

Learnings from Borefield Temperature Monitoring in an Operating Geothermal Energy Network Using Distributed Fiber Optic Sensing

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ABSTRACT

The first utility-led retrofit geothermal energy network (GEN) system in the US was built in Framingham, MA by Eversource in 2024. The system was designed to provide heating and cooling energy to 36 nearby buildings through a single ambient loop connecting three geothermal borefields. Although GEN systems are estimated to have a lifetime of 50 years, these systems may suffer from efficiency reductions due to subsurface thermal drifts after multiple years of operation, especially when the heating and cooling loads are not balanced. To ensure that the GEN system is operating in an optimal and sustainable manner, a ground temperature monitoring system based on distributed fiber optic sensing (DFOS) technique was designed and installed at the Framingham GEN system. Fiber optic cables were inserted in 14 (out of 90) boreholes among the three borefields to measure both the temperature distribution along the depth and its variation with time. This study focuses on ground temperature data collected from the Normandy Lot borefield of the GEN system during its first 16 months of operation. Measured borehole temperatures ranged from a summer maximum of 21 °C to a winter minimum of 9 °C, relative to an average initial ground temperature of 12 °C, indicating a substantially greater net heat injection during the summer period. Difference in borehole temperature responses were observed and can be attributed to multiple factors, including borehole position, pipe flow rate, drilling deviation, and grouting quality. Thermal interaction occurred within the top 50 meters of the subsurface and turns significant when temperature reaches extrema during the ground heating and cooling phases. Below 50 meters, thermal interactions were found negligible. As system continues to operate under imbalanced heating and cooling loads, the thermal interaction zone is expected to expand to greater depths, highlighting the importance of long-term subsurface temperature monitoring for maintaining GEN system performance and sustainability. Eventually, the recorded ground temperature data will be used to improve understanding of subsurface thermal response to building energy loads, validate the GEN system design, and optimize the system operation strategy.

1. INTRODUCTION

In response to global climate change, Massachusetts published its 2050 Decarbonization Roadmap in 2020, aiming to reduce statewide greenhouse gas emissions by at least 85% before 2050 and ultimately achieve net-zero emissions (Commonwealth of Massachusetts, 2020). As a way to align with this initiative, the first utility-led retrofit geothermal energy network (GEN) system in the United States was built by Eversource in Framingham, MA to explore cost-effective and equitable decarbonization solutions. The GEN system employs borehole heat exchangers (BHEs) to extract heating and cooling energy from the subsurface. By connecting multiple BHEs through a single ambient-temperature distribution loop, the GEN system can supply energy to all buildings in the nearby communities. Given that the building sector is consuming approximately 40 % of total energy consumption and emitting 38 % carbon emissions in the United States (U.S. Department of Energy, 2011), the potential of the GEN system in large-scale decarbonization can be substantial.

Due to the stable subsurface temperature, the coefficient of performance (COP) of the GEN system is generally higher than that of other technologies, such as air-source heat pump. It means the GEN system can deliver more energy while consuming less electricity and releasing less carbon emission, which is advantageous in decarbonization (Self et al., 2013). However, during operation, a decline in COP is frequently observed along with the change of underground temperatures (Alavy et al., 2023), particularly when the system is not operated optimally. To mitigate the degradation – or even enhance the system performance – strategies are usually developed using optimization and validated through the real-physic simulation of the GEN system (Hecht-Méndez et al., 2013). Among those strategies, seasonal thermal balancing is one of the most effective design principles that ensure the long-term performance of the GEN system and has been widely applied and studied (Reuss et al., 1997, Fiorentini et al., 2023).

Nevertheless, those approaches often neglect the true thermal response of the subsurface to system loads. While some studies incorporate Finite Element (FE) models to simulate the subsurface behavior (Chen et al., 2024), they are typically based on idealized assumptions, such as homogeneous heat conduction. In practice, subsurface conditions of borefields are far more complex, and variance in construction outcomes (drilling precision, TC testing, etc.) usually occurs. For instance, boreholes may not be spaced as uniformly as shown in design drawings; when boreholes are closer together, thermal interactions get stronger, which reduces the overall efficiency of the GEN system.

This disconnection between model prediction and practical performance is primarily due to the lack of the subsurface temperature data to properly update models, as it remains challenging to monitor the thermal response of the ground during the GEN system operation.

