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Ground Source Heat Pump Sub-Slab Heat Exchange Loop Performance in a Cold Climate

Nick Mittereder and Andrew Poerschke
IBACOS, Inc.

November 2013

Building America
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Ground Source Heat Pump Sub-Slab Heat Exchange Loop Performance in a Cold Climate

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Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

Golden, CO 80401

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Prepared by:

Nick Mittereder and Andrew Poerschke

IBACOS, Inc.

2214 Liberty Avenue

Pittsburgh, PA 15222

NREL Technical Monitor: Michael Gestwick

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Definitions

BEopt	Building Energy Optimization (software)
COP	Coefficient of performance
EWT	Entering water temperature
GSHP	Ground source heat pump
MBE	Mean bias error
TC	Thermocouple
TESS	Thermal Energy Systems Specialists, LLC

Acknowledgments

The authors thank Bill Rittelmann for the novel ground loop design and S & A Homes for the development and construction of the innovative test house associated with this project. The authors also thank the U.S. Department of Energy's Building America Program for funding this research. Additionally, thanks go to Jeff Thornton of Thermal Energy Systems Specialists, LLC for his TRNSYS modeling efforts associated with reviewing and updating the latest TRNSYS sub-slab analysis module.

Executive Summary

This report presents a cold-climate project that examines an alternative approach to ground source heat pump (GSHP) ground loop design. The innovative ground loop design is an attempt to reduce the installed cost of the ground loop heat exchange portion of the system by containing the entire ground loop within the excavated location beneath the basement slab. The horizontal sub-slab approach presented in this report will reduce installation costs by approximately $2,500/ton (Oberg 2010; Appendix A) compared to those of a conventional vertical bore well. For the 1.5-ton system installed in the cold-climate, 2,772-ft^2, two-story unoccupied test house in Pittsburgh, Pennsylvania (hereinafter referred to as the Pittsburgh Lab Home), a traditional vertical well system is expected to cost $17,800, compared to $14,000 for the horizontal sub-slab coils.

Prior to the installation and operation of the sub-slab heat exchanger in the Pittsburgh Lab Home, energy modeling using TRNSYS software (TRNSYS 2007) (in addition to traditional design efforts) was performed to determine the size and orientation of the system. Several design considerations were fundamental to the sub-slab GSHP design. Being a low-load home, the GSHP capacity is less than that for a typical house of the same size. Standard design of a GSHP allows for a margin of error for system undersizing, but with a low-load home, the margin of error is reduced. Additionally, a low-load home has longer shoulder seasons with reduced peak loads. The impact on the GSHP design is that heat is rejected and withdrawn from the ground in smaller, individual loads but over a longer time period than with a traditional GSHP. This design characteristic directly relates to the climate region where the house is located. A balanced climate region with a relatively equal number of heating and cooling degree days will have the effect of balancing the deep earth temperature and will help prevent overheating of the system.

This report analyzes the performance of the sub-slab heat exchanger for the approximate 1½-year monitoring period of October 2011 through February 2013.

Lower than anticipated soil heat transfer resulted in monitored leaving and entering water temperatures that exceeded the initial TRNSYS energy modeling predictions. Initial TRNSYS modeling predicted the maximum ground loop inlet temperature to be 29°C (84.2°F), whereas the measured maximum sustained inlet temperature was 45°C (113°F). During heating mode, the minimum measured inlet temperature was 1.3°C (34.4°F), and the minimum simulated inlet temperature was 1.72°C (35.1°F).

To investigate this discrepancy, an updated model was developed using a new TRNSYS subroutine for simulating sub-slab heat exchangers, Type 1267 (TRNSYS 2012). Appendix B discusses the updated results and model calibration with measured data. In this new model, the fluid piping, basement slab, and soil thermal interactions run as a single subroutine. Measurements of fluid temperature, soil temperature, and thermal energy transfer were used to validate the updated model. Most significantly, updated soil conductivity values were used in the new model, and the results closely corresponded to measured results.

Soil thermal conductivity plays a major role in the effectiveness of ground coupled heat exchangers, such as the sub-slab heat exchanger. The initial estimates for the soil thermal conductivity were slightly above the normal range and were based on observed installation

conditions. Based on this observation, the selection of soil thermal conductivity values for simulating a sub-slab heat exchanger should be closer to the drier end of the soil moisture range to allow for more realistic soil properties.

An engineering economic analysis was completed using the calibrated TRNSYS model to project energy use over a 30-year period and actual installed costs of the sub-slab GSHP versus a vertical well GSHP. The capital recovery indicates an annual $200 cost savings of a GSHP sub-slab ground loop heat exchanger.

Based on the measured data, the research team determined that the ground loop heat exchanger met the heating and cooling needs of the Pittsburgh Lab Home. The analysis indicates that a sub-slab GSHP is an effective strategy for capturing most of the advantages of a GSHP without the expense of drilling vertical wells adjacent to a low-load house in a suitable climate region. Because of the low margin for error in system design and the greater risk of an undersized system causing negative and compounding side effects, the sub-slab heat exchanger design requires more verification and stress testing before it will be ready for a production home environment.

1 Introduction and Background

1.1 Problem Statement

The rising cost of energy has become a significant portion of the household budget. Homeowners continually find it more and more expensive to heat and air condition their homes to achieve year-round comfort. Ground source heat pumps offer a safe and environmentally less impactful alternative to conventional heating and air-conditioning systems. Although GSHPs frequently offer efficient space conditioning performance, the added labor and material costs for installing ground heat exchange loops make these systems less competitive in a price-sensitive market (Goetzler et al. 2009). An alternative design, presented in this report, uses the soil under the slab as a thermal transfer medium to reduce installation costs while maintaining acceptable system performance.

A GSHP system was installed in the Pittsburgh Lab Home—a cold-climate, 2,772-ft^2, two-story unoccupied test house located in the Cobblestone community of Pittsburgh, Pennsylvania. The Pittsburgh Lab Home is considered a low-load home with a design peak load of 5.84 Btu/h-ft^2 and 3.546 Btu/h-ft^2 for heating and cooling, respectively (Stecher et al. 2013). This research investigated the viability of a potential solution that reduces system installation costs by placing the ground heat exchange loop in a horizontal plane within the excavated region beneath the conditioned basement slab. From March 2011 through February 2013, performance test data were collected for a GSHP system having a horizontal ground heat exchange loop. The design of this GSHP system was based on TRNSYS Version 16.01 modeling efforts from 2009 (Oberg and Bolibruck 2009; Appendix C). Figure 1 shows the Pittsburgh Lab Home, and Figure 2 shows the climate zone in which the Pittsburgh Lab Home is located.

Figure 1. The cold-climate Pittsburgh Lab Home

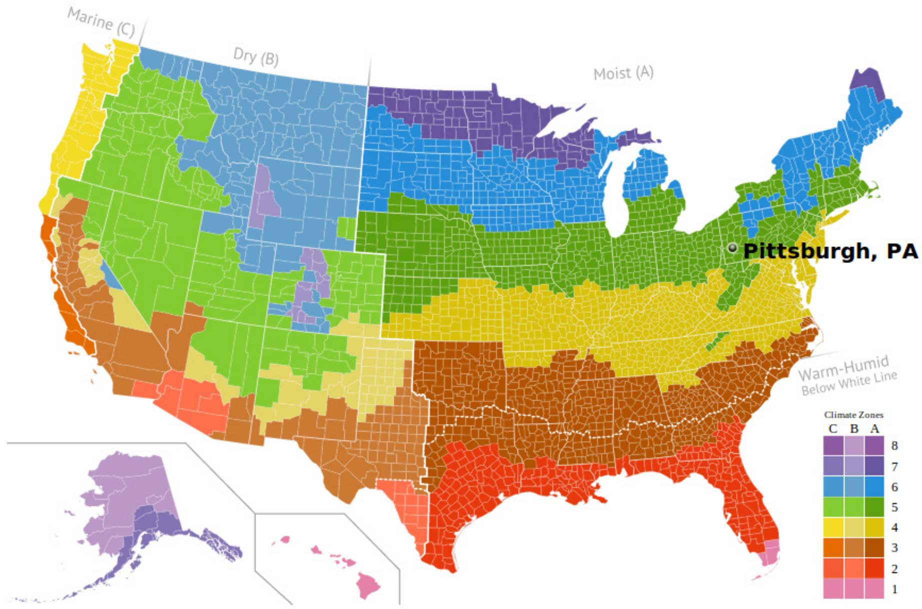

Figure 2. Building America climate map, showing the location of the Pittsburgh Lab Home

1.2 Project Objective

This research focused on the performance aspects related to the ground heat exchange loop installed beneath the basement slab of the Pittsburgh Lab Home. Based on cost data taken from earlier research projects conducted by IBACOS, the installed cost of the sub-slab loop was $2,500/ton less than that of the vertical wells (Oberg 2010; Appendix A). The IBACOS team based the design of the ground heat exchange loop on initial TRNSYS modeling.

The objective of this research project was to answer the following question: Is there a viable, lower cost, lower impact alternative to drilling vertical wells?

This research project helps meet important Building America goals by means of the following:

- The evaluation of the performance of this potentially cost-effective system through actual field test data
- Eventual development of a robust system design model, calibrated to test data and applicable to other homes in climate zones suitable for GSHP installations.

This report discusses the results from the summer of 2011 through the fall of 2012, along with the correlation of the TRNSYS model to measured results. Analysis of the differences between the modeled predictions and the actual measured results also is discussed.

1.3 Ground Loop Description

Figure 3 shows the installation of the two-pass overlapping horizontal piping loop for the GSHP at the Pittsburgh Lab Home. The entire slab area was excavated to the bottom of the wall footers, thereby allowing sufficient space for the piping loop, extra limestone fill, and R-10 insulation installed directly beneath the basement slab. Each pass of the piping loop consisted of approximately 200 ft of ¾-in. high density polyethylene pipe, arranged in an overlapping serpentine pattern, for a total nominal pipe length of 400 ft. This facilitated a lateral spacing of 1.0 ft between adjacent sections of pipe. The loop was anchored to heavy-gauge 6 × 6 flat-panel wire mesh with zip ties to keep it flat against the soil. Crushed limestone was chosen as the fill material because it provides a good balance between cost and material properties. The limestone was compacted in two layers to achieve maximum density and contact with pipes.

Figure 3. GSHP sub-slab ground heat exchange loop composed of ¾-in. high density polyethylene piping

2 Experimental Approach

2.1 System Operation

The subject sub-slab ground heat exchange loop was operational within the GSHP system of the Pittsburgh Lab Home from March 2011 to February 2013. Table 1 summarizes the parameters of the installed GSHP. Starting in June 2011 and continuing throughout 2012, the research team simulated internal sensible and latent heat gains from human occupancy according to the Building America Benchmark Definition 2009 schedule used for computer simulation models (Hendron 2008). Simulation was implemented with one heater and humidifier on the main floor and one heater and two humidifiers in each of three of the four bedrooms. The team simulated the different loads by intermittently varying the time of operation for the fixed output heaters and humidifiers.

Table 1. GSHP Parameters

Model	Carrier 50PTV-026-K-Y-E-30112
Capacity	2 tons
Operational Range	20°–120°F
Cooling Energy Efficiency Ratio (77°F)	19.9
Heating COP* (32°F)	4.0
Water Flow Rate	900–950 gpm
Heating Mode	Three-stage with electric backup (backup disconnected)
Cooling Mode	Two-stage
Refrigerant	R-410a

* Coefficient of performance

To accommodate concurrent operation in the home for short-term testing of the GSHP desuperheater (Mittereder and Poerschke 2013), a supplemental 2-ton air-conditioning unit was used to simulate winter conditions during the beginning of July 2012. Further desuperheater short-term testing occurred from the middle of August 2012 to the first week in September 2012. These short-term tests had a noticeable impact on the data for this research project and will be further discussed later in this report.

The predicted ground temperatures and heat transfer rates were determined by a horizontal sub-slab ground loop heat exchanger configuration using a TRNSYS Version 16.01 "Type" model developed by Thermal Energy Systems Specialists, LLC (TESS) specifically for this project (Oberg and Bolibruck 2009; Appendix C).

Key modeling simulation parameters for the initial sub-slab heat exchange simulation are as follows:

- Simulation length = 17,520 h
- Time step = 1/10 h
- Deep earth (average surface) temperature = 10.40°C (50.7°F)
- Thermal conductivity of soil layer = 9.9 kJ/h·m·K (1.589 Btu/h·ft·°F)

- Density of soil layer = 2,080 kg/m³ (129.8 lb/ft³)
- Specific heat of soil layer = 0.84 kJ/kg·K (0.2007 Btu/lb·°F)
- Fluid through pipes thermal conductivity = 1.65168 kJ/h·m·K (0.2651 Btu/h·ft·°F)
- Fluid through pipes density = 1,000 kg/m³ (62.4 lb/ft³)
- Fluid through pipes specific heat = 4.19 kJ/kg·K (1.001 Btu/lb·°F)
- Fluid through pipes viscosity = 3.2 kg/m·h (2.150 lb/ft·h)
- Pipe inside diameter = 0.0204 m (0.8031 in.)
- Pipe outside diameter = 0.025 m (0.9843 in.)
- Pipe thermal conductivity = 1.401895 kJ/h·m·K (0.2250 Btu/h·ft·°F).

2.2 Measured Parameters

Table 2 summarizes the relevant parameters for quantifying ground loop performance, along with their associated instrumentation types. The research team used the field data collected for these parameters to analyze the degree of relative loop-ground and loop-basement engagements. Figure 4 through Figure 9 illustrate instrumentation locations and typical installation examples.

