Ground Source Heat Pump System Performance: Evaluating the Ground Loop

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1 Introduction

This article is the first in a 3-part series that will highlight some of the lessons learned from over 100,000 hours of GSHP real-time monitoring data. This is written for GSHP installers of residential and light commercial systems who want to learn how to leverage real-time Performance Monitoring to build better GSHP systems, reduce their risk and callbacks, and ensure customer satisfaction.

The overall goal of this Performance Monitoring series is to engage the GSHP community in a discussion of both 1) what is possible and 2) what is useful. This first article focuses on how web-based performance monitoring data can be used to assess the performance of the ground loop relative to installed capacity. The second article will focus on using performance monitoring data to assess the overall performance (COP) of the system and how the ground loop, heat pump, and loop pump all contribute (or limit) system performance. The third and final article will discuss how performance monitoring can be used to develop and implement performance guarantee contracts. This initial series of artilcles will focus on heating applications in residential and light-commercial installations. Cooling applications that will be addressed in future articles this Fall.

2 Loop Temperature

There is a growing consensus (e.g. LinkedIn discussion on Ground Loop Performance) that monitoring Entering Water Temperature (EWT) is important, relatively easy, and helps to identify problems in system performance. There is less agreement as to what the minimum entering water temperature should be for a specific application or whether adhering to a uniform standard (e.g. ISO 13256) is best for all clients under all conditions. Regardless of your design preference and practice, EWT should be monitored to ensure that your systems are operating within the design limits.

As shown in Figure 1, there is a wide range of behavior in the EWT of GSHP systems in the Northeast. The variation is due primarily to differences in design and use. All loops shown in the graph below are vertical boreholes, but they range in design from open diffusion (one well for groundwater extraction and another for groundwater return), standing column wells with various levels of bleed, to closed loop systems. Geographically, they range from Connecticut to southern New Hampshire. The residential systems are dominantly used for heating and the commercial installation has a significant cooling load for most of the year.

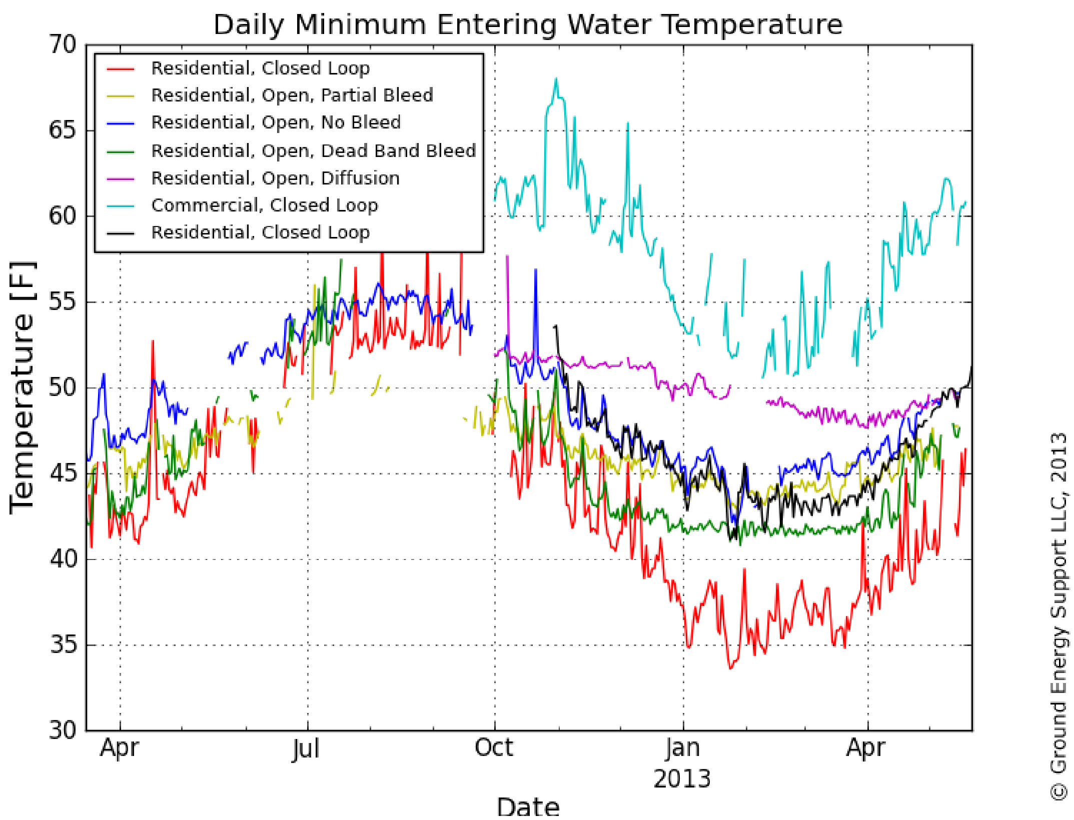

Figure 1: Daily Minimum Entering Water Temperature for a range of GSHP sites in New England. Values represent 1-minute sampling interval and are filter for conditions when heat pump is running.