The development of distributed fiber optic sensing (DFOS) technology in the past decades has enabled new possibility for monitoring subsurface temperature. DFOS is a sensing technology that uses Fiber Optic (FO) cable as the sensor to acquire high-resolution temporal and spatial data on temperature and strain along the cable (Soga & Luo, 2018). In the context of application in shallow geothermal research, DFOS utilizes FO cables embedded within BHEs to continuously measure temperature distributions along the borehole depth, providing new insights into dynamic thermal response of the ground. Such application is widely demonstrated in distributed thermal response tests (DTRTs), where thermal conductivity profile along the depth is calculated from the spatial distribution of temperature variation measured by DFOS system (Acuña et al., 2009, Fujii et al., 2009, Beier et al., 2022, Yang et al., 2022). Prior to the construction of the Framingham GEN system, three DTRTs were conducted at borehole drilling sites to assess the vertical distribution of thermal conductivity, proving DFOS’s capability to uncover detailed subsurface information (Sinha et al., 2024). Despite its unprecedented potential, the use of DFOS in operational geothermal energy networks (GEN) remains relatively limited, particularly in district-scale systems that is running under real-world energy demand. Expanding its use in this context could significantly improve the accuracy of subsurface modeling and facilitate the development of more robust, performance-based control strategies for GEN systems.

Hence, this paper presents the design and installation of a DFOS-based ground temperature monitoring system in the first utility-led geothermal energy network (GEN) system in the United States. Data collected over the initial 16 months of operation are presented and analyzed to demonstrate the capability of DFOS to capture both temporal and spatial characteristics of borehole temperatures during real-world operation. The results highlight the DFOS’s ability to reveal critical subsurface information that is often overlooked by conventional monitoring method. Eventually, the data collection will be continued for an additional two years, and they will be used to assess borehole thermal interactions, balance seasonal energy demand, and evaluate long-term subsurface performance under varying operational conditions.

2. DISTRIBUTED FIBER OPTIC SENSING TECHNOLOGY

2.1 DFOS Principle

Distributed fiber optic sensing (DFOS) is a technology that utilizes fiber optic (FO) cables as continuous sensors for temperature and strain monitoring. The fundamental principle involves an Optical Time Domain Reflectometry (OTDR) device – often referred to as an analyzer or interrogator – that emits light signal into the FO cable and subsequently collects the backscattered signal. As shown in Figure 1 (a), change in temperature or strain along the cable induce frequency shifts in the backscattered light, and by analyzing those shifts, the analyzer can determine the spatial distribution of temperature or strain along the entire length of the cable. Depending on the scattering mechanism, OTDR systems are typically based on Brillouin, Rayleigh, or Raman scattering, shown in Figure 1 (b). Among these, Brillouin scattering is the most widely adopted in commercial analyzers due to its ability to sense both strain and temperature change. However, limited by this dual sensitivity, special measures are needed for a temperature-only or strain-only measurement using Brillouin Optical Time Domain Reflectometry (BOTDR) device. Temperature compensation is required for a strain-only measurement, while for a temperature-only measurement, temperature FO cable with lubricant between fiber core and cover is necessary. In contrast, Raman scattering is influenced only by temperature variation and is unaffected by mechanical strain, making it more suitable for temperature-specific application. Although Raman scattering is sensitive to signal attenuation potentially caused by fiber length, splicing, and connector losses, this limitation can be effectively mitigated by minimizing the total cable length, reducing the number of splices, and ensuring high splicing quality. As a result, the Raman Optical Time Domain Reflectometry (ROTDR) technique is better suited for temperature monitoring task in this study and is therefore chosen for building the distributed ground temperature monitoring system.

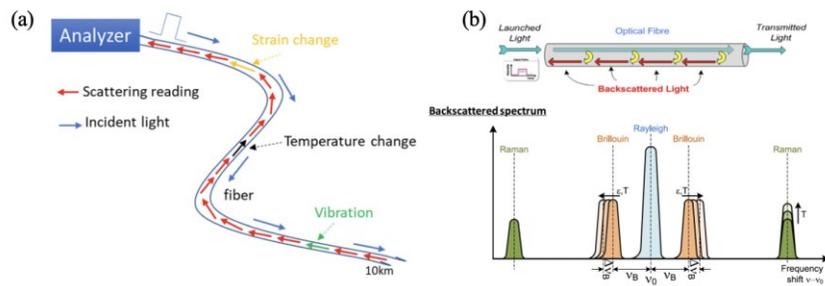


Figure 1: (a) A schematic of a distributed fiber optic sensor system and (b) three backscatter modes (Soga & Luo, 2018).

