.5 m).

3.2.2 Soil Temperatures

Figure 19 shows temperature with depth profiles at P8 for different dates ranging from April through September 2011. The depth of the active layer was 4.7 m at this location, and the temperature at a depth of 9.5 m ranged from -0.25 to -0.35 °C depending on the time of the year.

Figure 18. Permafrost depths from ground-truth borings.



Based on the temperature data from 17 locations, the depth of the active layer ranged from 1.3 to 5.6 m throughout the site, with a more shallow depth at the top part of the installation (Figure 20). The shallower depth could be seen at P1–P5. At P10 the active layer was in between the shallow and deep active layer. The deepest active layer was located at P12, and the shallowest active layer was located at P4 and P5.

The temperatures in Figure 20 are from data taken in September which is typically the time when the active layer is deepest. These temperature measurements corresponded well with what was found when the resistivity profiles were taken in September 2010 (Figure 15).

Figure 19. Temperature profiles at P8 for several dates in April–September 2011. The inset is a close-up of temperatures between -0.5 and 0.5 °C. The dashed line illustrates the depth of active layer (4.7 m) at this location.

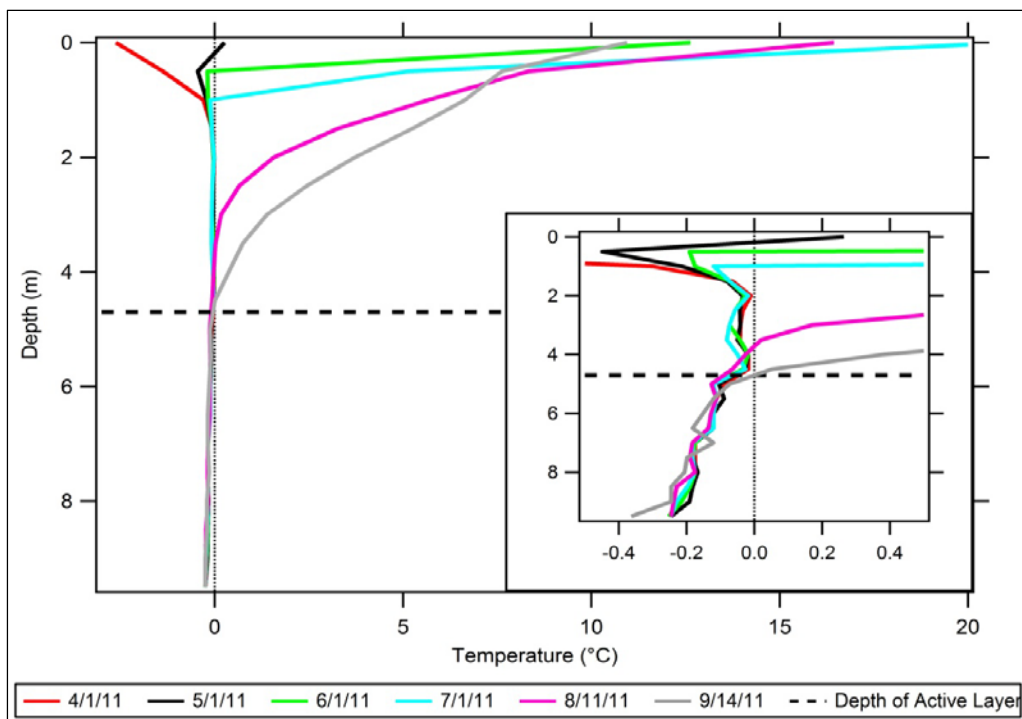
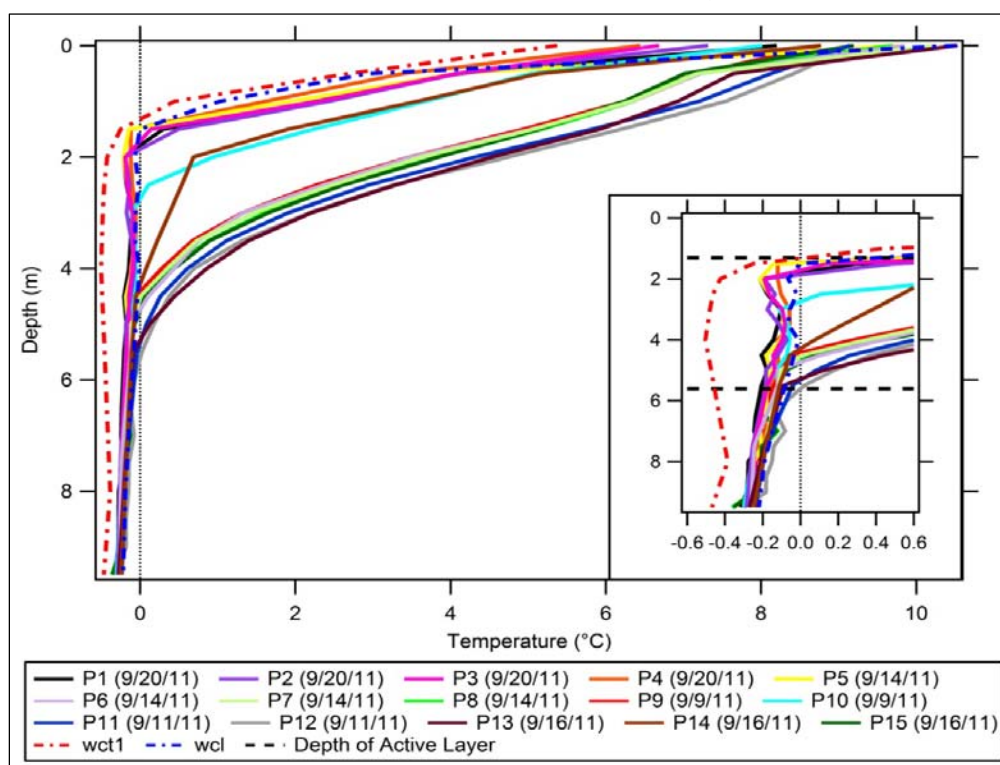