While the minimum EWT is a good indicator of ground loop conditions, the average of the entering and leaving water temperatures [0.5*(EWT+LWT)] is a more meaningful metric for evaluating how the ground loop is performing relative to heating and cooling load.

3 Building Load

Real-time monitoring data can be used to track building load under a wide range of conditions and assess system performance. Building load provides a critically important context for interpreting loop temperature data, as it enables the installer to demonstrate that their system is operating as designed and isolate factors that are outside of their control. For example, construction practices (insulation of windows and door jams, proper ductwork installation) can have a significant impact on an GSHP system. The installer is often provided the building specifications and leaves it to the building contractors to meet those specification and can't be on site to inspect all phase of construction or renovation. If the building envelope is not on spec, problems that arise in the heating/cooling system will likely fall in the lap of the installer – why isn't the system working? Also, installers can't control homeowner's thermostat settings, some of which may affect the efficiency of the system. However, by monitoring the system load, installers can identify discrepancies between operating and design conditions – discrepancies that may impact system performance and customer satisfaction.

The total building heat load is the sum of the GeoExchange and the heat produced by the compressor. In this discussion of Performance Monitoring, we focus on the GeoExchange portion of the building load as it is readily measured and is most closely tied to Ground Loop Performance. GeoExchange [MBtu/hr] is measured by multiplying the temperature difference (EWT - LWT) by the mass flow rate and the specific heat capacity of the circulating fluid. Most heat pumps operate at a constant flow rate and the flow rate can be adequately determined during the initial commissioning of the system. Some of the newer heat pumps that have modulated flow and systems with multiple heat pumps sharing a common loop may require a flowmeter for accurate calculation of GeoExchange. We have found that constant flow is reasonably accurate for single heat pumps operating off a dedicated flow center. This applies to open loop systems as long as the well is not also used for domestic water. If there are unexpected variations in flow rate, they show up in the delta T data and can be addressed accordingly (correct mechanical problem or install flowmeter). In the examples presented below, flow rate is measured in two systems and taken as a constant in the other two.