Table 2. Data Logging Equipment

Measured Parameter	Equipment	Quantity	Accuracy
Outdoor Ambient Temperature	Type-T TC*	1	± 1°C or 0.75%
Ground Loop Working Fluid Temperature	Type-T TC, Pipe-Mount Probe	2	± 1°C or 0.75%
Basement Floor Surface Temperature	Type-T TC	16	± 1°C or 0.75%
Soil Temperatures:			
Directly Below the Slab Insulation	Type-T TC	12	± 1°C or 0.75%
At the Surface of Undisturbed Soil	Type-T TC	12	± 1°C or 0.75%
24 In. Below Undisturbed Soil	Type-T TC	10	± 1°C or 0.75%
Basement Floor Heat Flux	Hukseflux HFP01	3	± 5.0%
Soil Moisture Content	Water Content Reflectometer	4	± 2.5%
Ground Loop Flow Volume	High Resolution Flow Meter (75.7 pulse/gal)	1	± 1.5%
GSHP Electricity Consumption	CCS WattNode	5	± 0.5%
Data Acquisition System	Campbell Scientific CR1000	3	

* Thermocouple

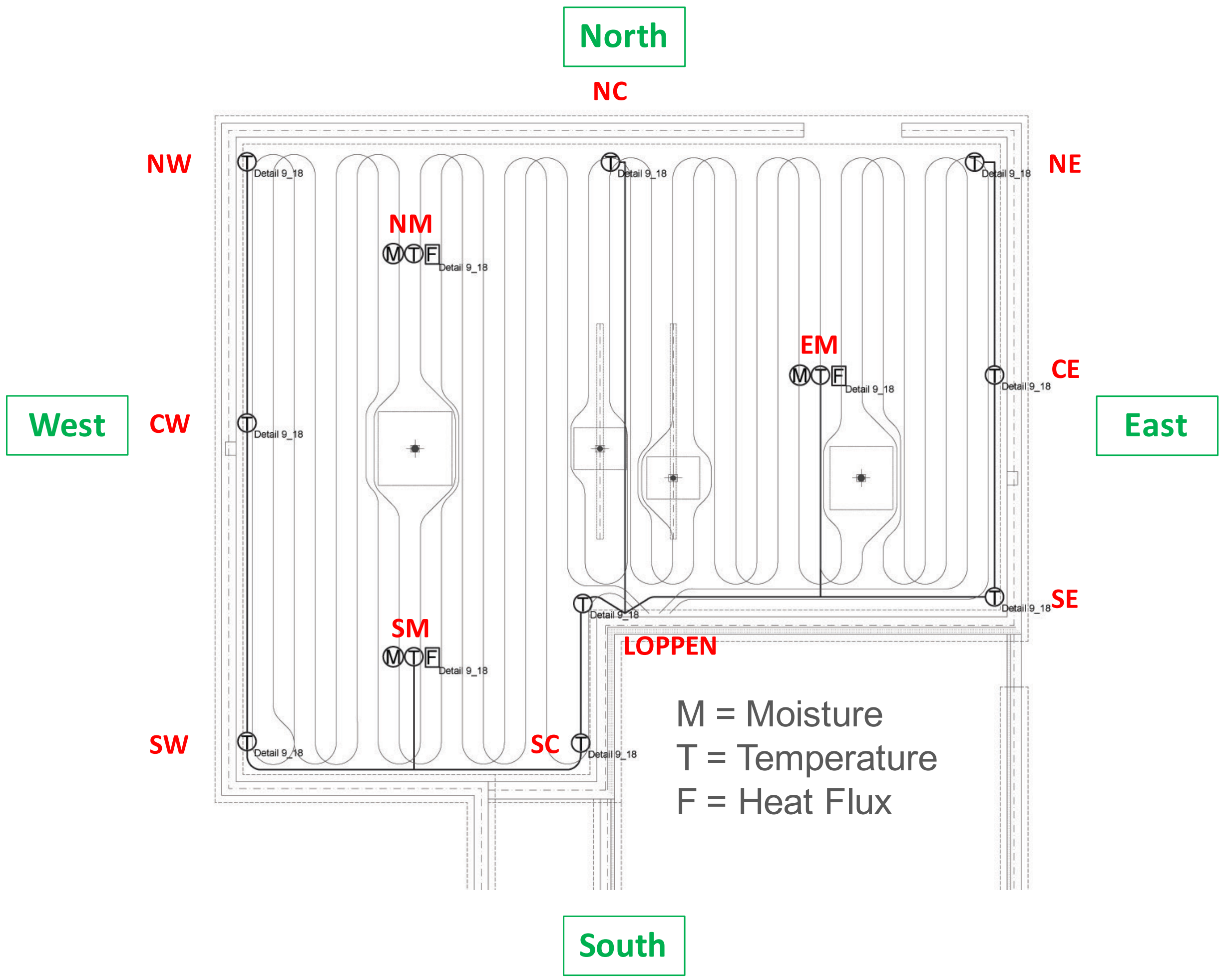

Figure 4. Plan view showing the type, location, and name of sub-slab loop instrumentation devices

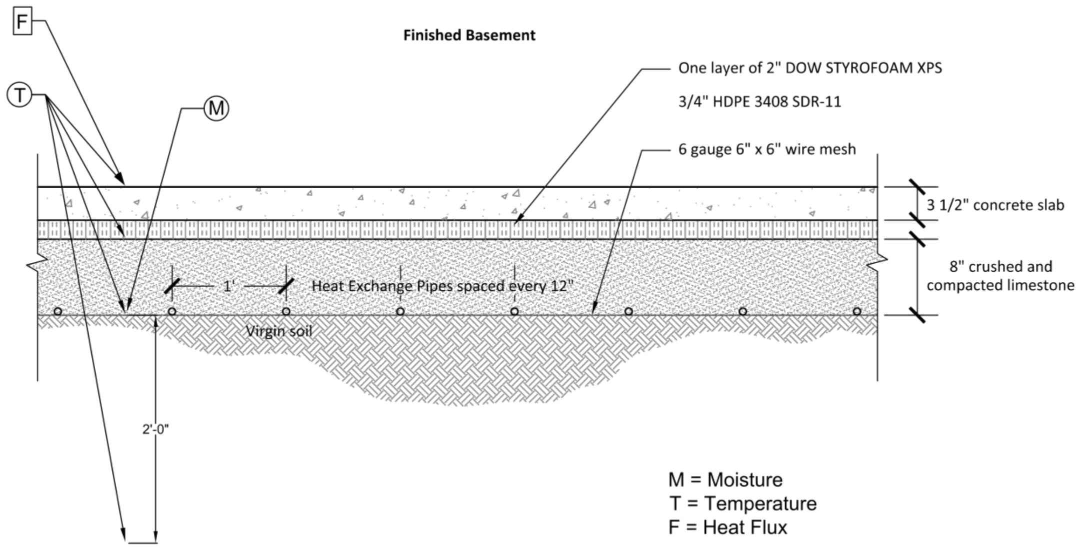

Figure 5. Section view showing the type and location of sub-slab loop instrumentation devices

Figure 6. Typical soil TC installation

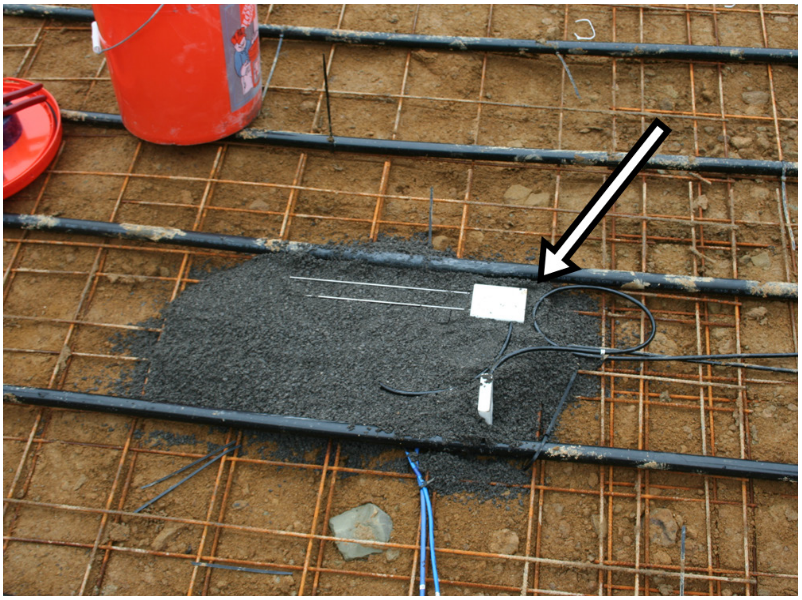

Figure 7. Typical soil moisture sensor installation

Figure 8. Typical TC installation for measuring soil temperature directly below the slab insulation

Figure 9. Typical installation of basement floor TC and heat flux sensor

3 Measured Results

The research team used LoggerNet 4.1 software (LoggerNet 2012) to record field data documented in this report. In general, daily average data were used to help characterize the performance of the ground heat exchange loop, and all figures in Section 3 display daily average quantities. The team also computed averaged quantities at a constant elevation, where applicable.

3.1 Basement Floor Temperatures

Figure 10 illustrates the daily average basement floor temperature distribution versus time over the sampling period from May 1, 2011 through October 23, 2012. Each curve plotted pertains to an individual TC whose floor location and name are indicated in Figure 4.

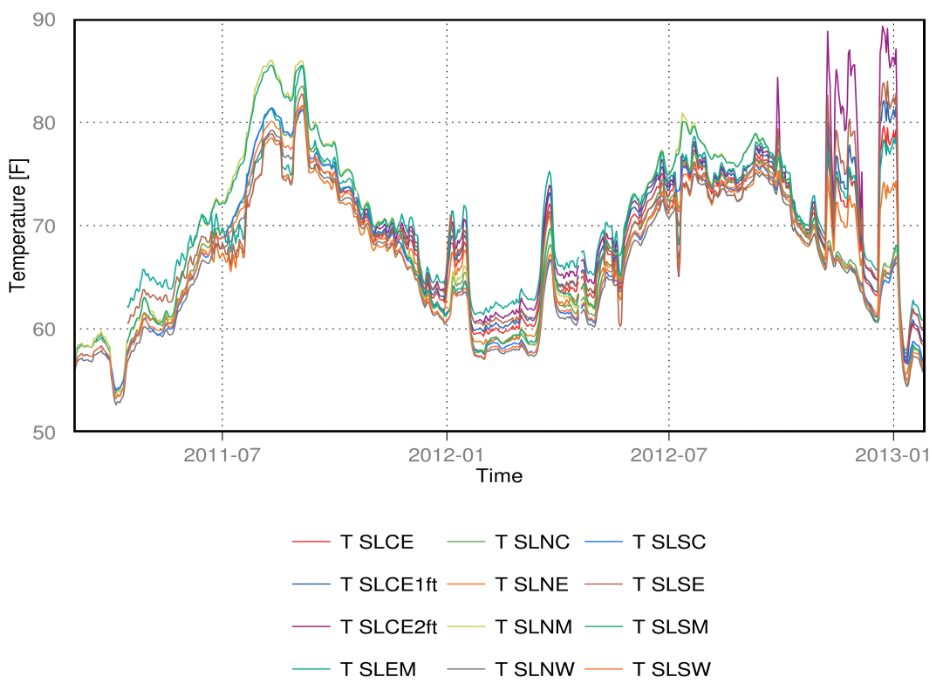

Figure 10. Basement floor temperatures

Figure 10 shows that, during the 2011 peak summer cooling season (May 1, 2011 to September 30, 2011), measured basement floor temperatures climbed within the range of 81.1°F to 86.2°F. With a summer thermostat set point temperature of 76°F, this trend tends to indicate that some additional heat load was being imposed on the house by the basement floor from July through October 2011.

3.2 Soil Temperatures

Figure 11 through Figure 13 illustrate the daily average soil temperature distributions at three different elevations beneath the basement slab over the monitoring period.

- Figure 11 pertains to temperatures taken at the elevation directly below the R-10 slab insulation layer.

- Figure 12 pertains to temperatures taken at the surface of the undisturbed soil, 8 in. below the slab insulation, and at the actual ground loop depth.
- Figure 13 pertains to temperatures taken at an elevation 24 in. below ground loop depth.