Figure 20. Temperature profiles in September 2011 for locations throughout the installation plot with an inset showing a close-up between -0.6 and 0.6 °C. Horizontal dashed lines show the depth of the active layer that ranges from 1.3 to 5.6 m.



4 Performance and Operation of the Temperature Warming system

4.1 PID Operation

Heater control used to simulate warming ground temperatures was accomplished using Watlow PID (Proportional, Integral, and Derivative) process controllers. The control (ambient) thermocouple (TCH1) and the three zone thermocouples (TCPH1, TCPH3, and TCPH5), produce a mV signal that is then retransmitted as a mA signal to the PID controllers. The transmitted current is between 4 and 20 mA, where 4 mA corresponds to -40 °C, and 20 mA corresponds to +30 °C. The temperature formula is non-linear and is calculated by the following expression:

$$T = 4.375I - 57.5$$

where:

T = temperature in °C

I = Current in mA

There were seven PID controllers located within the Temperature control panel (Figure 21). The Master temperature controller accepts the mA signal from the control thermocouple and displays the calculated temperature relating to that signal.

To heat the targeted soil volume to a desired set point above the ambient temperature, a temperature value can be added to the ambient value and retransmitted via the master temperature controller to the three zone controllers. Like the master temperature controller, the three zone controllers accept a mA signal from their corresponding zone thermocouples (TCPH1, TCPH3, and TCPH5), and calculate the temperatures. If the temperature received from a zone thermocouple is lower than the desired set point, then the controller for that zone will send a signal to the SCR panel which will turn on the heaters within that zone. A proportional setting within the controllers allows the operator to determine how much power, as a percentage of full power, the SCRs should deliver to the separate circuits within each zone. The proportional setting is given as a temperature

Figure 21. Control panel showing PID Controllers.



and causes the PID controller to output a linear signal to the SCRs. For example, if the proportional setting is set at 2 °C, the PID will output a signal as a percentage of full power if the error between the desired set point and the current zone temperature is between 0 and 2 °C. The heaters will be off when the error is 0 °C or negative (indicating the zone temperature is greater than the set-point temperature). An error of 2 °C or greater means the heater circuits within that zone will be turned on full power.

The zone alarm controllers monitor the zone temperatures and will cut power to the heater circuits in the event that a zone temperature overshoots the set point by a prescribed amount. For example, if the set point is set at 4 °C, and the zone alarm is set at 6 °C, the power to the heater circuits for that zone will be cut if the zone temperature reaches 6 °C. Power to the circuits will be restored once the zone temperature falls below the set point.