We use a Load Profile presentation of the measured GeoExchange as a function

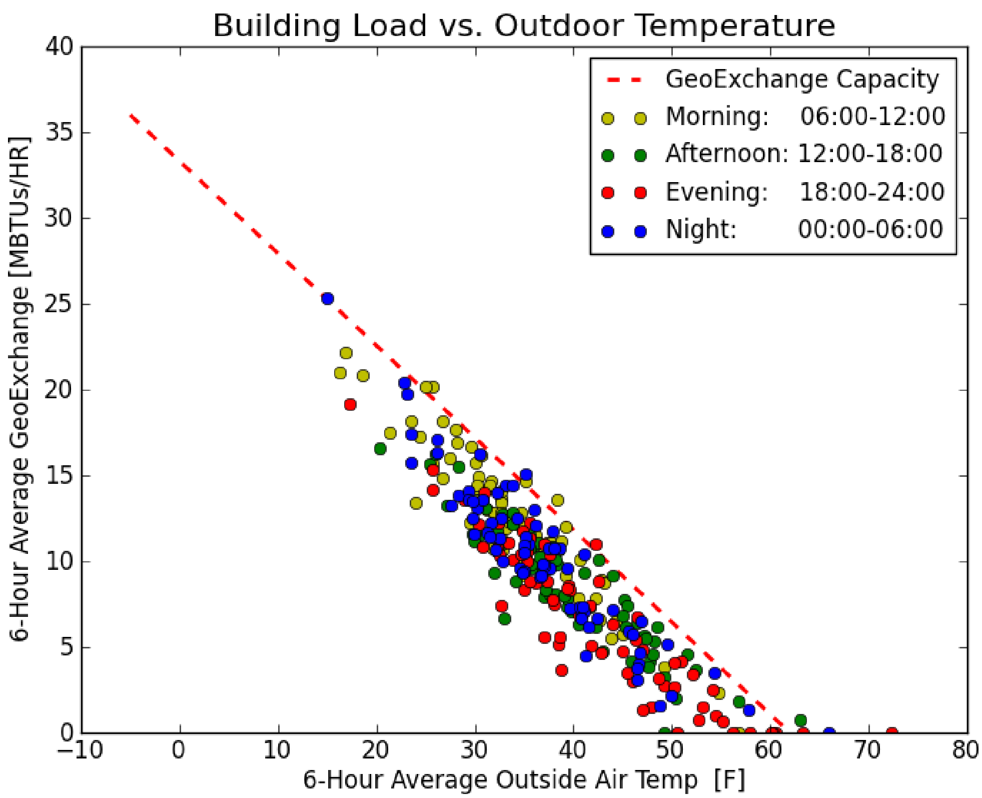

Figure 2: GeoExchange load profile of GSHP in heating mode. Data from a 4-ton residential system in southern NH and was collected between 2/13/13 and 04/01/13.

of outdoor air temperature (collected at 15-minute intervals from the nearest NWS weather station) to put the load data in the context of system design. Load Lines show the rate of ground energy extraction/rejection required to maintain the building at the heating/cooling set point temperatures given an outdoor air temperature. As a reference line, we show the installed GeoExchange Capacity. The GeoExchange Capacity is the straight line connecting the peak capacity point with the balance point. For heating, the peak capacity point is the equipment rated Heat of Extraction rate for low EWT (taken from manufacturer specifications) and the design heating temperature for the region (ASHRAE) . Connecting this peak capacity point to the balance point of 62 °F), we construct a reference GeoExchange Capacity load line. Load data is binned into sub-daily (6-hr) and daily values. The presentation here will focus on 6-hour averages as it helps to illustrate patterns in system use. The example above illustrates a system that is in balance with the outdoor conditions and is operating within its expected range under those conditions.

4 Case Studies

We present three case studies of how relatively basic real-time data can be synthesized into a comprehensive assessment of Ground Loop Performance. The examples presented here help to illustrate the relationship between usage over the 2012-2013 Winter with the corresponding loop performance, relative to the installed capacity.

4.1 Site A

Site A exhibits significant variability in building load as a function of outdoor air temperature. This is an excellent example of the usage pattern following the traditional approach of setting the thermostat down at night and up in the morning. While the usage pattern does not appear to be optimal from an equipment efficiency perspective, it may well reflect the personal preference of building occupants. As discussed in more detail below, the daily average building load is within the capacity of the heat pump equipment and does not appear to negatively impact the performance of the ground loop.

4.2 Site B

Site B exhibits a different load profile. For a given outdoor air temperature, there is a higher heating load during the evening and night time hours than during the day.