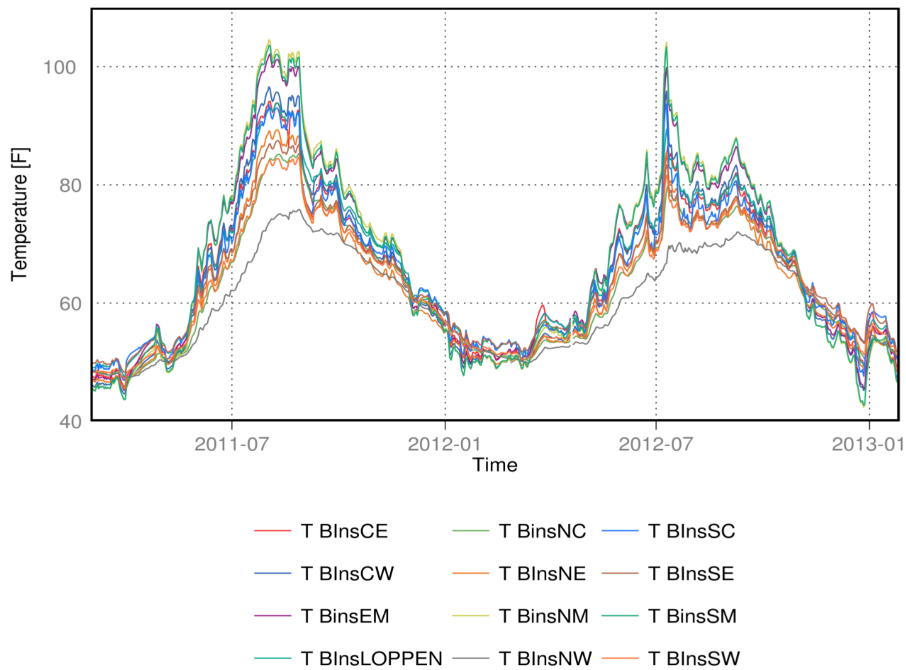

Figure 11. Soil temperatures measured directly below the slab insulation

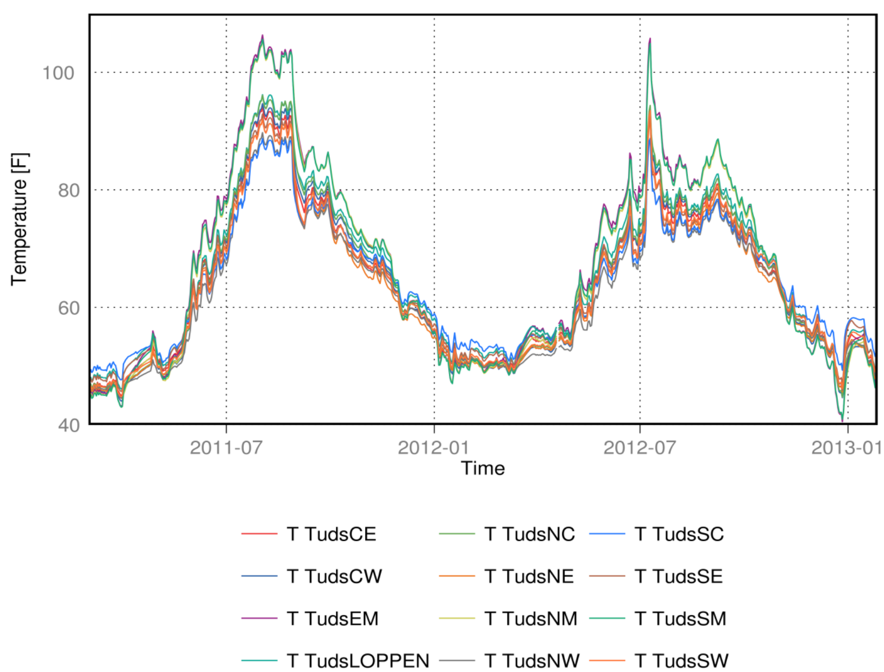

Figure 12. Soil temperatures measured at the ground loop depth

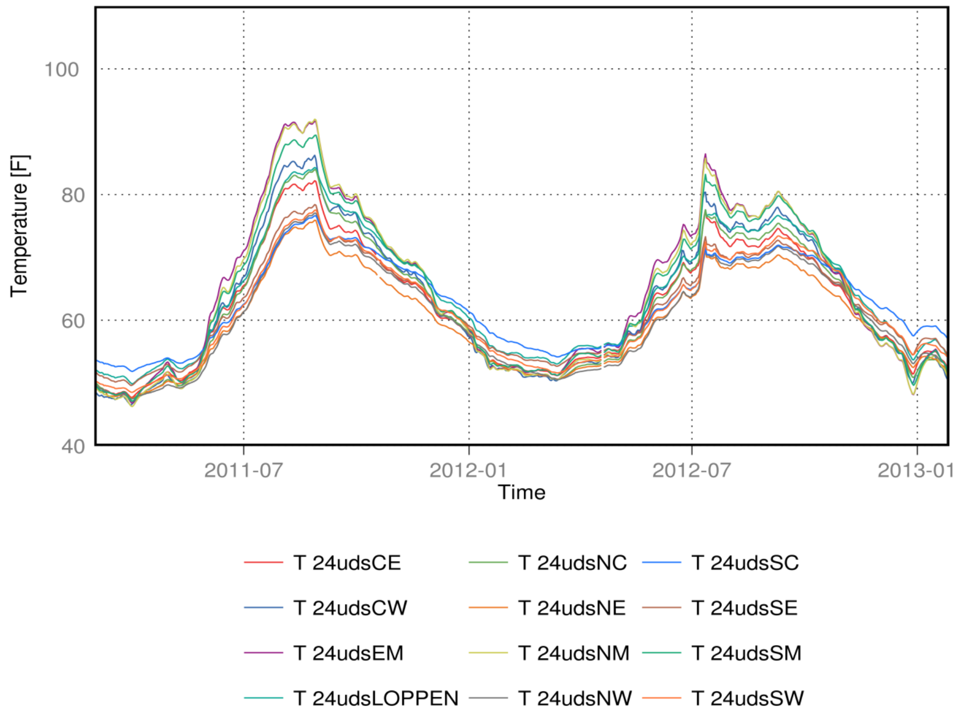

Figure 13. Soil temperatures measured 24 in. below the ground loop depth

Per Figure 11 through Figure 13, the following trends can be seen:

- As expected, soil temperatures are highest at the ground loop depth, as shown in Figure 12, particularly during the summer peak cooling seasons.
- Soil temperatures directly below the slab and at the ground loop depth exhibit more oscillatory behavior over time than those 24 in. below the ground loop, where thermal gradients through the soil have become more attenuated.
- The GSHP fan module failed during the last few days of August 2011, but it was repaired and returned to operation on September 9, 2011. The sudden decline in ground temperatures can be seen during this period.
- To accommodate concurrent operation in the home for short-term testing of the GSHP desuperheater (Mittereder and Poerschke 2013), the research team used a supplemental 2-ton air-conditioning unit to simulate winter conditions. This is apparent in the drop in ground temperatures during the first to second weeks in July 2012. Without this additional unmetered cooling, the 2012 summer temperature profile would most likely have appeared similar to the 2011 summer temperature profile.
- Further desuperheater short-term testing occurred from mid-August 2012 to the first week in September 2012. This testing consisted of three tests (each test lasted 1 week) that used the desuperheater and included domestic hot water draws. This diverted a portion of the compressor's rejected heat to the domestic hot water system in lieu of the

heat going to the ground loop. This is apparent in the change in soil temperatures that occurred in mid-August 2012.

3.3 Soil Moisture Content

Figure 14 illustrates the daily average soil moisture content distribution over the sampling period. The first three water content reflectometers shown in Figure 14 were located at the ground loop depth; the fourth sensor, measuring 23%, was located 2.0 ft below the East–Middle device.

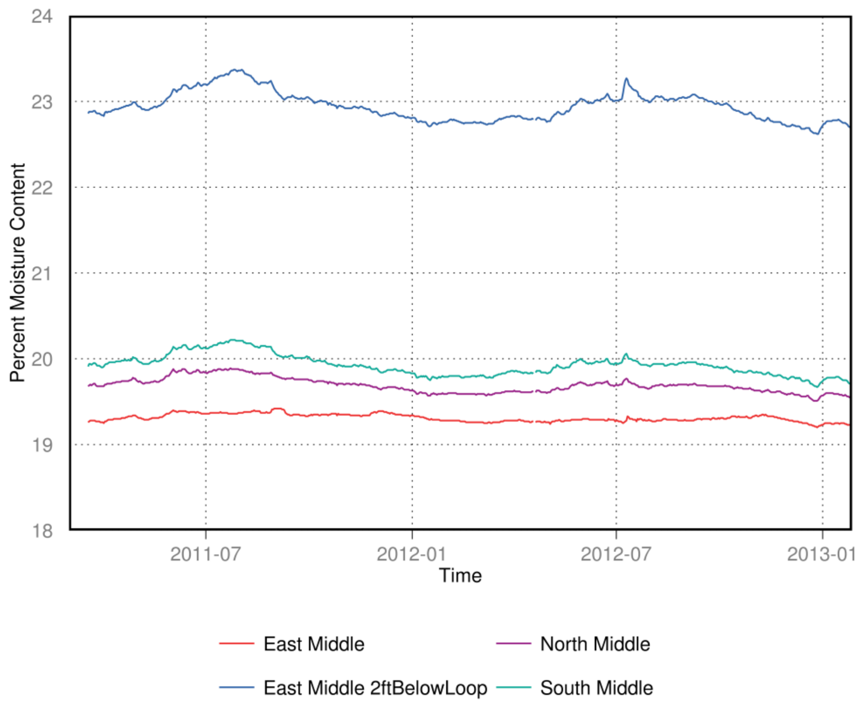

Figure 14. Soil moisture content

Per these data, the soil moisture content remained relatively constant throughout the sampling period, indicating little potential variability in the thermal transport properties of the soil during the calendar year. The low and constant moisture levels are the result of a well-installed French drain around the structural footing. In a typical horizontal ground loop installed in an open field, moisture levels would have been much greater. This has a significant impact on the heat transfer rates and associated ground temperatures.

3.4 Soil Thermal Conductivity

The *2005 ASHRAE Handbook—Fundamentals* describes the effect of moisture on soil thermal conductivity as follows (ASHRAE 2005, p. 25.13):

> Effective or apparent soil thermal conductivity (*k*) is difficult to estimate precisely and may change substantially in the same soil at different times due to changed moisture conditions and the presence of freezing temperatures in the soil… Although thermal conductivity varies greatly over the complete range of possible

> moisture contents for a soil, this range can be narrowed if it is assumed that the moisture contents of most field soils lie between the "wilting point" of the soil (i.e., the moisture content of a soil below which a plant cannot alleviate its wilting symptoms) and the "field capacity" of the soil (i.e., the moisture content of a soil that has been thoroughly wetted and then drained until the drainage rate has become negligibly small)… As heat flows through the soil, the moisture tends to move away from the source of heat. The moisture migration provides initial mass transport of heat, but it also dries the soil adjacent to the heat source, hence lowering the apparent thermal conductivity in that zone of the soil.

The *2005 ASHRAE Handbook—Fundamentals* further states (ASHRAE 2005, pp. 25.13–25.14):

> Trends typical in a soil when other factors are held constant are:
>
> - *k* increases with moisture content
> - *k* increases with increasing dry density of the soil
> - *k* decreases with increased organic content of the soil
> - *k* tends to decrease for soils with uniform gradations and rounded soil grains (because the grain to grain contacts are reduced)
> - *k* of frozen soil may be higher or lower than that of the same unfrozen soil (because the conductivity of ice is higher than that of water but lower than that of the typical soil grains). Differences in k below moisture contents of 7 to 8% are quite small. At approximately 15% moisture content, differences in the *k*-factors may vary up to 30% from unfrozen values.

The thermal conductivity that was estimated during the design phase of the sub-slab heat exchanger was 9.9 kJ/h·m·K or 2.75 W/(m·K). This value is slightly above the normal range of values indicated in the *2005 ASHRAE Handbook—Fundamentals,* Chapter 25, Table 5 (ASHRAE 2005, p. 25.14), which has a normal range of common soils of 0.6 to 2.5 W/(m·K).

During the monitoring period, the soil temperature did not approach the freeze point. Thus, the soil conductivity was not influenced by freezing conditions. During the construction period after the installation of the sub-slab heat exchanger and French drain system but before the monitoring period, it is possible that the soil dried out, causing the soil thermal conductivity to decrease. In effect, a moisture shadow exists under the house foundation and French drain.

3.5 Basement Floor Heat Flux

Figure 15 illustrates the daily average basement floor heat flux distribution over the sampling period. For these curves, positive values indicate heat flow from the house into the slab; negative values indicate heat flow from the slab into the house. All three heat flux transducers were affixed to the surface of the basement floor using thermally conductive grease to minimize the thermal contact resistance at the interface.

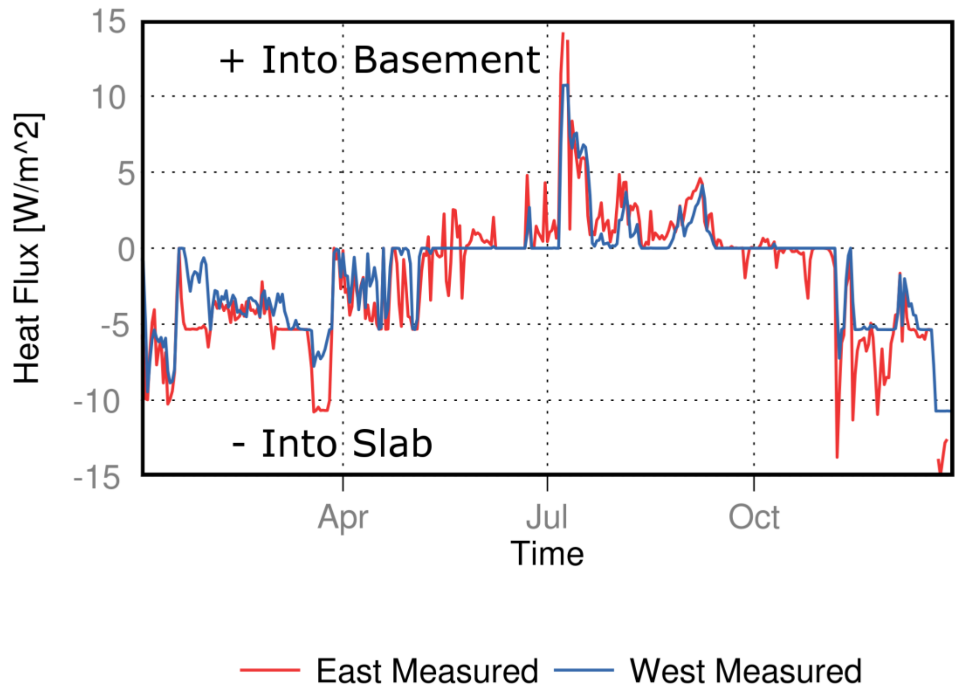

Figure 15. Measured basement floor heat flux

Per Figure 15, the following trends can be seen:

- For most of the summer sampling periods (i.e., for any day having a non-zero daily average heat flux), some net thermal exchange occurred between the slab and the house, thereby contributing additional load on the GSHP system.
- During the heating seasons, a net heat flow occurred from the house into the slab.
- During the swing season months, the basement floor heat flux was very low, indicating negligible thermal exchange between the slab and the house.

Initial TRNSYS modeling results for the heat transfer rates of the basement predicted that the heat transfer direction would always be from the basement into the ground and that the basement slab temperature would never be greater than the zone air temperature. These results differ from the measured data and the final TRNSYS model used for validation due to the change in thermal conductivity for the soil.

TRNSYS modeling predicted a summertime slab peak temperature of approximately 22.7°C (73°F), indicating that heat transfer upward through the slab was not anticipated because the peak temperature was lower than the cooling indoor set point of 24.4°C (76°F). Figure 16 shows the measured results for the basement slab temperatures. The peak slab temperature was higher than 25°C (77°F) for a 1-week period during the summer; however, this was only for a portion of the slab. Once the outdoor temperature extremes relaxed, the excess heat in the slab quickly dissipated. The higher-than-expected slab temperatures during the end of 2012 are an artifact of the position of the unfinished basement supply air duct. This duct was blowing directly onto the slab surface, giving an apparent rise to the measured temperature.