Adding Integral and Derivative control to the Proportional control can provide additional dynamic control to the zone temperatures around the set point. It was determined through trial and error that only proportional control was necessary for this installation. A proportional setting of 0.5 °C kept the zone temperatures tracking the set point within 0.1 of a degree.

4.2 Thermocouple Troubleshooting

Some issues were encountered with the original design as it pertained to the thermocouple transmitters. During a September 2011 site visit by Stan Wullschleger and Jeff Riggs of ORNL, it was discovered that temperatures being received from the zone thermocouples were not reliable. The ground temperatures at the thermocouple depths of 3.5 m were approximately 0 °C at the time. The transmitted temperatures were showing errors as high as 20 degrees. After several days of troubleshooting, it was determined the thermocouple transmitters, which convert the mV signal from the thermocouple to a mA signal, may have been defective, and new ones were ordered. The replacement transmitters were bench tested by Jeff Riggs of ORNL and shipped to Fairbanks for installation. Once the replacement transmitters were installed, however, the same errors occurred. Onsite tests confirmed that the transmitters were operating properly, but it was discovered that *grounded* thermocouples had been installed which introduced a reference conflict with the transmitters. New un-grounded thermocouples were shipped to Fairbanks and installed in December 2011. The result of installing new thermocouples was a reduced error as compared to the grounded thermocouples, but there were still unreliable temperatures being transmitted.

Testing of individual components within the zone temperature loops confirmed that all components were working individually, but when coupled together, errors occurred. All components within the loop (except the transmitters) were substituted with surrogates with varying success. The most compelling evidence seemed to indicate that the transmitters were not compatible with the thermocouples or were not operable within this temperature environment. The thermocouple manufacturer agreed to loan a transmitter that it knew performed well with its thermocouples. The loaner transmitter arrived at the end of January 2012, and after several days of observing its performance, it was determined that the issue was resolved. New thermocouples were purchased and installed with resulting success in February 2012.

4.3 Temperature Data

Scenarios of 2, 4, 6, and 8 °C set points above ambient soil temperatures were successfully tested, and data collected with the Campbell Scientific datalogger showed that temperatures could be tightly controlled.

During initial turn on of the system on 4 April 2012, it was observed that the zone temperatures overshoot and oscillated above the set point of 4 °C. This was due to the default PID settings not being applicable to this particular system setup. Eventually, Integral and Derivative settings were removed, and several proportional control settings were applied until a proportional setting of 0.5 °C produced acceptable results.

Figure 22 shows the performance of the system during initial turn on and subsequent performance after adjustments to the PID settings were made. Figure 23 shows set-point tests with proportional control set at 0.5 °C. In each scenario, the temperature and SCR panels were removed from power, allowing the ground temperatures to equilibrate before running a new set-point scenario.

Over-temperature alarm set points were set at 2 °C above the desired zone temperatures. Initially, during the 6 °C delta set-point test, the over-temperature set point was kept at 6 °C, causing power to be cut to the heater circuits whenever the set point was reached. The effect on zone temperatures can be seen in Figure 23. The over-temperature alarm set point was then set to 8 °C, allowing for smooth operation of heating circuits.

4.4 Energy Usage

Energy usage of each of the six heater circuits was monitored using the E-mon Energy data logger. Figure 24 shows energy usage for each of the six heater circuits during warming scenarios of 4, 6, and 8 °C delta scenarios. As illustrated in the graph, those circuits with the greatest number of heaters also had greater energy consumption. Circuits 1a, 1b, 1c, 2, 3a, and 3b consisted of 19, 18, 24, 30, 18, and 18 heaters, respectively. The energy usage graph shows that demand peaked when the system was first turned on while running a scenario. This was directly related to the temperature error between the zone temperature and the desired set point. As the zone temperature reached the set point, energy demand began to settle out. Likewise, energy demand increased with larger set points. It would be expected that over time, as the ground temperatures continue to