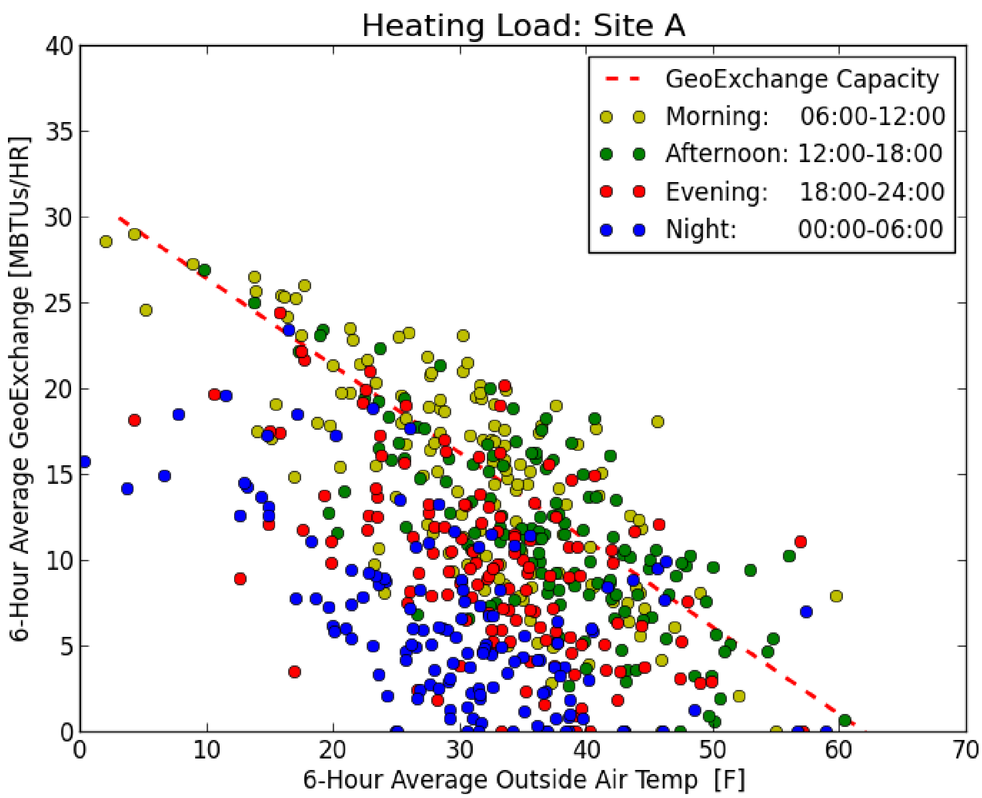

Figure 3: GeoExchange load profile of GSHP in heating mode. Data from a 4-ton residential system in southern NH and was collected between 11/01/12 and 04/01/13.

This could reflect a different pattern in building occupancy or a significant source of passive solar. The system is operating comfortably within designed capacity.

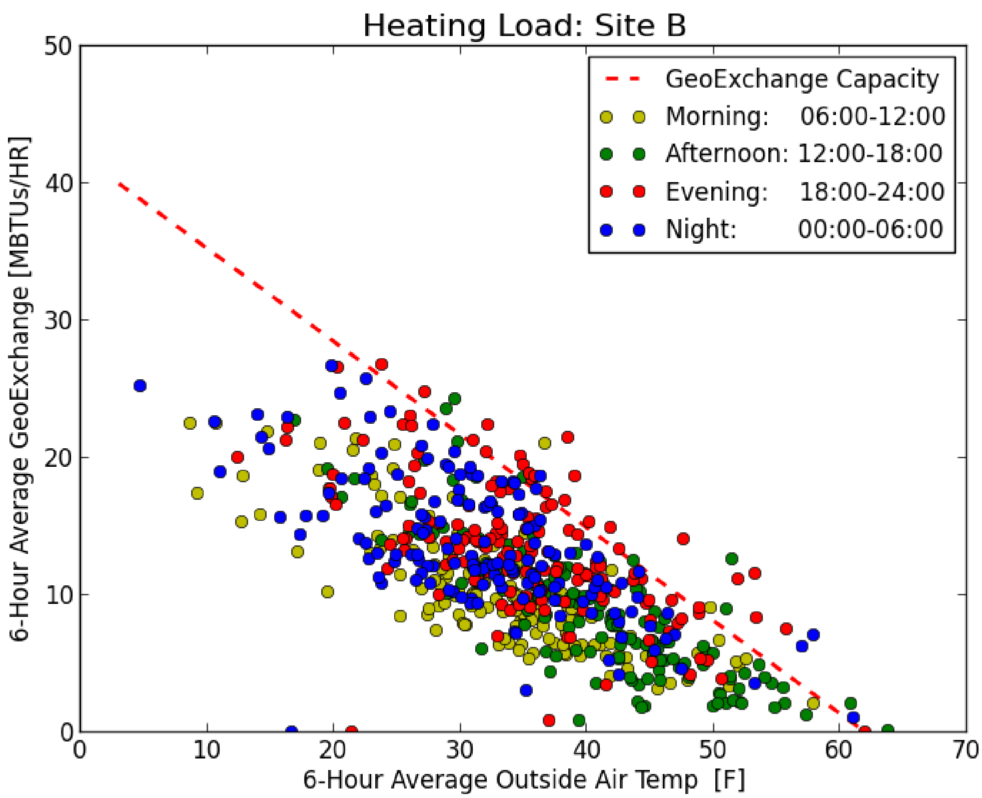

Figure 4: GeoExchange load profile of GSHP in heating mode. Data from a 6-ton residential system in central Connecticut and was collected between 11/01/12 and 04/01/13.