2.1 VIAVI FTH-9000 Interrogator

In this study, FTH-9000 Adaptive Fiber Test Head (shown in Figure 2), a ROTDR-based analyzer manufactured by VIAVI Solution Inc. (<https://www.viavisolutions.com/en-us/products/fth-9000#overview>), was used as the sensing instrument. By integrating high-resolution ROTDR and optical switch technology, FTH-9000 enables stable and accurate temperature measurements and allows sequential data acquisition from multiple FO cables during constructions. Before field deployment, a water bath test was conducted to evaluate the temperature measurement accuracy of FTH-9000. A 1-km FO cable, rolled on a spool, was connected to the device, and submerged in a controlled water bath. The water temperature was incrementally increased from 35 °C to 45 °C in steps of 5 °C every 15 hours using the temperature control system of the water bath. FTH-9000 was set to continuously record the temperature along the FO cable with a spatial resolution of 1 meter and acquisition time of 5 minutes. The results indicate an overall Mean Absolute Error (MAE) of 0.3 °C. Plots in

Figure 3 present the temperature readings over time at different cable locations and the temperature readings along the cable at different times, respectively, with grey zone indicating the \pm MAE range. The slightly higher temporal variation compared with the spatial variation is attributed to minor fluctuations in water temperature, as it is difficult to maintain a perfectly constant temperature over time. Generally, FTH-9000 can provide an accurate temperature measurement and satisfies the ground temperature monitoring requirement in this study. It should also be noted that, in field application, this accuracy might decrease due to site factors such as a higher number of splicing points and reduced splicing quality do to challenging site conditions.



Figure 2: The VIAVI FTH-9000 adaptive fiber test head.

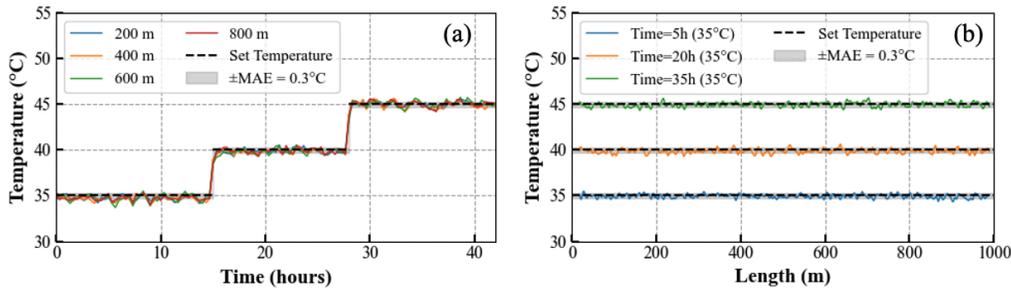


Figure 3: The result of water bath test using FTH-9000: (a) temperature over time at different cable positions and (b) temperature along the FO cable at different time.

3. CASE DESCRIPTION

3.1 Framingham Project Introduction

As the pilot project, a geothermal energy network (GEN) was built in Framingham, Massachusetts by Eversource to explore the potential of GEN systems as a renewable, affordable, and scalable alternative for building heating and cooling. As shown in Figure 4, the Framingham GEN consists of three borehole fields – Normandy Lot, Rose Kennedy, and Fire Station – which are interconnected via a single ambient-temperature distribution loop. This loop supplies the heating and cooling energy from the borefields to 36 nearby buildings, including 31 residential and 5 commercial buildings. In total, the system services approximately 130 end users. The Fire Station and Rose Kennedy borefields have 30 and 25 vertical boreholes, respectively, connected in parallel. Each borehole is 600 ft deep, spaced 20 ft apart, and equipped with a single U-pipe for heat exchanging. In contrast, the Normandy Lot borefield employs inclined boreholes installed with double U-pipes, each approximately 700 ft in length and up to 15 degrees of deviation. These boreholes are distributed across two drilling platforms – North Platform with 17 boreholes and South Platform with 16 boreholes – and connected in parallel. In total, the Framingham GEN comprises 88 boreholes and represents a large-scale demonstration of community-based geothermal infrastructure.

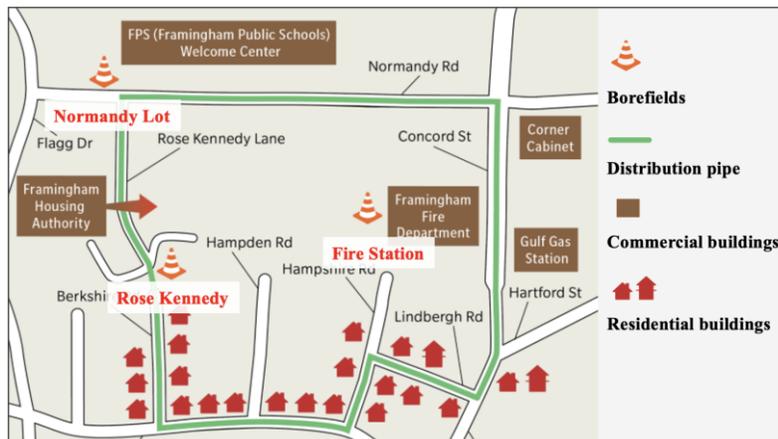


Figure 4: Overview of the Framingham geothermal energy network (GEN) system. (<https://www.eversource.com/residential/save-money-energy/clean-energy-options/geothermal-energy/geothermal-pilot-reference-guide>)