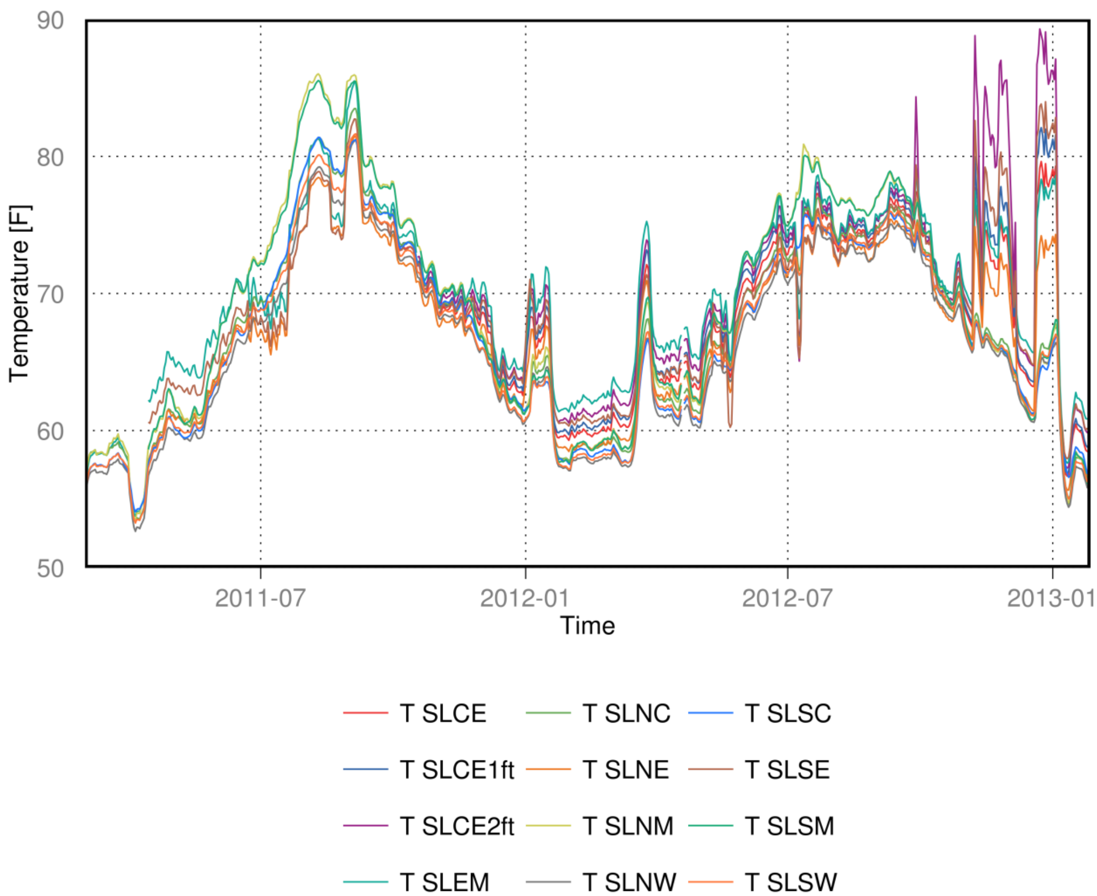

Figure 16. Measured results for basement slab temperatures

3.6 Ground Loop Working Fluid Temperatures

Figure 17 illustrates the daily average temperatures for the outdoor ambient, ground loop fluid, and elevation-averaged soil over the sampling period. Entering water temperature (EWT) and leaving water temperature were averaged only for values occurring during the system run. Because of an undetected malfunctioning pipe-mounted TC probe, successful recording of ground loop fluid temperatures did not begin until August 2011.

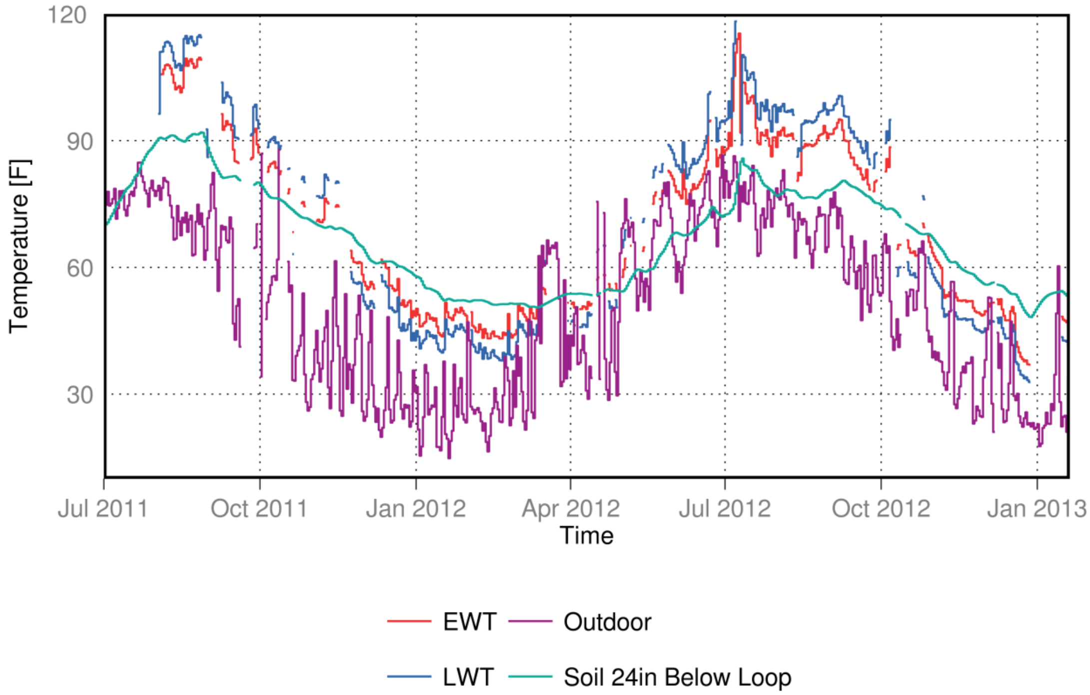

Figure 17. Daily average outdoor ambient, ground loop fluid, and soil temperatures

Figure 17 shows the following trends:

- The largest loop-soil temperature difference occurred during the peak summer cooling seasons.
- A rapid drop in loop fluid temperature occurred in late August 2011 during a short GSHP shutdown period and then again in mid-July 2012 as a result of desuperheater testing. This rapid decay of soil temperatures indicates that short breaks in outdoor ambient temperature extremes can effectively prevent overheating below the slab.
- Throughout nearly all of September through December 2011, the loop inlet temperatures continued to remain higher than the loop outlet temperatures, indicating the GSHP was operating in the cooling mode. This further indicated continued heat flow into the ground because the outdoor ambient temperatures fell only modestly during the 2011 autumn season.
- Because of the unusually mild winter season, there were several occasions where space cooling was taking place in the home as a result of high thermal insulation and consistent simulated internal loads.

Figure 18 is a composite of measured and simulated fluid temperatures. The significant temperature increase in the horizontal loop during July is attributed to the performance of the heat exchanger and not an abnormally warm summer as indicated by the average July outdoor air temperature relative to Typical Meteorological Year 3 data.

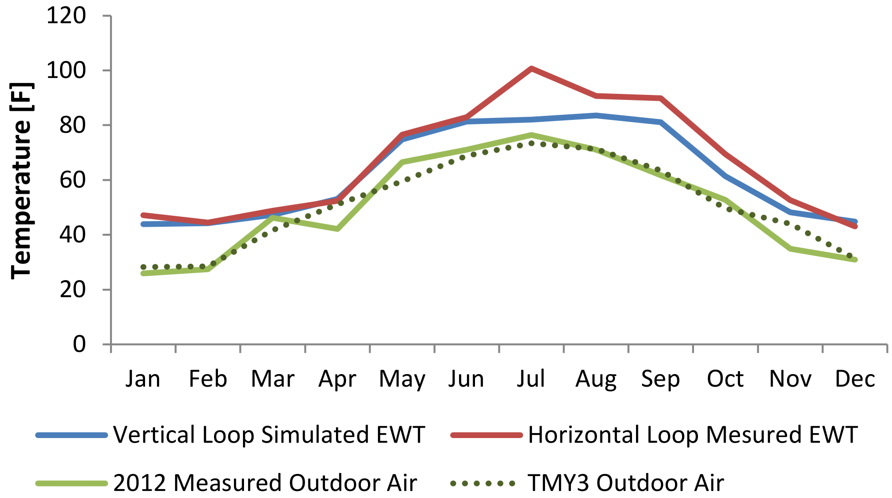

Figure 18. TRNSYS results for ground loop temperatures

Decreased heat pump COP due to less advantageous EWT is a concern with the sub-slab heat exchanger. Table 3 summarizes the COP for a TRNSYS simulated vertical well system and measured data from the sub-slab heat exchanger. COP values are determined from the average EWT during system operation and expected heat pump performance trends from manufacturer-supplied catalog data. Figure 19 indicates the average COP for average monthly EWTs.

Table 3. Summary of COP Values

	Heating	Cooling
Vertical Loop COP (Simulated)	4.58	5.16
Horizontal (Sub-Slab) COP (Measured)	4.11	4.41
Percent Change	–11%	–17%

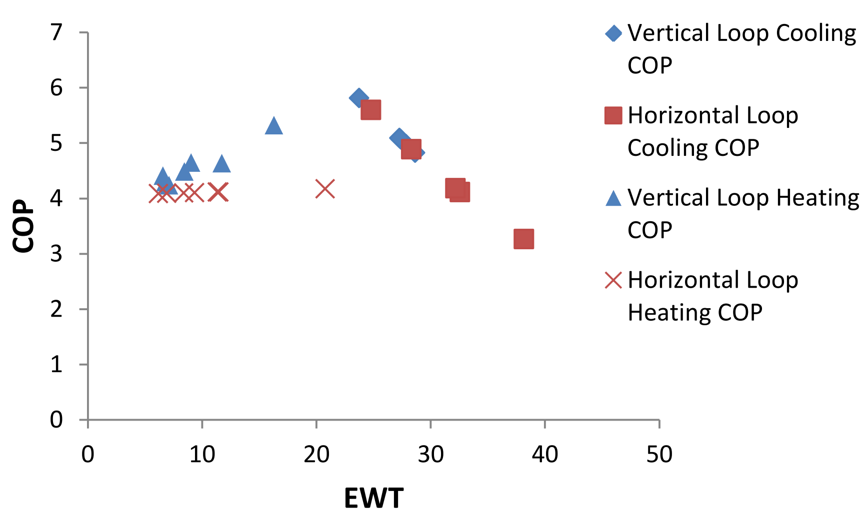

Figure 19. Heat pump COP versus EWT

Continuous operation of the desuperheater, with regular hot water draws, could reduce the necessary heat rejection to the ground, lowering the horizontal loop summer temperatures. Although this could possibly improve the cooling COP, occupant behavior can vary widely, making this an unreliable design strategy.

4 Economic Analysis

To confirm the net economic gain of using a sub-slab heat exchanger, the research team conducted a simple 30-year economic analysis. The team used BEopt+ 1.4 (BEopt) to predict the cost of a vertical well heat exchanger for a 1.5-ton system in the Pittsburgh Lab Home. The team then subtracted the assumption of $2,500/ton savings from this value to determine the equivalent cost of a sub-slab heat exchanger installation (Oberg 2010; Appendix A). The capital recovery factor predicts the annual payment on a 30-year mortgage (Masters 2004).[1]

Finally, the research team calculated the annual electricity cost by using measured monthly electricity consumption and then reducing this amount by the ratio of COPs for the sub-slab heat exchanger to the vertical well heat exchanger as predicted by TRNSYS. Based on simulated and measured monthly average EWTs, the team used catalog performance data to estimate the COP, calculated an annual cost of the loan plus energy, and then compared that cost to the cost of the standard vertical well system.

Table 4 summarizes the results of the economic analysis, which indicate that, compared to the standard vertical well system, the sub-slab heat exchanger is $200/year less expensive to operate. Additionally, the team determined that the annual fuel escalation rate would have to be greater than 10% for the increased costs of electricity consumption to negate the reduced installation cost.

Table 4. Cost Analysis of Vertical Versus Sub-Slab Heat Exchange Loops

	Vertical Heat Exchanger	Sub-Slab Heat Exchanger
Annual Interest Rate, *i* (%)	0.05	0.05
Duration of Mortgage, *n* (years)	30	30
Capital Recovery Factor	0.065	0.065
Average COP	4.867	4.262
Electricity Use (kWh)	2,768	3,167
Additional Loan (System Cost)	$17,763	$14,000
Annual Payment	$1,155	$911
Monthly Payment	$96.29	$76
Annual Utilities	$312	$357
Annual Loan Plus Energy	$1,467	$1,267

Because of the experimental nature of the sub-slab heat exchanger, the team did not conduct a more in-depth analysis involving maintenance cost and tax incentives. Likewise, the team did not conduct a comparison to other heat pump systems because this was beyond the scope of the research.

[1] $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$, where i is the annual interest rate and n is the duration of mortgage in years (Masters 2004).

5 Discussion and Conclusions

5.1 Heat Exchanger Parameters

Based on the measured data, the ground loop heat exchanger met the heating and cooling needs of the Pittsburgh Lab Home. Furthermore, the measured data and analysis indicate that a sub-slab GSHP is an effective strategy for capturing the advantages of a GSHP without the expense of drilling vertical wells adjacent to a low-load house in a suitable climate region. Although the installed cost is lower, the overall COP of the system is lower due to the reduced effectiveness of the sub-slab heat exchanger at rejecting thermal energy to the soil. With strategies to raise the thermal conductivity and improve the pipe layout, the negative thermal consequences could be mitigated. Despite the slightly increased annual energy usage, over a 30-year economic analysis, the sub-slab system is less expensive than a vertical well system.

Because of the low margin for error in system design and the greater risk of an undersized system causing negative and compounding side effects, the sub-slab heat exchanger design requires more verification and stress testing before it is ready for a production home environment. Heat waves or prolonged cold snaps will more significantly affect the system performance due to the small immediate soil volume for heat transfer. The shallow depth of the basement slab also results in greater influence from the soil surface temperature relative to a deep vertical well system. The R-410A refrigerant used by the heat pump loses one-fourth of its ability to transfer energy per cycle at the peak sub-slab EWT of 50°C (122°F) compared to the design EWT of 30°C (86°F). Beyond 50°C, the ability of the heat pump to operate efficiently is significantly compromised (ASHRAE 2005, Figure 14, p. 20.30). Additional study may indicate that certain climate zones and soil types will result in refrigerant temperature extremes beyond the operating limits of a standard heat pump compressor. Regardless, this system is effective for a low-load-density building such as a building meeting the Passivhaus standard. Temperate regions with a balanced number of heating and cooling degree days and a neutral deep earth temperature around 10°C (50°F) are best suited for this system. Because basement surface area is the limiting factor in system size, a single-story ranch house would be most effective for sub-slab installations.

Several factors could improve the system performance and increase the range of acceptable houses. One possibility includes increasing the excavation depth for the loop to a level below the base of the footing or installing the loop in a different geometric layout that extends deeper into the earth. Another solution could be to control the moisture content by adding small amounts of water beneath the slab to increase the moisture content, thus improving the thermal heat transfer of the ground. Increasing the R-value of the insulation below the slab would reduce the heat flux through the basement floor.