4.3 Site C

Site C exhibits a higher heating loads during that daytime hours. While the time-of-day load is similar to Site A, there is much less variability suggesting smaller swings in the thermostat settings. The more striking aspect of Site C is the GeoExchange load relative to the installed capacity. The system consists of two single-stage heat pumps with a combined nominal capacity of 8 tons. However for this 2300 SF new-construction residence, it appears the the actual load is much less than the installed capacity. We revisit each of these case studies below to look in more detail at how

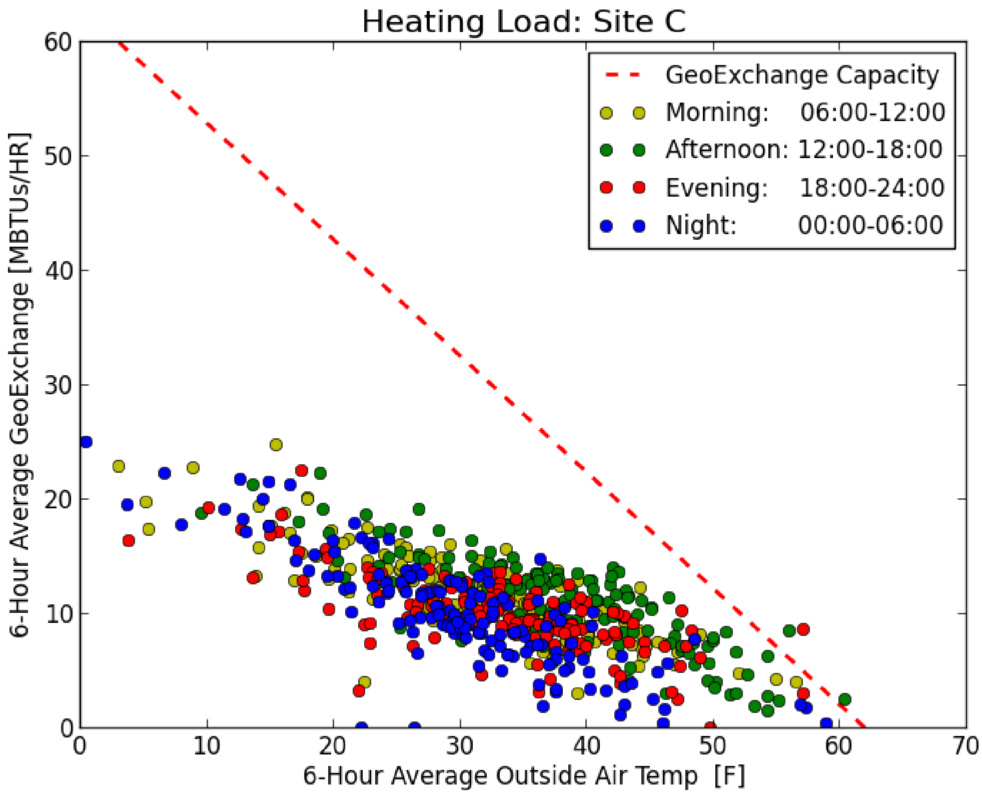

Figure 5: GeoExchange load profile of GSHP in heating mode. Data from a 8-ton residential system in southern New Hampshire and was collected between 11/01/12 and 04/01/13.

the building load relative to installed capacity affect ground loop performance.

5 Connecting Loop Temperature and Building Load Data

We see that we can collect temperature data as a screening tool for problems with the ground loop and when we combine that with flowrate, we can compute GeoExchange rate and assess patterns building load as a function of outdoor temperature and installed capacity. How then do we use this information to assess the ground loop performance?

The fundamental link between ground loop temperatures and building load is the flow of heat towards the loop in response to the thermal drawdown caused by heat extraction. The simplest expression of this heat flow process is the radial heat flow equation where the temperature is calculated at some effective well radius. In groundwater parlance, this is the Theis Solution. We have developed a simple screening tool using the line-source (or cylindrical-source) model and the principle of superposition to represent thermal drawdown due to time-varying heat extraction from a well. The model also works for single or multiple boreholes, provided there is no interference between the wells. There are more sophisticated models available and we do not advocate the use of this simple model for design purposes. However, because of its simplicity it can be used with minimal user input (thermal conductivity, heat capacity, effective well radius, and loop length). Based on our use of the model to date, we have found that the following parameters work well:

- Closed Loop Systems with 1" HDPE U-tube loops:
  - Effective well radius = 2/3 well bore radius
  - Effective thermal properties (conductivity and heat capacity) are ˜70% of the host rock properties
- Standing Column Well Systems w/ No Active Bleed:
  - Effective thermal conductivity is ˜120% of the host rock.