3.2 Selection of Monitoring Boreholes

While monitoring the temperature of every borehole can be challenging, it is still feasible to capture the key characteristic of subsurface thermal behavior by instrumenting boreholes at critical positions. As shown in Figure 5, the selection principle is based on identifying boreholes located along a representative crossline (indicated by the blue line in the figure), which is expected to provide a meaningful approximation of the temperature distribution across a typical cross-section of the borefield. This approach allows for an improved understanding of the heat dissipation mechanisms within each borefield under system load. In total, 7, 4, and 2 monitoring were selected for the Normandy Lot, Fire Station, and Rose Kennedy sites, respectively. It should be noted that, despite the idealized monitoring plant, practical constraints during construction required deviations from the original plan to accommodate on-site drilling activities. For example, at the Fire Station site, the monitoring boreholes were shifted from B3 to B1 and from C6 to D8' due to uncertainty in drilling activity. Such adjustments show unavoidable compromises that arise from the inherent uncertainties associated with borehole drilling and cable installation.

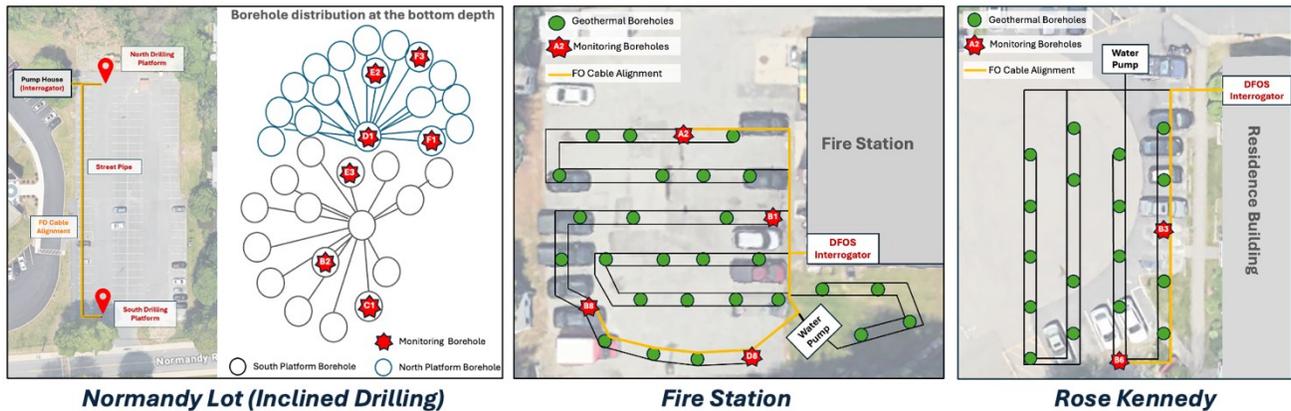


Figure 5: Configurations of three geothermal borefields with monitoring boreholes marked.

3.3 FO Cable Installation and Interrogator Setup

The construction of the Framingham GEN project started in Aug. 2023 with the initiation of borehole drilling. With collaboration of SRG, HEET, and Celsius (the drilling contractor), FO cables were installed in the selected monitoring boreholes. and tight operational schedules, only a single FO cable could be installed in each borehole, as opposed to having one cable attached to the downward pipe and the other to the upward pipe. The FO cable, with a reflector affixed to the bottom, was taped in place between the downward and upward pipes with an interval of 30 ft and grouted inside the borehole (shown in Figure 6 (a) and (b)). The borehole drilling and cable installation phase was finished by Jan. 2024, which is followed by a trenching phase. During this phase, horizontal pipes and street pipes are installed to connect boreholes to the buildings, as shown in Figure 6 (c). Meanwhile, cable splicing was performed to connect the vertically installed FO cables to horizontal cables, which were attached along the horizontal pipes and buried underground. These horizontal cables were routed to the pump house or other designated indoor locations where the interrogator was installed and configured for data acquisition (shown in Figure 6 (d)).



Figure 6: Installation of the DFOS system in the field: (a) taping the FO cable to the bottom of the U-pipe; (b) taping the cable to the U-pipe at 30 ft intervals (c) attaching the horizontal FO cable to the street pipe; (d) setting up the VIAVI FTH-9000 in the pump house.

Setup of the complete monitoring system is showcased in Figure 7. The interrogator was set up with a micro-computer and mobile hotspot, forming an integrated unit capable of not only managing data acquisition from multiple FO cables but also processing the incoming data and uploading real-time temperature reading to google drive for remote access. While the data is protected and not accessible to the public,

research teams involved in the Learning from the Ground Up (LeGUp) project can access these real-time data stream for their study, and to facilitate the intuitive understanding and monitoring of data, an internal web-based visualization platform was developed and deployed on Heroku, enabling interactive visualization of ground temperature data during operation. Overall, this ground temperature monitoring system, based on DFOS technology, enables continuous data recording, sharing, and visualization of subsurface temperature during the operation of the Framingham GEN system. It is valuable for both system operation and management as well as for research and analysis purposes.