The research team was able to show a high degree of accuracy using the latest TRNSYS model for predicting the working fluid temperatures of a sub-slab GSHP as described in Appendix B. When possible, the team used known physical properties of materials as inputs. Of all the inputs, the team adjusted only the soil thermal conductivity within reasonable ranges to improve the accuracy of the simulation. The TRNSYS model could be used to accurately design future systems if the soil properties are well known and understood. Additionally, the TRNSYS module could accurately function as part of a larger, whole-house model to predict overall performance of building systems that use sub-slab heat exchangers.

5.2 Design Considerations

Several important factors must be considered when designing a sub-slab heat exchanger:

- House specific peak heating and cooling loads
- Annual heating and cooling loads
- Soil thermal conductivity
- Soil thermal diffusivity
- Fill aggregate conductivity
- Excavation depth
- Heat exchanger geometry
- Slab insulation
- Balance between number of heating degree days and cooling degree days.

When considering the feasibility of a sub-slab heat exchanger, the two most important characteristics to consider are the house-specific peak load relative to the basement floor area and the soil thermal conductivity. Initial analysis points toward a potentially strong relationship between these two values, indicating the approximate range of load densities possible for the soil thermal conductivity of a given location. Figure 20 illustrates a possible relationship useful in the early stages of system design. This relationship would be derived from many simulations across climate zones. Typically, only the specific peak load is a controllable parameter in system design. Soil thermal conductivity is a property of the house site; however, in some situations, conductivity may be modified by controlling moisture content. The relative location of the Pittsburgh Lab Home is indicated on Figure 20.

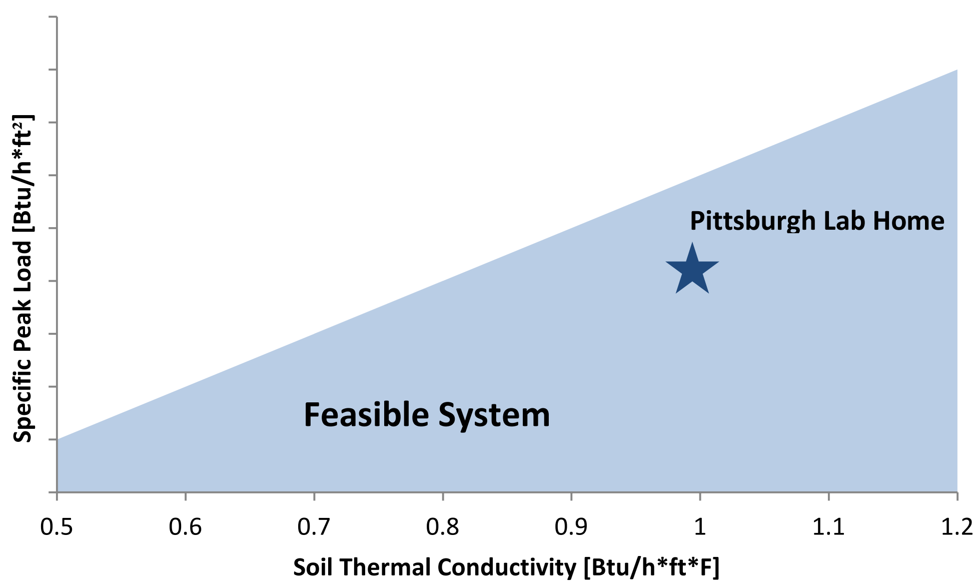

Figure 20. Estimated relationship between soil thermal conductivity and specific peak load

Once it has been determined that a sub-slab heat exchanger is feasible, the other factors contribute to an optimal system design.

Between geographical regions, soil thermal conductivity can vary widely. As such, each system design will need to consider the local soil conditions directly under the house (ASHRAE 2005, p. 25.13). Results from the updated modeling effort suggest that knowledge of soil properties to a depth of 30 ft is sufficient for system design.

Soil thermal conductivity plays a major role in the effectiveness of ground coupled heat exchangers, such as the sub-slab heat exchanger. The initial estimates for the soil thermal conductivity were slightly higher than normal ranges and were based on initial site conditions in an open field. The soil thermal conductivity may have decreased during the period after installation of the French drain and sub-slab heat exchanger and prior to beginning soil moisture content measurement. Based on this observation, the chosen soil thermal conductivity values for a sub-slab heat exchanger design should be closer to the “wilting point” or drier end of the thermal conductivity range of the soil.

5.3 Future Research

Initial research and analysis indicate valuable topics for future work. Much of this future work would be similar to the research and modeling that have been undertaken for vertical well systems, with the intent to understand the additional sensitivities of the sub-slab system. The following are topics for future research:

- Analyze the effect of a heat wave or long cold snap on soil temperatures and system operation to determine if the heat pump will fail to meet the building load.
- Study the effects of the depth of the ground loop on system performance. Consider the extremes of a slab-on-grade house or a deep basement with additional excavation.
- Develop the relationships between soil conductivity and diffusivity, balance between the number of heating degree days and cooling degree days, and load density. Guidance could be developed for feasible system parameters.
- Develop a regional map outlining soil conductivity and diffusivity, balance between the peak heating and cooling loads, and building load density.
- Study the effect of continuous desuperheater usage on the peak summer loop temperatures and COP.
- Empirically validate a model across multiple locations and climate zones.

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Appendix A: Excerpt from “Cooperative Agreement DE-FC26-08NT02231. Building America Final Technical Report” (Oberg 2010)—Pittsburgh Lab Home Heating, Ventilation, and Air Conditioning

- When insulating sheathing, housewrap, and drywall ceiling on the second floor installed, and only penetrations through sidewalls and top and bottom plates were sealed, blower door tested enclosure airtightness was 2.86 air changes per hour at 50 Pa.
- After strategic airsealing with closed cell spray foam insulation at the attic floor, blower door tested enclosure airtightness was 0.91 air changes per hour at 50 Pa.
- After closed cell spray foam insulation was applied to the band joists, blower door tested airtightness was 0.87 air changes per hour at 50 Pa.
- After the wall cavity was insulated with blown fiberglass and interior drywall applied, blower door tested enclosure airtightness was 0.65 air changes per hour at 50 Pa.

In summary, the testing demonstrated that the exterior housewrap and insulating sheathing system, with strategic airsealing of penetrations acts as a very effective air barrier. The fact that the closed cell spray foam insulation application at the band joists had a minimal airtightness impact reinforces that the wall system was already airtight even though wall cavities were un-insulated and no interior drywall was installed. Strategic airsealing of the second floor ceiling with closed cell spray foam insulation was shown to have the largest airtightness impact during the testing, highlighting the importance of this practice.

2.1.4 HVAC

During 2010, IBACOS continued its focus on researching very high performance HVAC technologies. In particular, IBACOS completed constructability research necessary to establish cold climate options for the lab house and broadened energy use and system performance modeling studies to include other climate zones. The investigations focused on the applicability of a ground-source heat pump system and sub-slab heat exchanger; the same system that is in the IBACOS Lab House.

Earlier simulation work as documented in the "2009 IBACOS Building America Annual Report for Budget Period 2" (IBACOS 2010) identified a ground-source heat pump system as the lowest energy solution when it was also integrated with the domestic hot water system (**Figure 2.31**). The system was further optimized for energy and cost savings by modeling the system with a variety of water storage tank configurations and ground-loop configurations. A dual-tank DHW system achieved the lowest energy use and a horizontal sub-slab ground-source loop is now being tested as a viable cost-saving alternative to conventional vertical wells or horizontal loops outside the footprint of the house. Detailed research questions can be found in **Appendix 2.H** of this report.

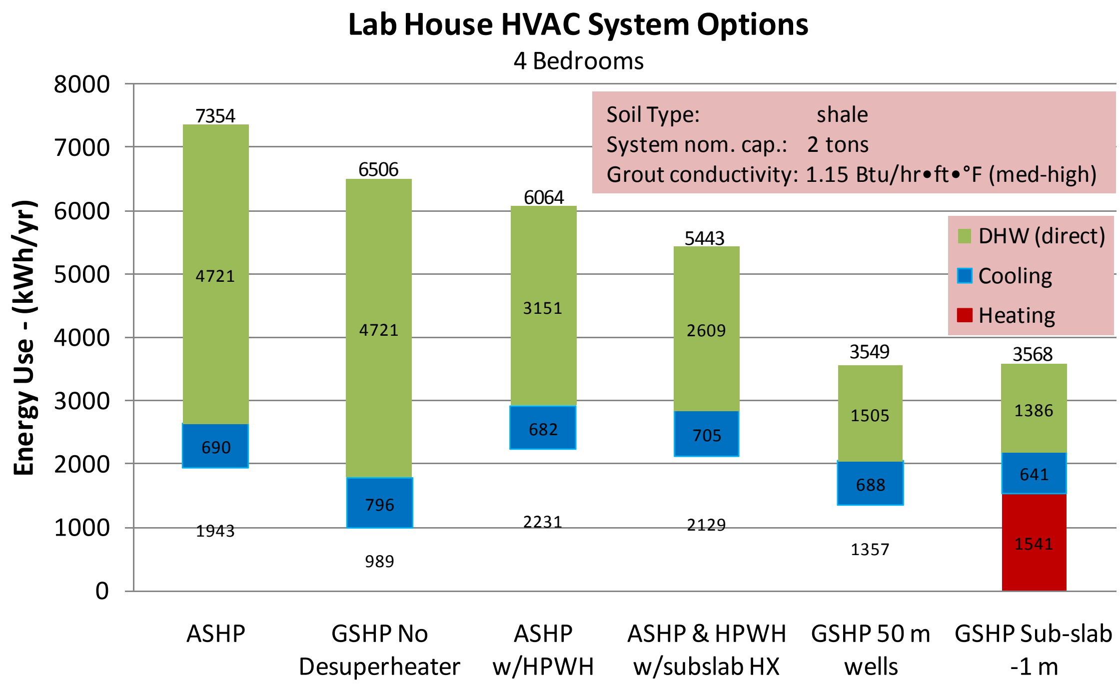

Figure 2.31: Lab House System Options

Figure is a schematic depiction of the HVAC/DHW system installed in the Lab House. Much of the apparent complexity is due to thermocouples, meters, extra valves, and bypasses that were installed for research purposes. A production system would be much less complicated and therefore less expensive. Missing from this schematic are any representation of the sub-slab and vertical-well ground-coupled piping loops on the right side of the diagram. The two different ground-loop configurations are redundant and each contains two piping circuits. Eight shut-off valves enable each circuit to be individually isolated.

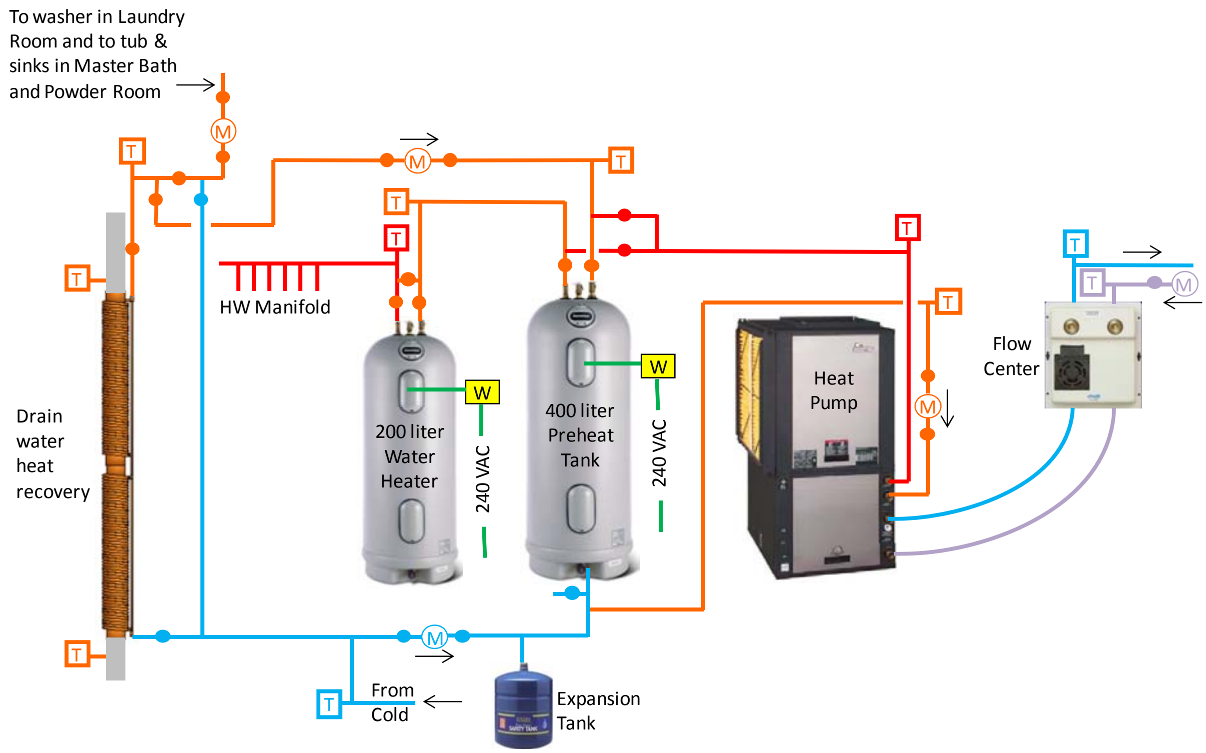

Figure 2.32: Lab House HVAC/DHW System Schematic

Sub-Slab Ground-Source Heat Pump Loop

Progress in this area of HVAC research within the Lab Home in 2010 focused on acquisition of equipment, installation of equipment and monitoring sensors, determination of specific research questions and the creation of testing and monitoring schedules to be implemented in 2011.

While it is not expected to be as efficient as a vertical well configuration, the horizontal sub-slab approach will reduce installation costs by approximately $2500/ton. With simulated peak hourly heating and cooling loads reduced to not much over one ton and peak average daily loads well under that, the load on the heat exchanger is reduced to the point where the area of the slab is sufficient to handle the load. Figure illustrates the distribution of the annual system heating load on a daily basis. The total number of heating days are 222 with 30% requiring less than 1,000 Btu/hr and less than 9% requiring more than 8,000 Btu/hr. At an operational COP of 4.0, the load on the sub-slab heat exchanger is 25% less than the loads shown in **Figure 2.33**. This means the maximum daily average load on the heat exchanger is 7,150 Btu/hr and 83% of the heating season imparts a load of less than 4,500 Btu/hr. These loads include operation of the DHW desuperheater, which could be disabled during the heating season to reduce the heat exchanger load if necessary.