When bleed or significant groundwater flow is present, the model does not work well, as it is not accounting for important heat flow processes. Because the model only accounts for conductive (rather than advective) heat flow, it can also be used as a tool to identify when advective heat flow processes may be significant, as shown below.

In addition to providing a simple means to synthesize the heat production with thermal drawdown, we also expect the model will be a useful screening tool to assess how different loop technologies (e.g. double U-tubes, TWISTER, or the Gi4) affect thermal response.

We now revisit the case studies above to connect the measure building load with the measured ground loop temperatures.

6 Building Load in the Context of System Capacity

We present three examples of how relatively basic real-time data can be synthesized into a comprehensive assessment of Ground Loop Performance. The examples presented here help to illustrate the relationship between usage over the 2012-2013 Winter with the corresponding loop performance, relative to installed capacity.

6.1 Case Study A: System Capacity aligned with Building Load

As discussed above, this example illustrates a system that is arguably sized to meet the existing building load, and not much more. The system consists of a 4-ton heat pump and is served by a closed vertical loop. The building load data and ground loop temperature data show that the system is operating largely as expected. As noted above, the building load data suggests that the user is setting the thermostat back at night, resulting in a higher heat demand in the morning. While this behavior may affect overall system efficiency (longer runtimes at full load), the overall loop performance – as represented with the average daily loop temperature – does not appear to be adversely effected. Using the daily GeoExchange rates to in the model described above results in very close correspondence between observed and simulated values – suggesting that the loop is operating as designed and heat flow is dominated by conduction.

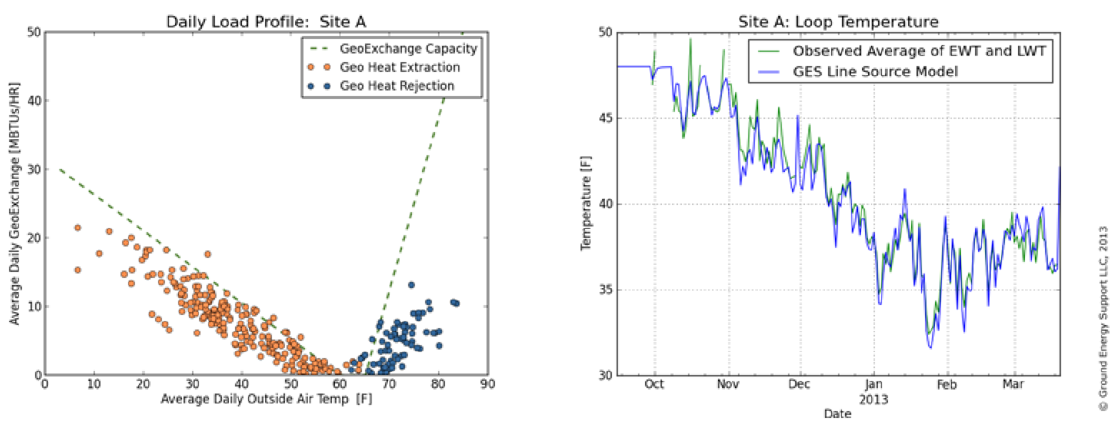

Figure 6: Daily GeoExchange load profile (left) and comparison of simulated and observed ground-loop temperature (right) for a 4-ton residential system in southern New Hampshire. Heat flow in ground loop appears to be dominated by conductive heat flow.

6.2 Case Study B: System Capacity slightly greater than Building Load

This example illustrates a system with an installed capacity that is slightly higher than the measured load profile. The system consists of 6 tons of installed capacity and a vertical closed loop consisting of 2 boreholes separated by 50 feet. The thermal drawdown through the Fall is consistent the hypothesis that heat flow is dominated by conduction. However, the observed minimum loop temperature and the asymmetric recovery response suggest that groundwater may play a contributing factor. One hypothesis is that an ambient groundwater flow helps to mitigate the minimum temperature in January but then slows recovery as the groundwater flowing past one cools the second well.