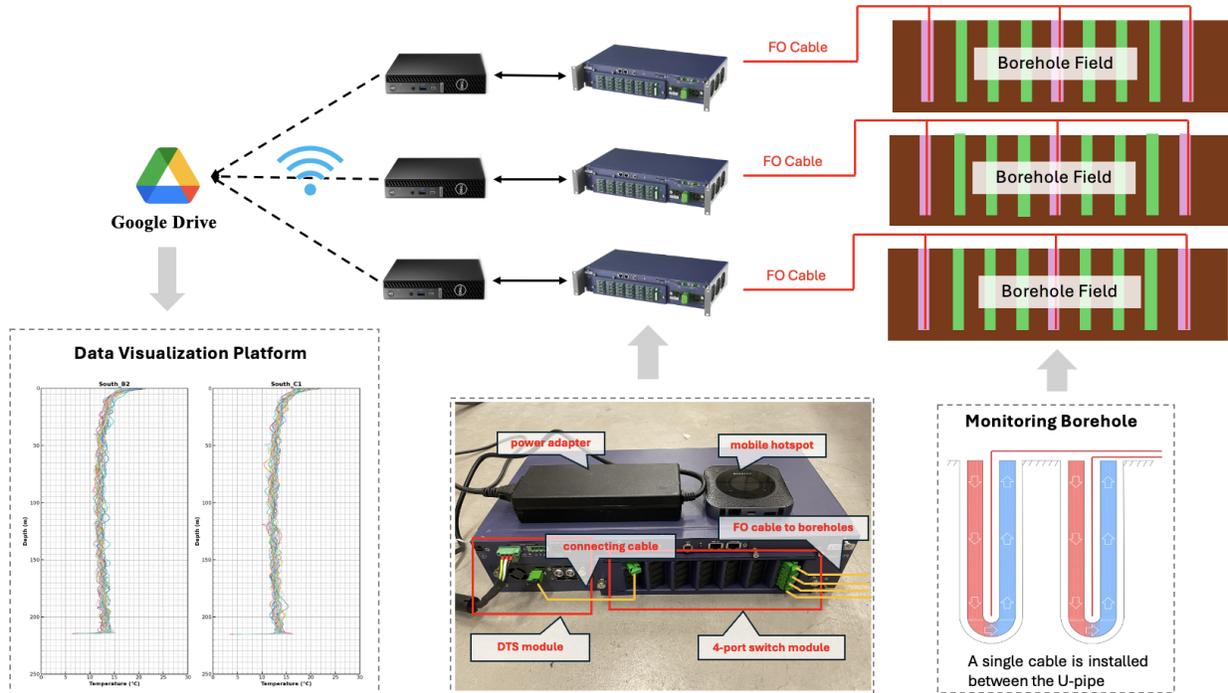


Figure 7: General configuration of the DFOS-based ground temperature monitoring system.

4. RESULTS

Among those three borefields, the Normandy Lot is of particular interest due to its inclined borehole with double-U-pipe. At shallower depths, the small spacing between boreholes leads to a stronger thermal interaction and consequently more rapid temperature increase/decrease. As boreholes diverge with depth, the spacing increases, resulting in weaker thermal interference and slower temperature changes. While this behavior aligns with physical intuition and has been observed in numerical simulations, it remains essential to validate the phenomena using the field collected data. The DFOS-based ground temperature monitoring system provides a direct and effective method for capturing high-resolution, depth-dependent temperature profiles. Accordingly, this result section focuses on analyzing the ground temperature data collected from the Normandy Lot monitoring system, demonstrating the ability of DFOS technology to provide detailed insights into the thermal dynamics of the borefield to support design validation, system management, and operation optimization.

4.1 Ground Temperature Variation with Time

Construction of the Framingham GEN project was completed in Aug. 2024, followed by loop testing of borefields and building conversions which connects customer accounts to the GEN system. The data collection of the Normandy Lot borefield started on Aug. 14, 2024, and by the time this paper was completed, data of 16 months during the operation of the system had been collected. Figure 8 showcases the variation of the average borehole temperature with time from August 2024 to December 2025, with subplot (a) illustrates the boreholes in the North Platform and subplot (b) illustrates the boreholes in the South Platform. Based on the operation status, the timeseries can be broken down into four phases: system testing, ground cooling, ground heating, and ground cooling.

4.1.1 Operation Phases of the GEN System

System testing phase (August 2024 to November 2024)

A virtual building cooling load was applied to the system starting on August 20, 2024, to evaluate the system performance. Following this, the ground temperature rose rapidly reaching a peak of 17 °C on September 10, 2024 – an increase of about 5 °C above the initial ground temperature. Right after the peak, all South Platform boreholes, and several North Platform boreholes (e.g. North_D1 shown in Figure 8 (a)) were disconnected from the ambient loop for maintenance. A significant temperature drop was observed in those disconnected boreholes, featured by a rapid decrease followed by a gradual return toward the initial ground temperature.