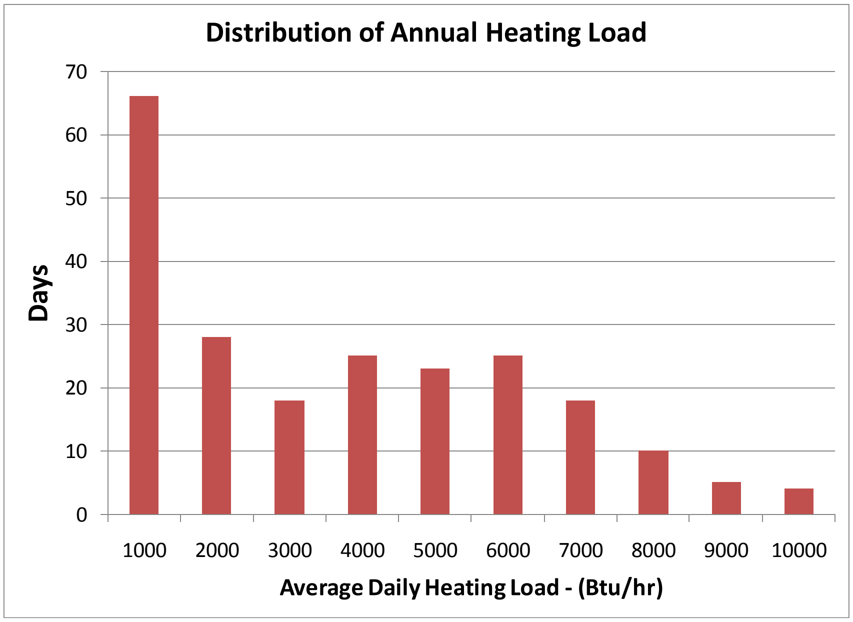

Figure 2.33: Lab Home - Distribution of Space Heating Load

Figure 2.34 shows the installation of two horizontal sub-slab piping loops for the Lab House ground source heat pump. To prepare for the installation, the entire slab area was excavated to the bottom of the wall footer to allow more room for the installation of the piping, extra limestone fill, and insulation beneath the slab. Each piping circuit consists of approximately 400 feet of ¾" HDPE pipe installed beneath the basement floor slab. A "folded" serpentine configuration was chosen to serve two purposes; it enables the circuit inlet and outlet to be in the same location, and it allows for a larger bending radius while maintaining a maximum spacing of one foot. A horizontal slinky configuration was also considered, but was ruled out due to the numerous pipe crossings and less-even distribution of the pipe within the limited slab area. The piping is anchored to heavy-gauge 6 x 6 flat-panel wire mesh with zip ties to keep it flat. Wire mesh from roll stock should NOT be used. Long steel pins such as those used for securing pipes to the side of a trench would be an acceptable alternative method. The one-foot radius bends are about the limitation for cold bending.

Figure 2.34: HDPE ¾" tubing installed beneath the basement slab will serve as the ground loop for the ground-source heat pump.

The sub-slab system will serve the ground-source heat pump system for the entire calendar year of 2011. A redundant vertical-well system was also installed at the time of construction. This system will be used in 2012 to provide a benchmark comparison to the experimental sub-slab system.

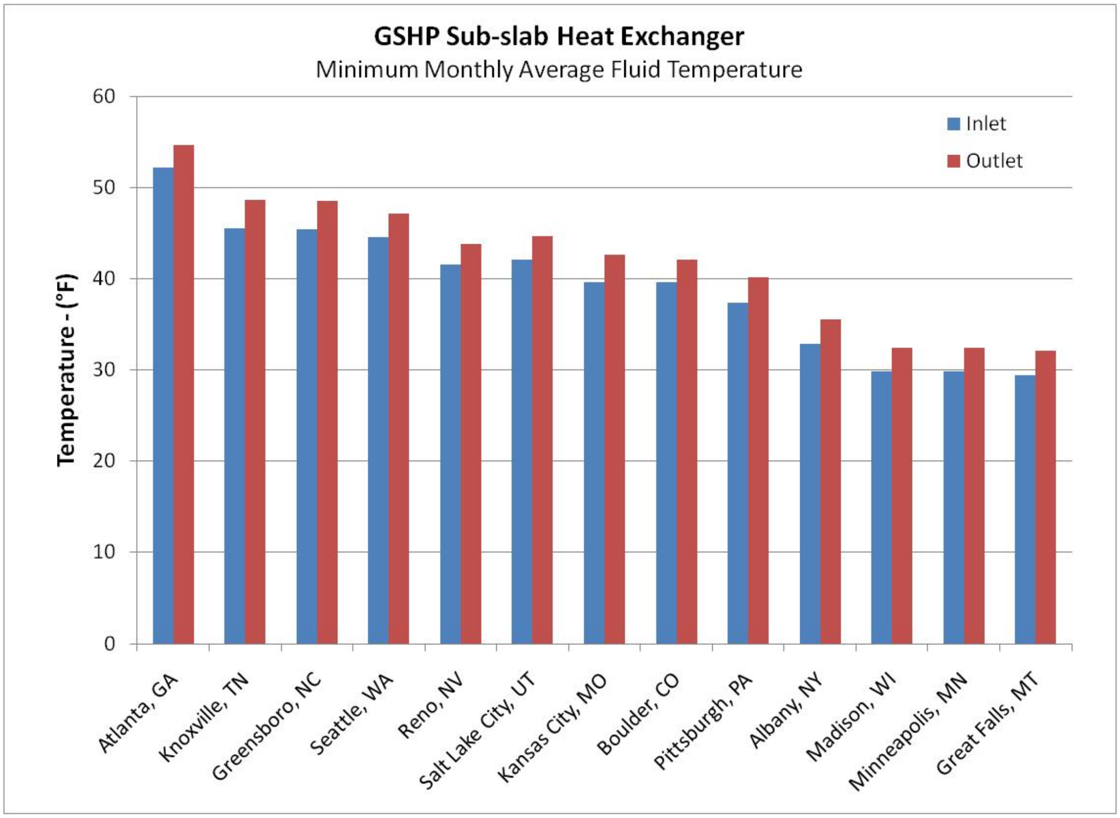

Figure 2.35: GSHP Sub-Slab Heat Exchanger - Minimum monthly average fluid temperatures

As expected, the annual space conditioning and DHW energy use in **Figure** is inversely proportional to the minimum sub-slab temperatures shown in **Figure 2.35**. **Figure 2.36** also shows the relatively small contribution the desuperheater is providing to reducing the domestic hot water load in mixed and cold climates. This indicates the potential for a dedicated domestic hot water function on the heat pump, provided it is controlled to eliminate the risk of freezing the ground beneath the slab.

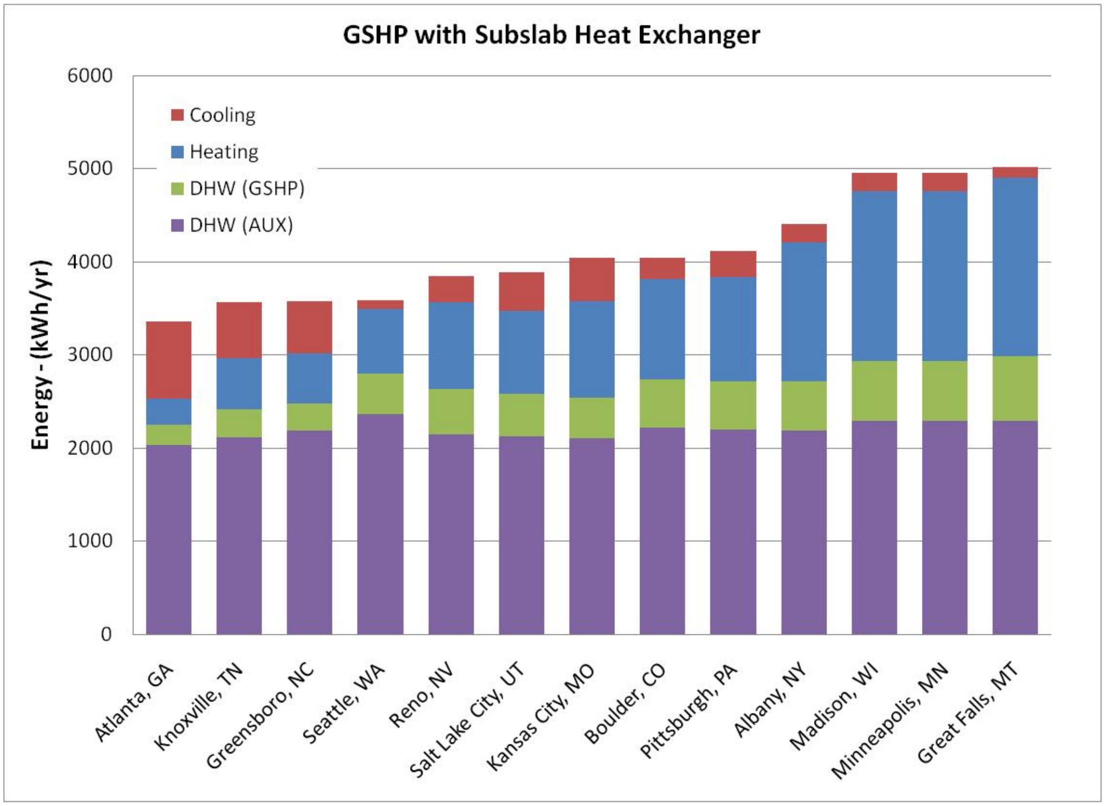

Figure 2.36: GSHP with Sub-Slab Heat Exchanger: Annual space conditioning and DHW energy use

Air Distribution System

Progress in the area of air distribution systems research within the Lab Home in 2010 focused on acquisition of equipment, installation of equipment and monitoring sensors, determination of specific research questions and the creation of testing and monitoring schedules to be implemented in 2011. Research questions can be found in Appendix D.1 of this report.

Table 2.6 illustrates the three different test modes of the air distribution system. Mode "A" is the most conventional system, designed using ACCA guidelines for duct velocity and ASHRAE guidelines for supply air outlet velocity. Mode "B" utilizes one large supply air outlet will serve each floor and the only air circulation will be via the ventilation system. Mode "C" will utilize the PVC distribution of the ventilation system, which will act as a high-velocity system. Main duct velocities will be approximately 1,750 fpm compared to a typical design maximum of 900 fpm. Diffuser outlet velocities will remain the same in Mode "A" and "C".

Table 2.6: Air Distribution System Operation Schedule

Mode	System	Zones	Outlets	Cycle Time
A	Ductboard	2	Multiple	2 weeks
B	Ductboard	1	2	2 weeks
C	PVC	1	Multiple	2 weeks

Appendix B: Updated TRNSYS Simulation and Model Validation

Simulation Results

After the Pittsburgh Lab Home was in an operational state for more than one year, the IBACOS team began a renewed modeling effort to take advantage of the latest subroutines available. The initial design stage TRNSYS simulation used a combination of the Type 701b basement module as well as Type 706 sub-slab heat exchanger module. The results from this simulation indicated favorable heat transfer into the soil and that the slab surface temperature would not rise to a level that would transfer energy into the basement zone. In 2012, TESS released a new sub-slab module that combines the capabilities of Type 701 and Type 706. This new module is called Type 1267 (TRNSYS 2012). The research team compared the results of this model to simulated data to determine the accuracy of the model.

Type 1267 utilizes a fully implicit finite difference solver to calculate energy exchange through a number of predefined nodes. Nodes are manually defined by a process that considers the geometry of the pipe network, building, and soil. An optimized node layout is generated to provide smaller grid spacing in areas of interest, while balancing system run time. This node specification file is then used by the Type 1267 module. Currently, because of the manual nature of the process, a large portion of the set-up time for a simulation is configuring the node file. For this analysis, the file contained approximately 600,000 nodes. Due to the level of detail and the number of soil nodes, an annual simulation of 8,760 hours takes approximately four days to complete on a quad core laptop.

The IBACOS research team provided TESS with a data set with all measurements pertinent to the sub-slab heat exchanger on a five-minute-period basis to use as a calibration aid. In addition to the measured data, the team gave TESS pertinent information regarding the system operation, including information on the duct switch-over schedule and other abnormal behavior in the house. TESS ultimately provided the IBACOS research team with a working model and soil node file, which the team was able to run for the final simulation. Table 5 compares the initial and final simulation values.

Table 5. TRNSYS Simulation Parameters

Parameter	Initial Value	Final Value	Units
Simulation Length	17,520	8,760	h
Time Step	1/10	1/12	h
Deep Earth (Average Surface) Temperature	10.40 (50.72)	10.40 (50.72)	°C (°F)
Thermal Conductivity of Soil Layer	9.9 (1.589)	6.24 (1.002)	kJ/h·m·K (Btu/h·ft·°F)
Density of Soil Layer	2,080 (129.854)	2,100 (131.103)	kg/m^3 (lb/ft^3)
Specific Heat of Soil Layer	0.84 (0.2007)	0.96 (0.2293)	kJ/kg·K (Btu/ lb·°F)
Fluid Through Pipes Thermal Conductivity	1.65168 (0.2651)	1.775 (0.2849)	kJ/h·m·K (Btu/h·ft·°F)
Fluid Through Pipes Density	1,000 (62.43)	963.2 (60.133)	kg/m^3 (lb/ft^3)
Fluid Through Pipes Specific Heat	4.19 (1.001)	4.097 (0.9788)	kJ/kg·K (Btu/ lb·°F)
Fluid Through Pipes Viscosity	3.2 (2.150)	4.387 (2.948)	kg/m·h (lb/ft·h)
Pipe Inside Diameter	0.0204 (0.803148)	0.021539 (0.84799)	m (in.)
Pipe Outside Diameter	0.0250 (0.98425)	0.02667 (0.08988)	m (in.)
Pipe Thermal Conductivity	1.401895 (0.2250)	1.728 (0.2774)	kJ/h·m·K (Btu/h·ft·°F)

During verification, the model was driven using measured fluid temperature and flow rate leaving the heat pump. As an additional level of detail, the fluid temperature was set to decay toward the measured air temperature; however, all calculations regarding the validation of the model occurred only when the system was operating at full flow. Outputs were collected from the temperature of fluid returning from the sub-slab heat exchanger, as well as the temperature and heat transfer to all materials. These initial tests appear to show good correlation between measured and simulated temperatures.