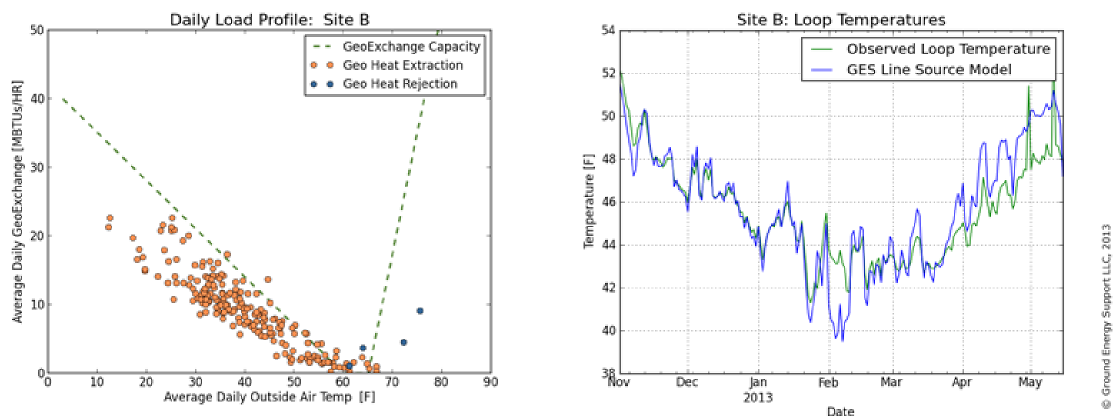

Figure 7: Daily GeoExchange load profile (left) and comparison of simulated and observed ground-loop temperature (right) for a 6-ton residential system in central Connecticut. Heat flow in ground loop appears to be dominated by conductive heat flow but the minimum loop temperature and recovery may be impacted by local groundwater flow.

6.3 Case Study C: System Capacity much greater than Building Load

Based on the data collected from Site C, it appears that the installed capacity of 8 tons is considerably more than the actual building load. However, because the ground loop is a standing column well, the well could be set up with a dead-band bleed system to accommodate the required flow rates. The benefit of the bleed is clearly illustrated in the difference between the modeled loop temperature (assuming no bleed) and the actual loop temperature with bleed.

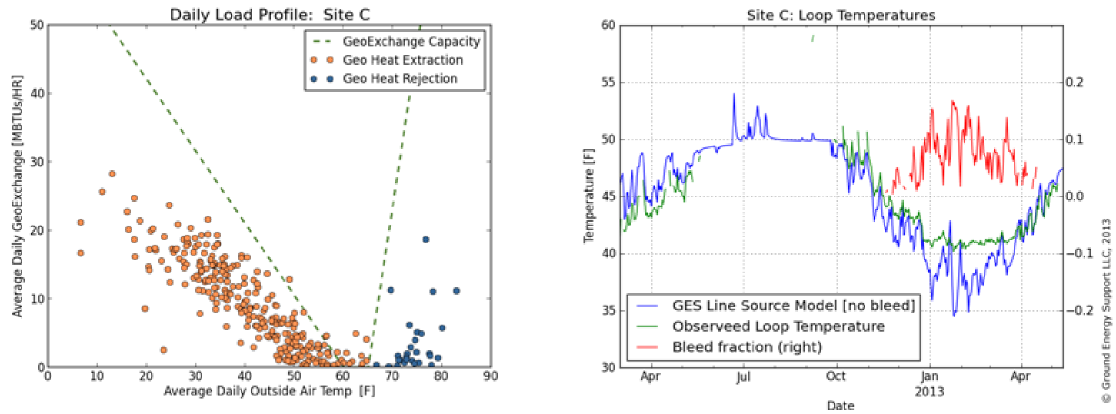

Figure 8: Daily GeoExchange load profile (left) and comparison of simulated and observed ground-loop temperature (right) for a 8-ton residential system in central Connecticut. Heat flow in ground loop appears to be dominated by conductive heat flow but the minimum loop temperature and recovery may be impacted by local groundwater flow.

The examples presented above illustrate a range in system designs and will likely spark some discussion about which design is 'best'. The building load data in Example 1 suggests that the homeowner may consider modifying their usage next winter to see if the system performance can be improved, but the thermostat settings may be out of personal preference rather than optimal efficiency. The use of open loop standing column wells is common in the Northeast and it is clear that a dead-band bleed is an effective approach for installing a high capacity system without requiring cost-prohibitive ground loops.

7 Address ISSUES before they become PROBLEMS

In this final example, we look at another open loop (standing column well) system where the usage (while arguably not optimal) is within the system's installed capacity. Here, the simulated loop temperature is one that would be expected for an open loop system (average daily water temperature 40 °F) and it is compared with the observed daily loop average temperature. One doesn't need a line source model to pick up on the problem that is emerging. If the minimum average loop temperature is expected to remain above 40 °F) and it is seen to get very close to that mark in mid-December, that's a pretty good sign that there is a problem. By looking at the building load analysis, it is clear that the system is being operated within its expected capacity. The problem was that the bleed valve had not been turned on.