Ground cooling phase (December 2024 to April 2025)

As Framingham entered winter, the ground temperature decreased below the initial ground temperature due to heat extraction from the subsurface to meet the building heating demand. It should be noted that the customer accounts were connected to the GEN system progressively, and full building conversion was not completed until May 2025. As a result, the temperature drop was moderate, with a total decrease of approximately 3 °C, reaching a minimum of 9 °C. The temperature change remained relatively gradual during this phase.

Ground heating phase (May 2025 to November 2025)

Entering the summer season, ground temperature began to rise as the thermal energy was injected into the subsurface for building cooling. By this time, most buildings had been connected to the GEN system, so the cooling load was higher than the heating load in the past winter season. The ground temperature reached the maximum of 21 °C in July, an increase of 9 °C, coinciding with the peak ambient temperature in Framingham. After August, ground temperatures declined gradually as the building cooling demand with falling outdoor air temperature.

Ground cooling phase (December 2025 to present)

As Framingham entered the winter season, the dominant energy demand shifted from building cooling to heating. Consequently, thermal energy was extracted from the subsurface, leading to a decline in ground temperature to levels below the initial ground temperature.

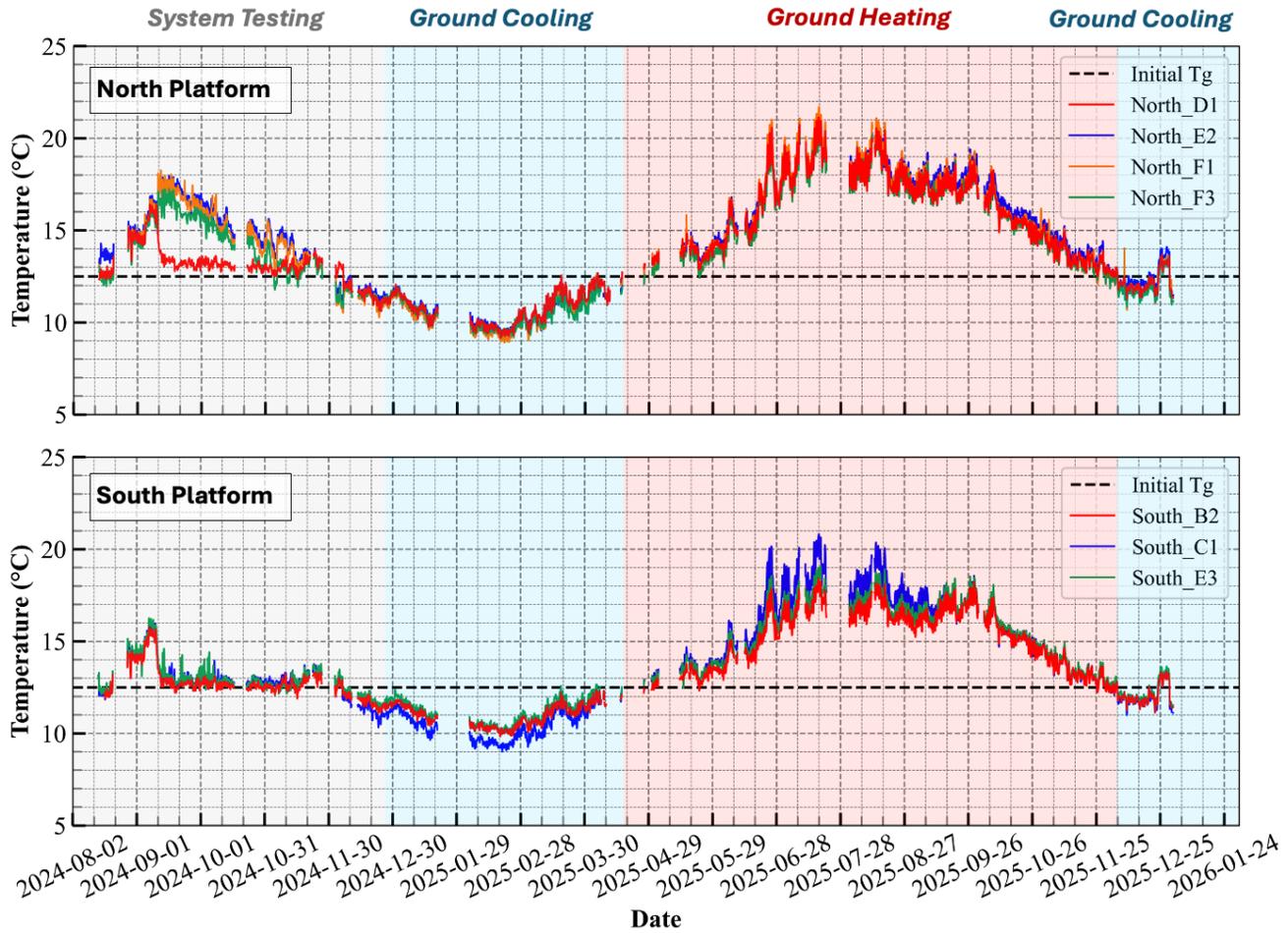


Figure 8: Borehole temperature variations during the first 16-month operation of the Framingham GEN system: (a) North Platform boreholes; (b) South Platform boreholes.

4.1.2 Spatial Variation in Borehole Temperature Response

Besides the general temporal trend in ground temperatures, differences in temperature responses between boreholes were also observed. Generally, boreholes located on the south platform exhibited slightly smaller temperature variations compared to those on the north platform. It might be attributed to the slower flow rate in south platform boreholes, resulting from longer distance to the pump house and the associated increase in pipe hydraulic resistance.