Figure 22. Initial turn on of system and adjustments of PID proportional control

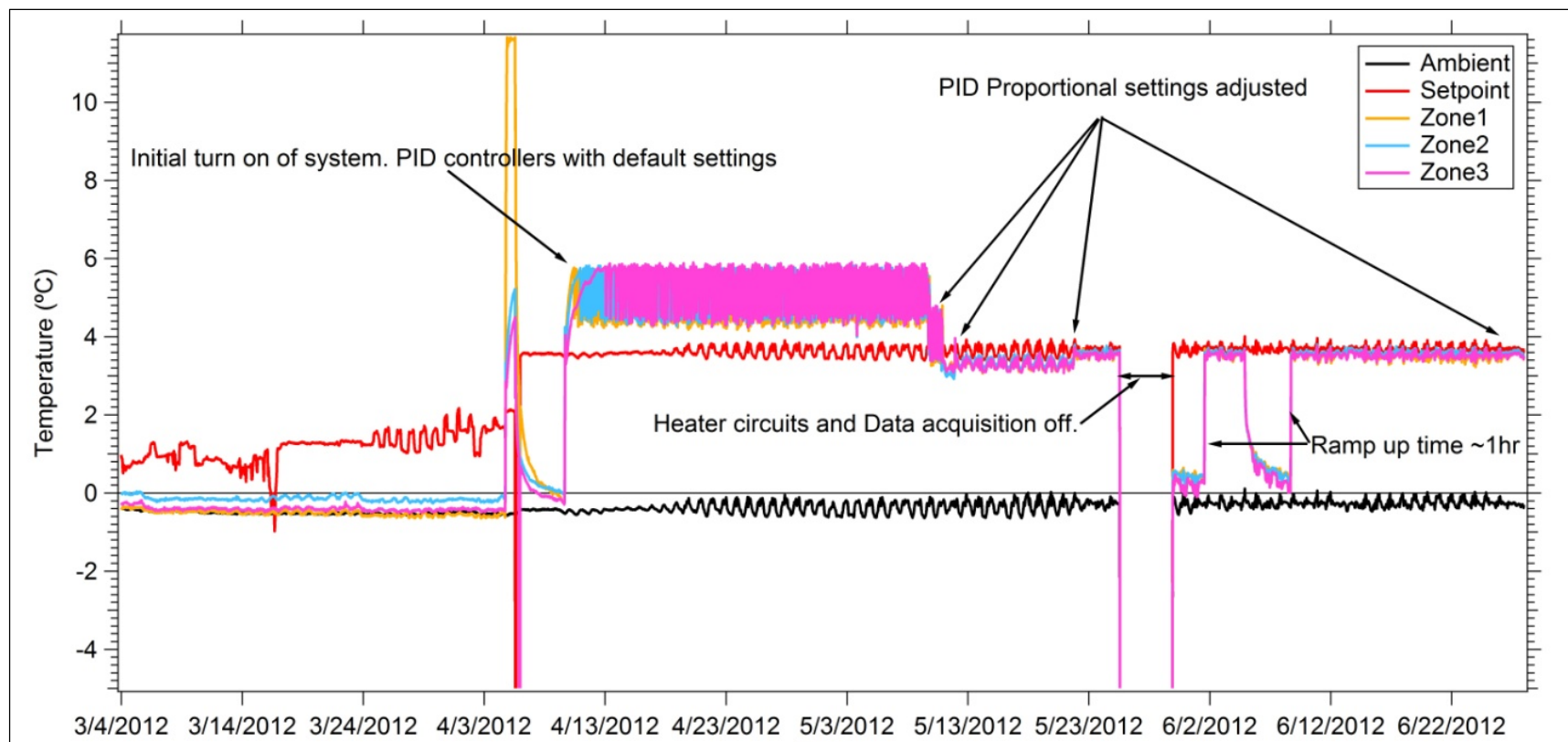


Figure 23. Set point tests of 2, 4, 6, and 8 °C, showing heating and cooling curves.