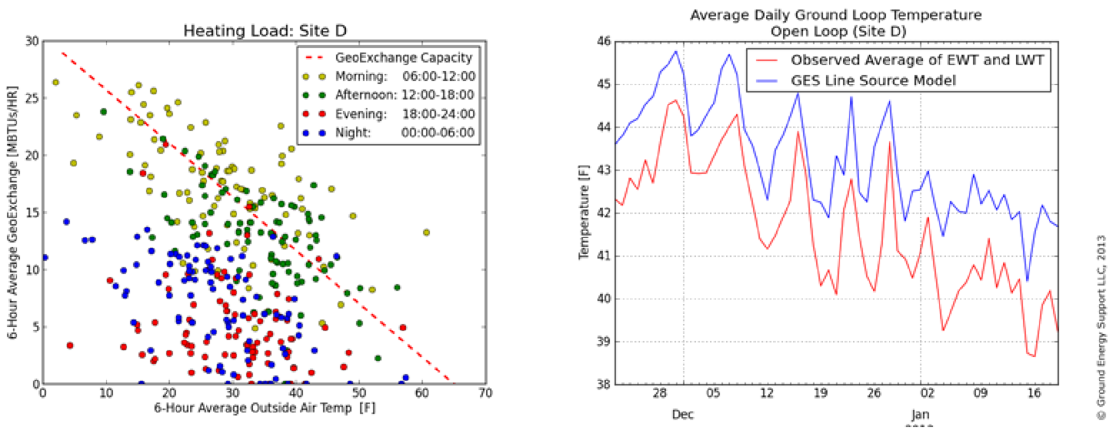

Figure 9: 6-hr average GeoExchange load profile (left) and comparison of simulated and observed ground-loop temperature (right) for a 6-ton residential system in central Connecticut. Simulated loop temperature reflects expected temperatures for open loop system with minimum loop temperature 40 °F. Observed loop temperatures are well simulated due to lack of bleed (as opposed to higher than expected heating load)

Using real-time monitoring, the homeowner was alerted to the low entering water temperatures in time to prevent any damage. The installer then made a routine service call and turned on the bleed. With the bleed system on, the system continued to operate without further incident.

8 Web-Based GSHP System Monitoring

There are several options for web-based ground loop monitoring on the market today, and more options will undoubtedly come onto the market in the future. The following discussion pertains to GES's monitoring system, the GxTracker. The GxTracker system is modular, with components added or subtracted based on the characteristics of your GSHP system, and what your monitoring objectives are. For reference, a basic GSHP monitoring system for up to two heat pumps that can produce the data shown above can cost less than $1,000.

The basic components of the GxTracker monitoring system include 1) sensors and optional meters that capture data about the temperatures and optionally, the flow and electrical consumption of your GSHP system; and 2) cloud-based data processing software presented in an easy-to-use online interface.

8.1 Data Capture

The GxTracker measures¡em¿ entering and leaving water temperature¡/em¿ with calibrated sensors attached to the the outside of the EWT and LWT pipes for each heat pump. The sensor design and installation instructions ensure a good thermal connection with the pipe. For example, the sensors must be attached to metal, and are equipped with special thermal pads to maximize the thermal connection. The system flow rate is either taken as constant (system design rate) or measured with a flowmeter(s). The heat pump on/off status is detected either with a current switch, current transducer, or flow meter (if installed). GSHP system ¡em¿kWh usage¡/em¿ is based either on heat pump design specifications coupled with heat pump runtimes OR is captured by installing an optional power meter(s). Power meters and associated benefits are discussed in next week's article. In addition, we pull outdoor air temperature from the nearest NWS weather station every 15-minutes.

8.2 Data Analysis and Presentation

At the web interface, GxTracker users can see a variety of useful system information, including system settings, real-time data, and system performance data analyses, and cost and carbon benefit analyses. Data downloads are available through a password-protected user account. The user can download minute resolution data for the previous three months. Daily system performance metrics (total BTUs, geoexhange from each heat pump, runtimes, minimum EWT, kWh, heating and cooling degree days, and hot water generated for systems equipped with the GxTracker Hot Water kit) are archived and available to the user indefinitely.