Within the south platform (Figure 8 (b)), the temperature response of South_C1 is notably faster than those of South_B2 and South_E3. This discrepancy may arise from multiple factors, one of which is borehole drilling deviation. Boreholes, while designed to be straight, may spiral or curve during the drilling process, bringing them closer to adjacent boreholes and thereby increasing the thermal inference.

In addition, poor grouting quality may also contribute to the observed behavior, as inadequate heat transfer to the surrounding ground can lead to heat accumulation within the borehole, resulting in more rapid temperature increases/decreases.

Those observation cases also demonstrate the capability of DFOS-based monitoring system in assessing the borehole drilling and installation quality within the GEN system.

4.2 Ground Temperature Distribution along the Depth

The temperature distribution of boreholes along the depth at selected time points are shown in Figure 9. The leftmost plot illustrates the initial ground temperature measured before the initiation of loop test. This initial profile exhibits a decreasing temperature trend with depth above 100 meters, followed by an increasing trend below 100 meters. It suggests a shallow ground temperature gradient of approximately 15 °C/km.

During the operation of the GEN system, the temperature profile along the borehole depth becomes more uniform than the initial ground temperature, especially at the phase transition stage. Distinct thermal interaction zones – depth intervals where temperature changes more rapidly due to interaction of nearby boreholes – can be observed above a depth of 50 meters. Those zones are significant when the temperature reached its maximum during the ground heating phase and its minimum during the ground cooling phase. This behavior is expected, as boreholes are densely spaced near the surface, with a horizontal spacing less than 1 meter. Below the depth of 50 meters, the thermal interaction turns negligible. It is worth noting that the thermal energy injection and extraction over the annual cycle is not balanced. With higher net energy injection during the summer, the ground temperature will increase progressively over time, potentially causing the thermal interaction zone to extend to greater depths. Overall, the DFOS technology works well in revealing the spatial distribution patterns of borehole temperature during the operation of the GEN system.