Figure 21 represents typical winter operation of the GSHP. The simulated and measured EWTs closely aligned during continuous system run. The results of this initial simulation indicate that the module developed by TESS is accurately predicting the heat rejected to the ground. As indicated in Figure 22, the simulation slightly underpredicted the summer EWT. This aligns with the simulation underpredicting the soil temperature, likely the result of assumed input parameters such as deep earth soil temperature.

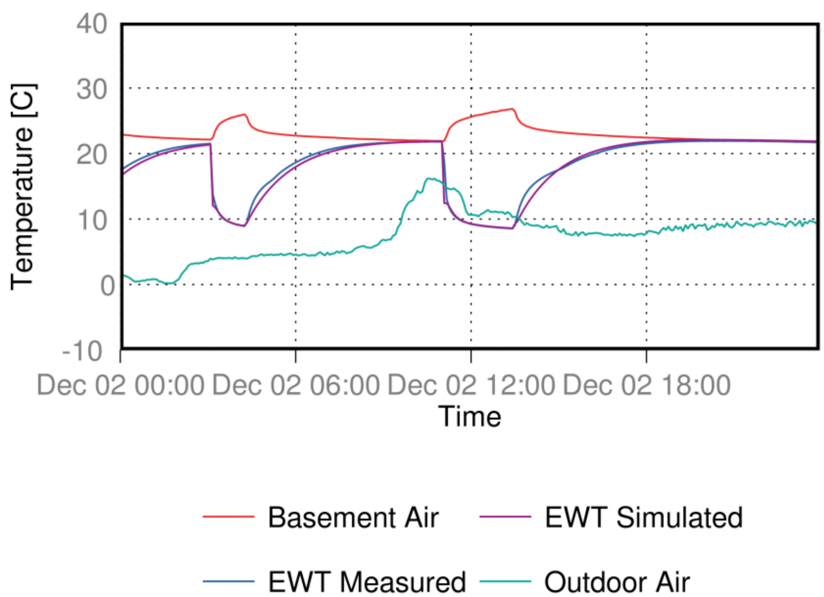

Figure 21. Typical heating season operation: ground loop fluid temperatures

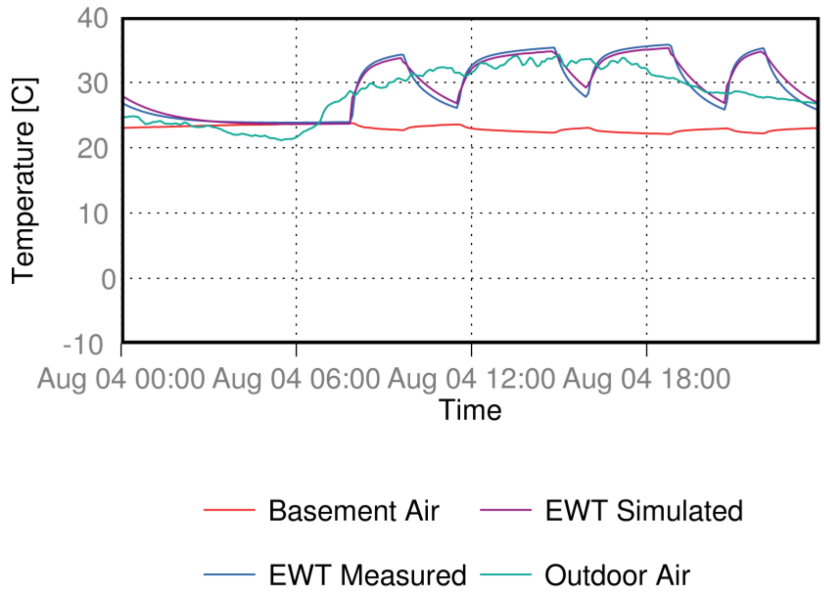

Figure 22. Typical cooling season operation: ground loop fluid temperatures

Error Analysis

Figure 23 provides a seasonal breakdown of the error associated with the simulated fluid temperatures. Seasonally, the summer was the least accurate because the model overpredicted heat transfer to the deep earth. There was significantly less system operation during the swing seasons, and the total variation relative to the mean was slightly greater as well, indicating the simulation is not as accurate at predicting the fluid temperature when the system mode is changing. Winter includes December through February, and spring includes March through May. Summer includes June and July, and fall includes August through November.

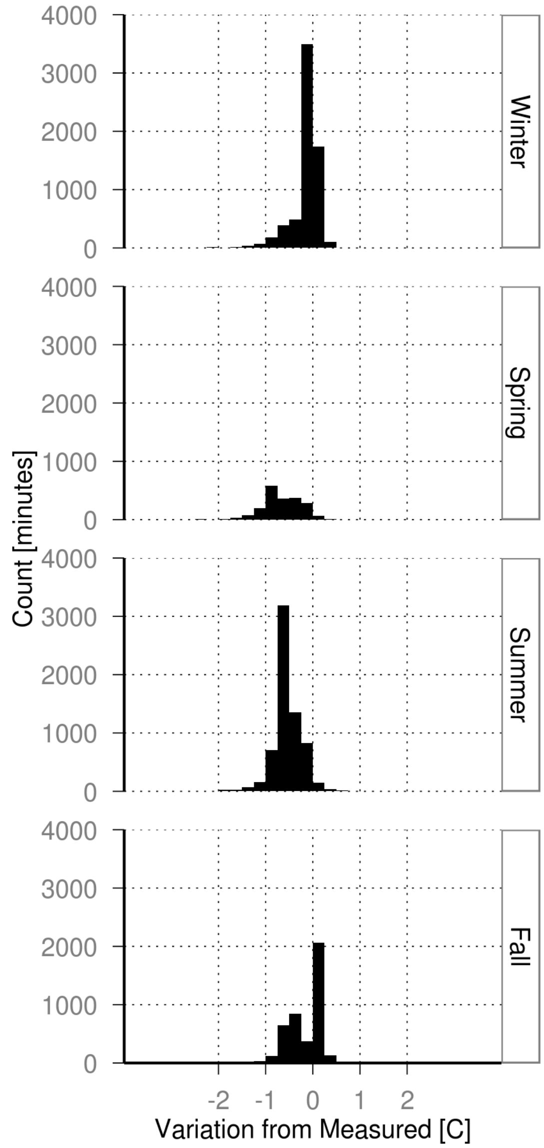

Figure 23. Simulated EWT variation from measured data

To estimate the error in the model, the research team performed a mean bias error (MBE) calculation on the measured entering fluid temperature, as compared to the simulated entering fluid temperature during system operation. Figure 24 shows a slight negative offset to the simulated EWT.

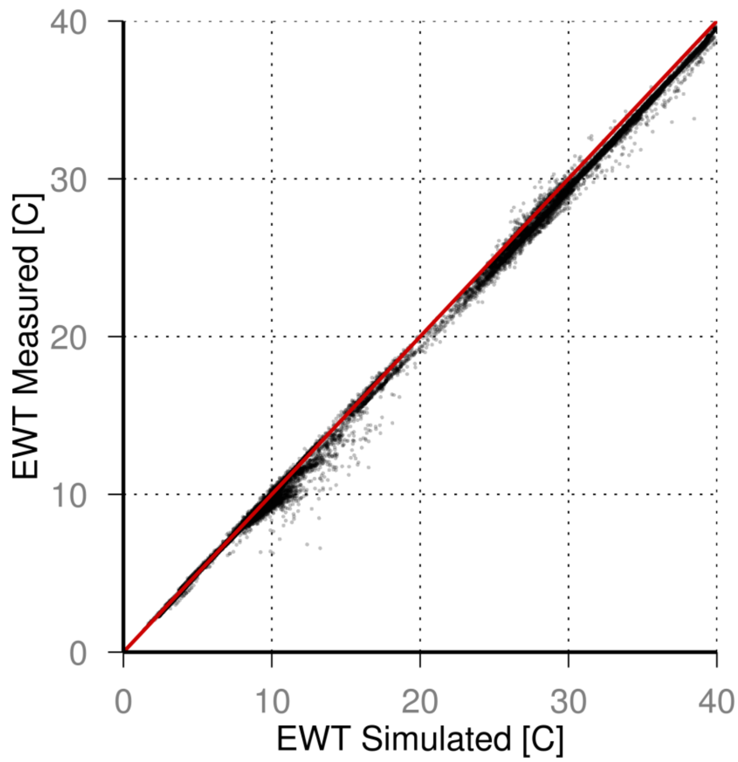

Figure 24. MBE—simulated versus measured EWT

The MBE was calculated using Equation 1,

$$\mathrm{MBE} = \frac{\Sigma(\mathrm{Simulated} - \mathrm{Measured})}{n}, \tag{1}$$

where n is the sample size.

Table 6 summarizes the results of the error analysis. Each percentage value was calculated by dividing the MBE by the average of the value. For this analysis, the most important value is the percentage error in the ground loop fluid temperatures. The simulated EWT shows accurate correlation, and the overall percentage of the mean shows minimal error.

Another metric to consider is the average error of the absolute value of the change in fluid temperature. This percentage is slightly higher and gives an indication of the percentage of error associated with the energy transfer to the ground. On an annual basis, the model is predicting slightly lower fluid temperatures than reality.

Overall, the soil temperature also exhibits low error and tracks with the fluid temperatures. The western portion of the slab under the finished basement exhibits slightly greater error, indicating that, in reality, heat is building up to a greater extent than predicted by the model.

Table 6. MBE of Loop and Soil Temperatures

Variable	MBE	Percentage
Fluid Temperature Returning from the Ground Loop (°C)	–0.34	–1.7
Fluid Temperature Delta T [°C]	–0.34	–12
North–West Soil Temperature 24 In. Below the Loop (°C)	–1.58	–9.0
South–West Soil Temperature 24 In. Below the Loop (°C)	–0.99	–5.5
East–Middle Soil Temperature 24 In. Below the Loop (°C)	–0.46	–2.5
LOPPEN* Soil Temperature 24 In. Below the Loop (°C)	–1.26	–7.1
Energy Rejected to the Loop (kWh)	–0.01	–10.7

*The portion of soil directly below the loop piping entrance

Deep earth soil temperature influences the overall rate of heat transfer. For this simulation, the deep earth temperature was assumed to be the annual average surface temperature. Some of the model's inaccuracy during summer months can be explained if the deep earth soil temperature is higher than assumed, based on regional climate data. The Pittsburgh Lab Home is located on southern sloped terrain with no surrounding trees, resulting in greater energy flux into the soil from solar irradiance.

Another important measure of error during system design is the overall heat transfer into the soil. The calculated MBE for the energy rejected to the loop is based on the absolute value of the calculated energy transfer. Figure 25 illustrates the cumulative annual energy transferred into the soil through the ground loop. These values are calculated from measured temperatures and flow rates, as well as the simulated water temperature leaving the ground loop. Although there is a slight skew in the absolute value of the simulated results, the slopes of the two values match throughout the simulation period.

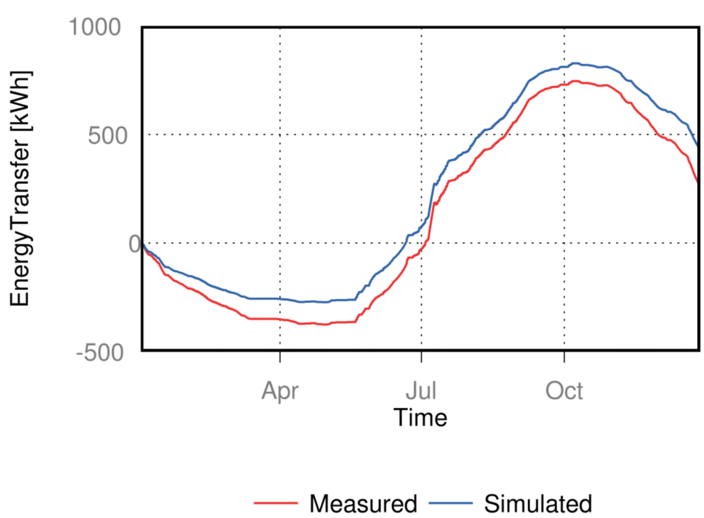

Figure 25. Cumulative energy transfer to soil from loop fluid

Basement Heat Flux

Another area of interest is the accuracy of the simulation to predict the heat transfer from the sub-slab heat exchanger into the basement zone. Energy transferred through the slab will contribute to the cooling load in the summer and the heating load in the winter, thereby increasing the overall energy use of the system. Initial TRNSYS predictions indicated that soil and slab temperatures would not be elevated to a degree that would contribute to this exchange. However, measured results indicate higher than expected soil temperatures and consequently greater transfer of energy into the building zone. Figure 26 and Figure 27 represent the cumulative heat transfer as measured and simulated by the model for the West and East sections of the slab, respectively. These results indicate that the model is accurate at predicting the net heat transfer for each season. Discrepancies could arise from the assumption of a constant coefficient of convection from the slab into the zone air. The East section of the slab was subject to greater variation in airflows due to changing of air distribution layouts for additional testing in the rest of the house. Throughout the summer months, the direction of heat transfer was into the basement. This is apparent during the period of July through October, when the curve undergoes a minimum and has a positive slope.