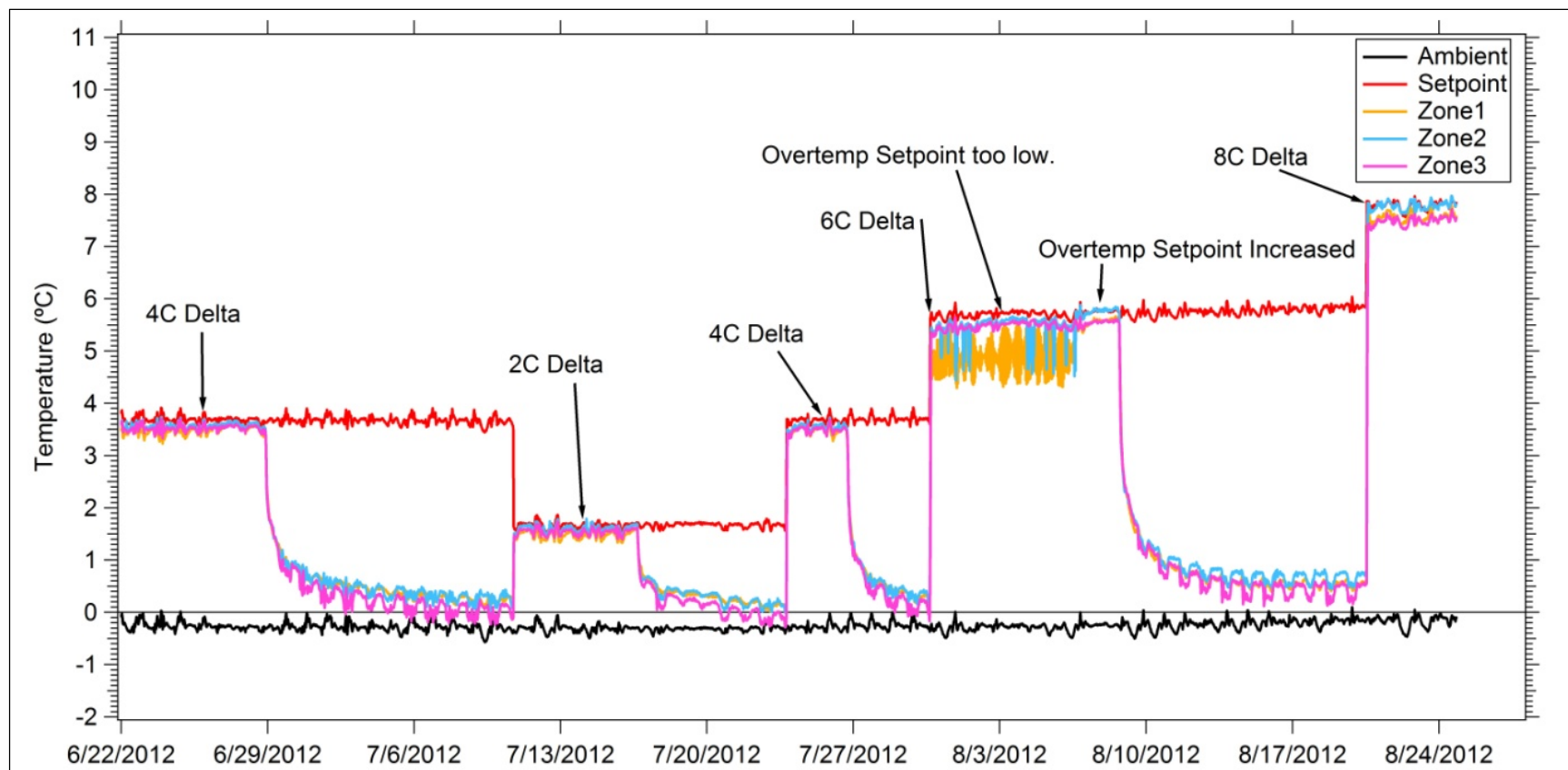
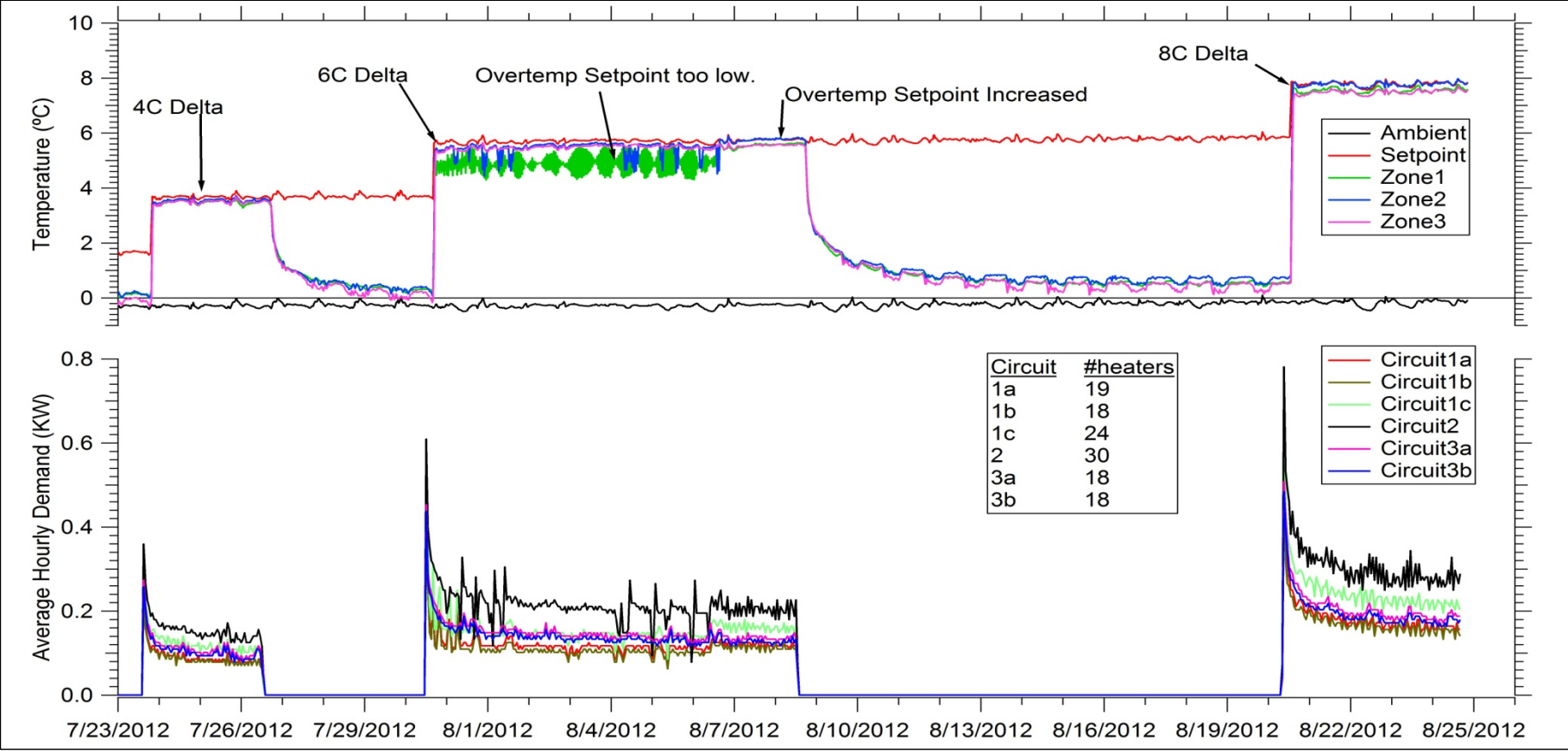