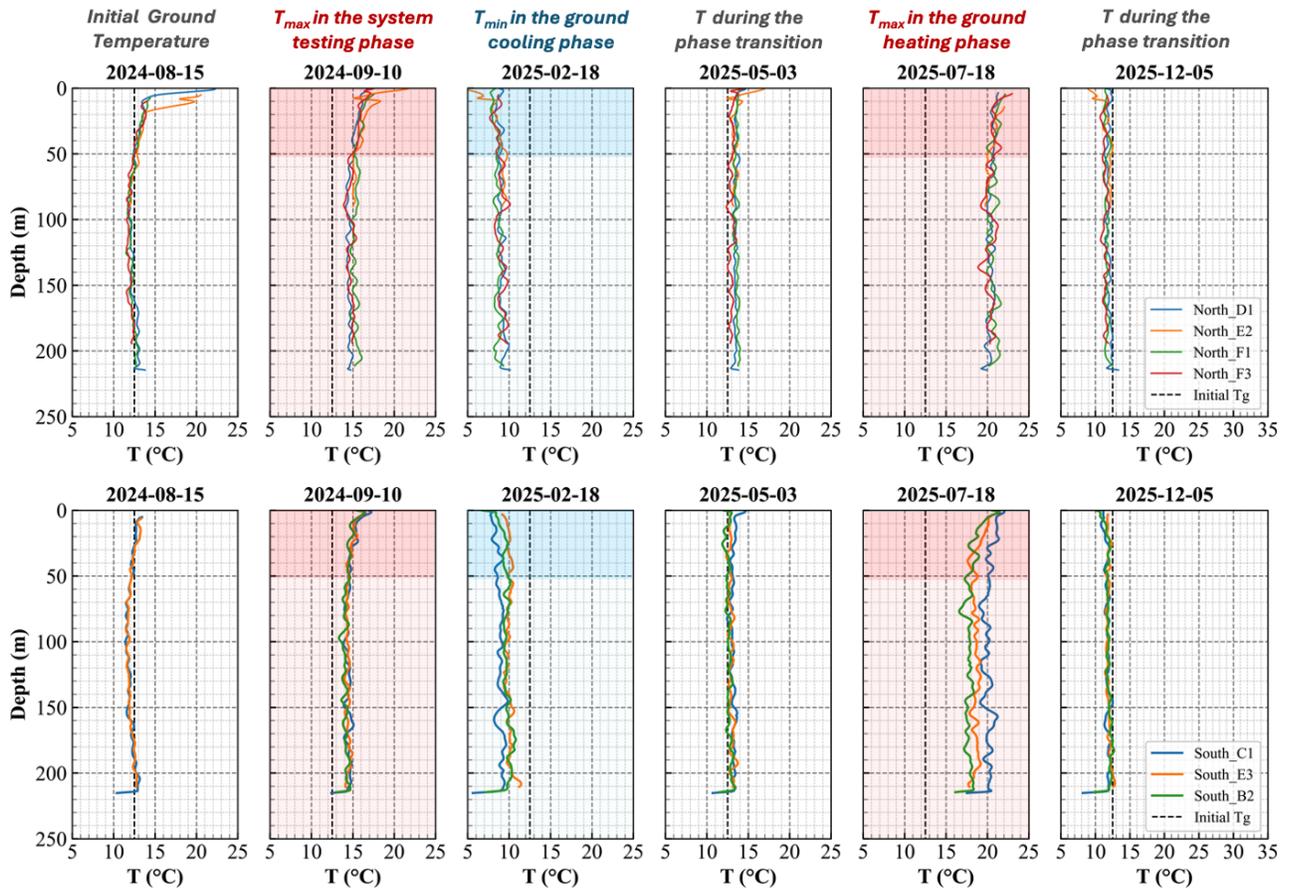


Figure 9: Temperature distribution along the borehole depth at different times during operation of the GEN system.

4.3 Stability of the Monitoring System

During the 16-month data collection period, several data gaps occurred in the Figure 8. Multiple factors contributed those data losses, among which the primary cause was system instability in the initial deployment phase. Since the FTH-9000 device itself lacks the ability to automatically recording data from multiple FO cables, a computer was required to interface with the FTH-9000 via API for data acquisition, extraction, and storage. However, this communication link was initially unstable due to technical issues, leading to occasional disconnections. This problem has been substantially mitigated through collaboration with experts from VIAVI Inc. Another significant cause of data loss was system reboots caused by power outages and automatic Windows update. To address this, the monitoring system

was reconfigured to automatically resume operation upon power restorage. Overall, since this is the first ever long-term DFOS-based ground temperature monitoring system of a utility-deployed geothermal network, the past 10 months has been an important learning process not only for temperature monitoring but also for improving the robustness of the data acquisition system. Continuous enhancements have been made to increase the stability, aiming to minimize future data loss and ensure reliable continuous temperature monitoring over the lifetime of the system.

5. CONCLUSION AND FUTURE WORK

In this study, a DFOS-based ground temperature monitoring system was designed and implemented in the Framingham GEN system. The ground temperature variations were recorded during the initial 16 months of system operation. By analyzing the temperature data from the Normandy Lot borefield where the inclined borehole with double-U-pipe embedded is installed, several preliminary conclusions are drawn as follows:

- DFOS technology demonstrates its strong performance in continuously recording temperature variations within each monitoring borehole. Over the past 16 months, borehole temperatures varied from a maximum of 21 °C (+9 °C), observed during ground heating phase, to a minimum of 9 °C (-3 °C), observed during the ground cooling phase. These results indicate imbalance of the thermal energy injection and extraction during the past annual cycle, with substantially higher net heat injection during the summer period. Going forward, the thermal profile of the subsurface may change now that all the buildings and boreholes are connected to the system.
- Spatial variations in borehole temperatures were observed across the borefield, attributable to multiple factors including borehole position, pipe flow rate, drilling deviation, and grouting quality. This pattern further demonstrates that DFOS can indirectly assess borehole drilling and installation quality, which ultimately influences the overall thermal performance and efficiency of the GEN system.
- The temperature distribution along the borehole depth reveals distinct thermal interaction zones for inclined boreholes. Based on operational conditions over the past 16 months, the thermal interaction occurred within the top 50 meters and turns significant when the borehole temperature reaches its maximum during the ground heating phase and its minimum during the ground cooling phase. Below 50 meters, the thermal interaction between boreholes is negligible. As system operates under imbalanced heating and cooling loads, the thermal interaction zone is expected to expand to greater depths.

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