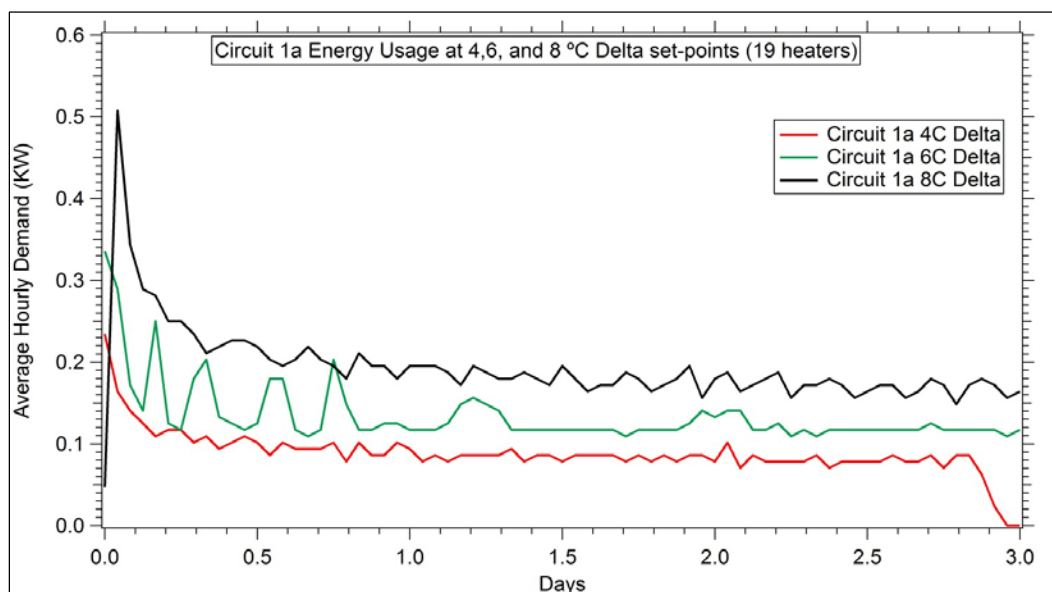


Figure 24. 4, 6, and 8 °C delta scenarios vs. energy usage.

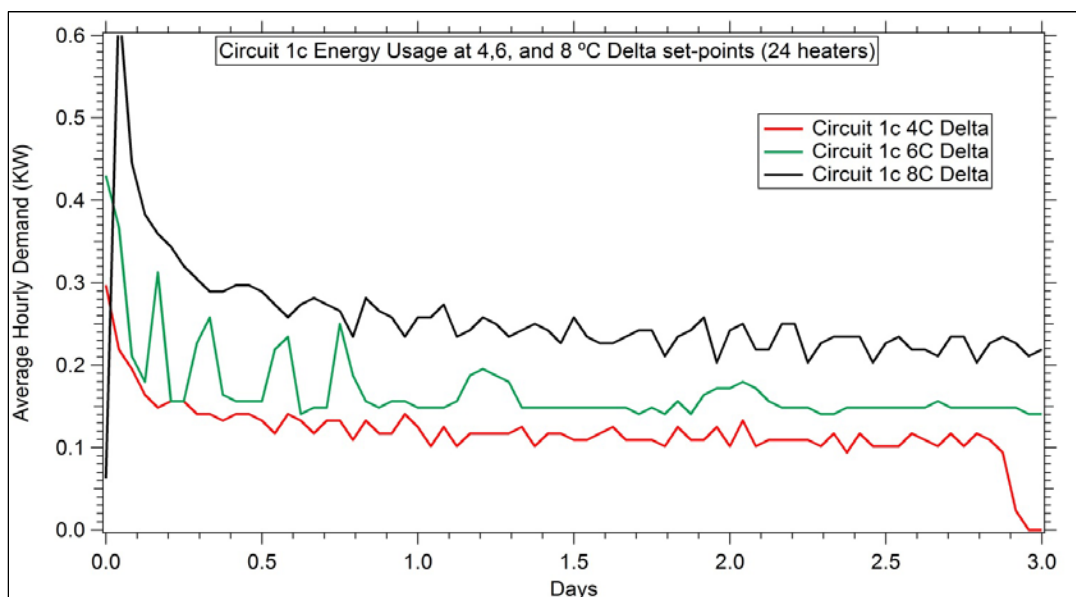


increase, energy demand would decrease due to the reduction in temperature differential between soil temperature and the desired set point. Figure 25 compares energy usage of various circuits with differing number of heaters while running set-point scenarios of 4, 6, and 8 °C delta over a period of 3 days. This figure further illustrates that energy demand was greatest when zone temperature and set-point error were greatest.

Figure 25. Energy use for circuits 1a, 1c, 2, and 3.

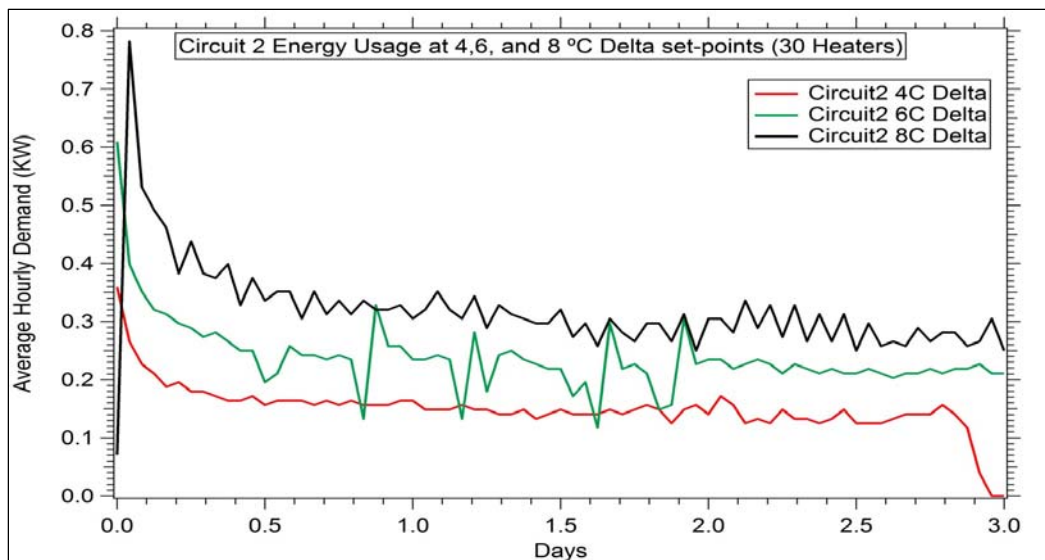


a. Circuit 1a.

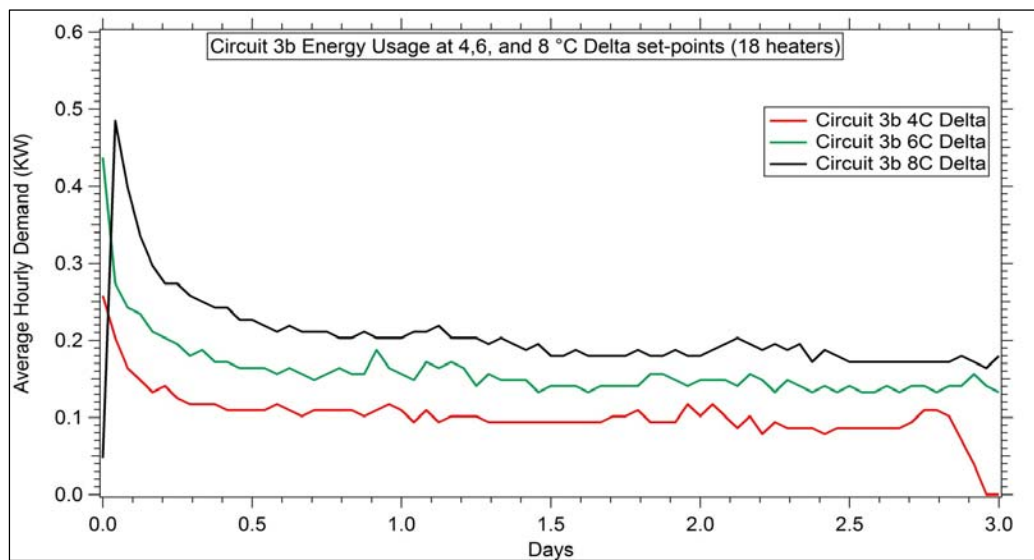


b. Circuit 1c.

Figure 25. (concluded).



c. Circuit 2.



d. Circuit 3b.

5 Results and Discussions

Testing results indicate that this system provides a promising means to simulate a soil-warming scenario and sets the stage for larger test plots to be installed in the future. It has been demonstrated that it is possible to install the ORNL system in a permafrost environment. Warming scenarios of 2, 4, 6, and 8 °C show that, with minor design changes, meaningful warming can be simulated.

Although there were no major design issues, some challenges with components operating within an arctic environment were encountered. Thermocouple transmitters that were originally provided with the system proved not capable of handling arctic conditions even though they were rated for arctic temperatures to -40 °C. Issues with frost jacking of some of the heaters have been observed with some heaters having jacked up to 30 cm in 2 years (without running the system). Frost jacking will affect the depth at which the heating elements influence the soil temperature. Because the system sat idle for over a year before operating, it is not clear how much frost jacking would or would not have occurred if heat was applied soon after installation.

This report presents the installation of a soil-warming system proposed for use in studies of warming permafrost. Instrumentation issues and remedies and operational system performance for various warming set-point scenarios over short time periods (several days) were documented. Longer-term tests should be performed to observe additional challenges that may occur during periods of prolonged operation and to identify further issues that, unless resolved, could cause costly problems associated with larger or more remote installations in the Arctic.

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