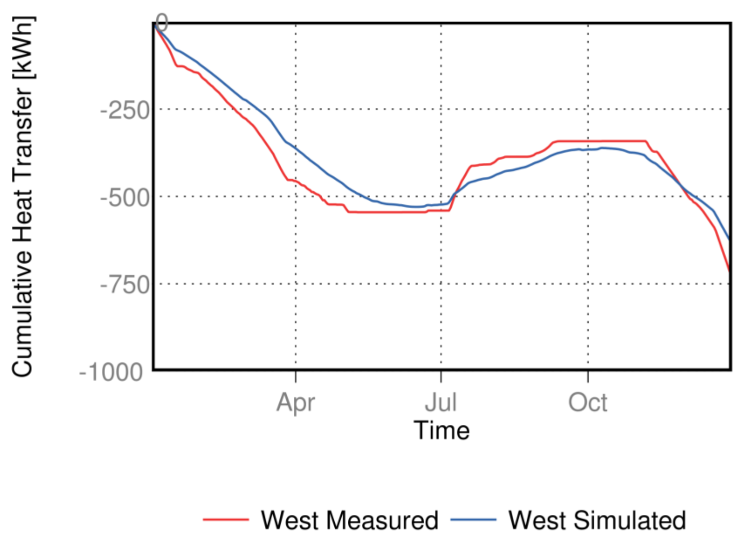

Figure 26. Cumulative heat transfer, West slab

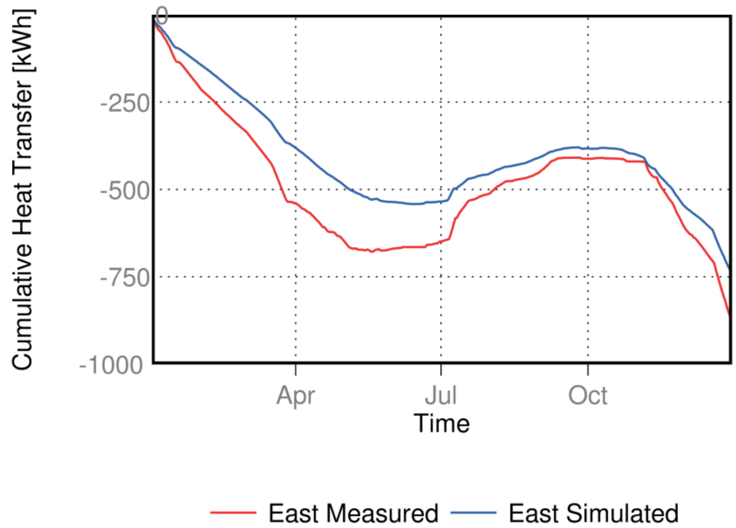

Figure 27. Cumulative heat transfer, East slab

Heat Exchanger Geometry

Results from the modeling efforts suggest the large impact of heat exchanger geometry on the ability of the system to reject heat to the ground. Figure 28 indicates the location of the temperature slices relative to the house basement.

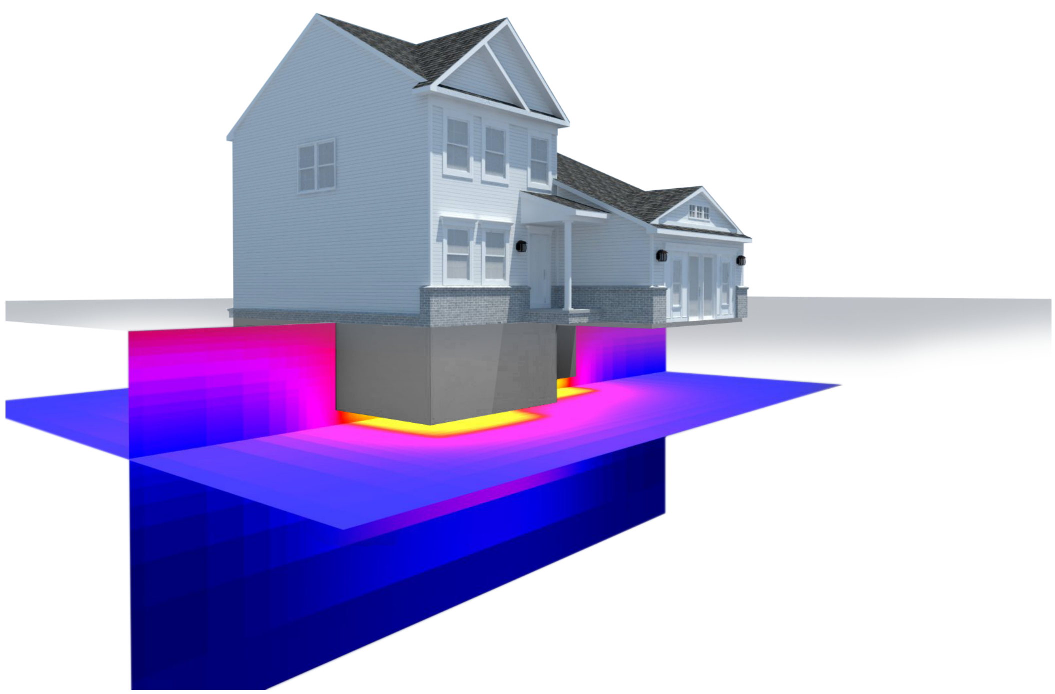

Figure 28. Locations of soil temperature slices (not to scale)

Figure 29 indicates that, for the Pittsburgh Lab Home, the flow arrangement associated with the piping below the eastern unfinished basement offers a more efficient design. The hottest fluid is running through the perimeter of the system; thus, the greatest amount of energy can be conducted away from the exchanger. Alternatively, the flow arrangement associated with the western portion under the finished basement routes the hottest fluid directly into the center of the system, causing a buildup of temperature in the center and reducing performance. Curiously, the structural engineering recommendations for the system design were to group the loops as close to the center of the slab as possible to avoid excessive excavation near the perimeter. The ideal design would route the hottest fluid near the perimeter of the slab while maintaining a margin of safety around the footings.

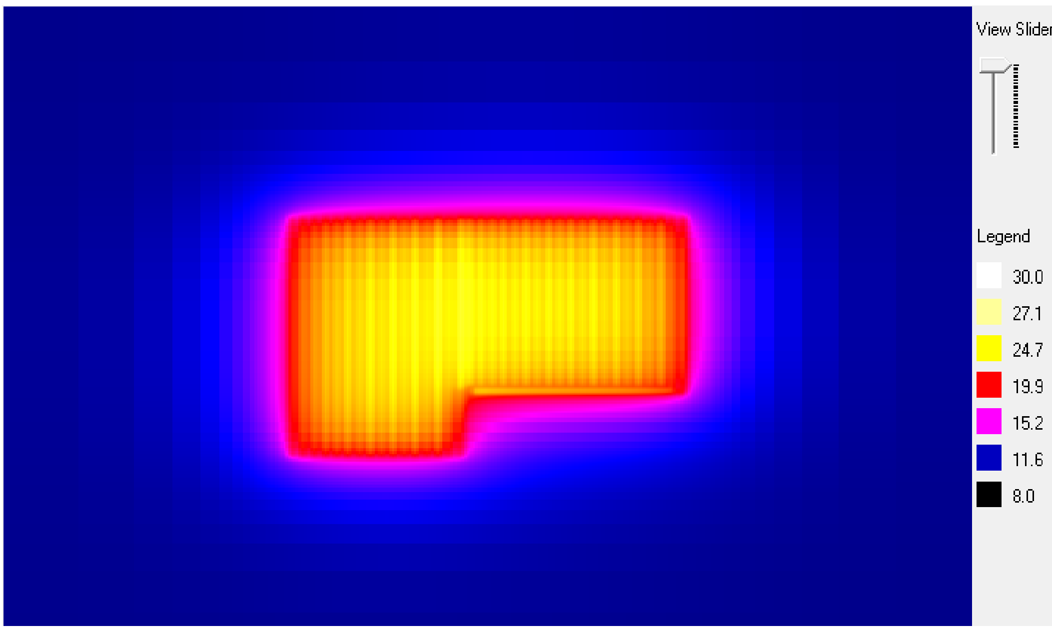

Figure 29. Horizontal temperature profile at loop level during summer operation (°C)

The model developed by TESS is capable of simulating a wide variety of heat exchanger geometries, including placing the loops on the outside perimeter of the foundation as proposed by Oak Ridge National Laboratory (Hughes and Im 2013) and investigated in several publications.

The seasonal soil temperature changes are an interesting output of the model and can be analyzed. The soil temperature at various depths exhibits extensive seasonal variation, as shown in Figure 29 through Figure 31. A pocket of warm soil exists under the slab during autumn, which improves the efficiency of the system during the early heating season. The horizontal slice is located at the pipe layer.

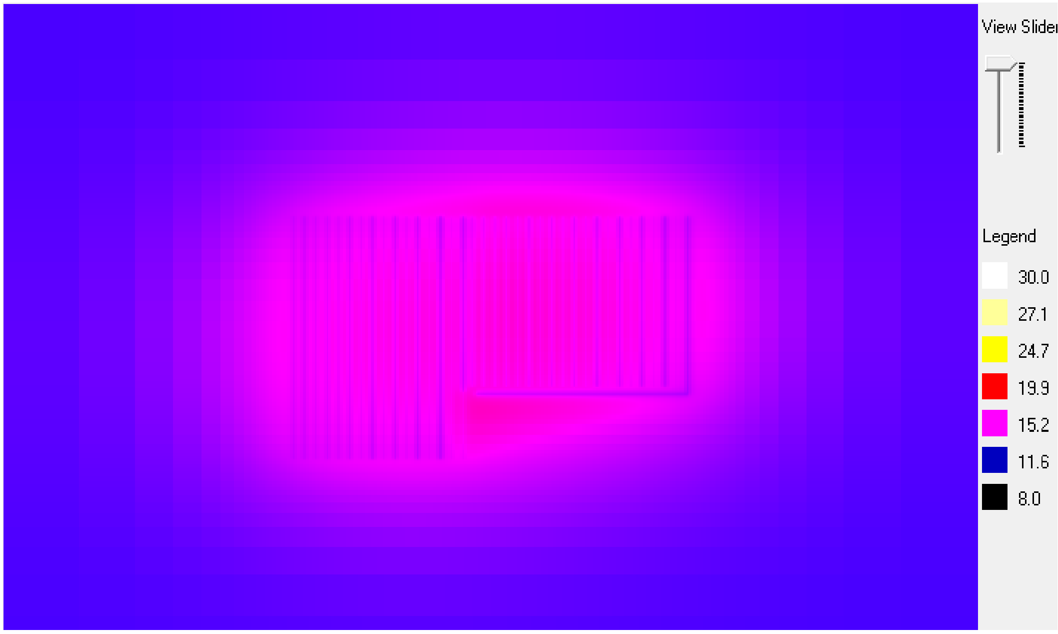

Figure 30. Horizontal temperature profile at loop level during fall operation (°C)

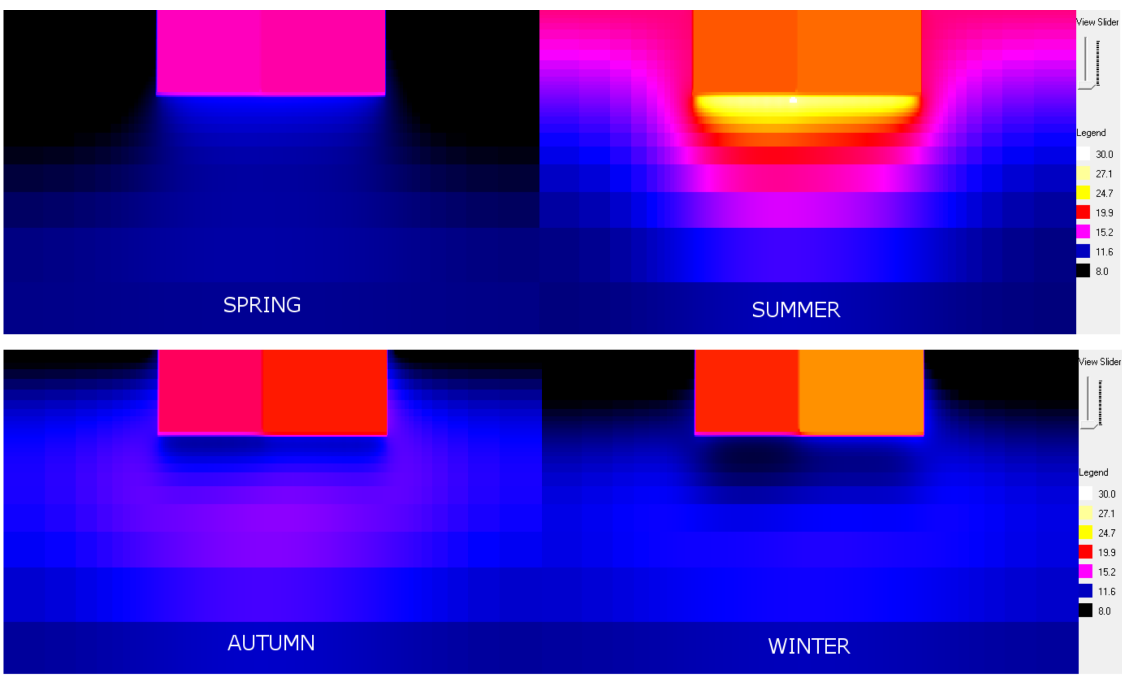

Figure 31. Vertical slice of soil temperatures (°C)

Modeling Conclusions

The final test is to determine whether accuracy is maintained when the sub-slab model is driven with simulated heat pump operation and water temperatures. The assumption is that if individual components of a model are accurate, the model as a whole will be accurate. Although not presented in this report, simulation results indicate that when using catalog performance data to simulate leaving water temperatures, the accuracy of the model is maintained. The simulation runtime of 4–5 days offers a significant hurdle for using this model in a parametric manner to run a large number of simulations. Provided there was a strong interest in using this model for system design, an effort to reduce system run time through multicore code or code utilizing the latest graphics processing unit parallel computing technology could be undertaken. Additionally, the manual process of creating the soil node layout could be automated by updating an existing tool provided by TESS.

As with any computer-based simulation, the results are only as accurate as the assumed input values. Given ideal knowledge of the soil and material properties, the TESS model can be used as an accurate design tool in a wide variety of system geometries, not limited to underslab loops. However, the sub-slab heat exchanger model has a number of inputs with values that are difficult to measure and that change over time. Because the sub-slab system is more sensitive to variations in simulation inputs than a vertical well, worst-case scenario values should be considered to give a range of operational conditions.

References

Hughes, P.; Im, P. (2013). Foundation Heat Exchanger Final Report: Demonstration, Measured Performance, and Validated Model and Design Tool, January 2012, Revised January 2013. Oak Ridge, TN: Oak Ridge National Laboratory. http://web.ornl.gov/sci/ees/etsd/btric/publications/ORNL-FHX%20Final%20Report_Jan%202012%20for%20Distribution_rev_01152013.pdf.

TRNSYS (2012). Transient System Simulation Tool, Version 17.1. Madison, WI: Thermal Energy System Specialists, LLC (TESS). www.trnsys.com/.

Appendix C: Excerpt from "Cooperative Agreement DE-FC26-08NT02231. Building America Final Technical Report" (Oberg and Bolibruck 2009)—Pittsburgh Lab Home Sub-Slab TRNSYS Results

Sub-slab heat exchanger

IBACOS constructed a TRNSYS model of the ground source heat pump (GSHP) system with a horizontal sub-slab heat exchanger configuration using a new TRNSYS "Type" developed by TESS, Inc. specifically for this project. The component combines a ground-coupled basement model with a sub-slab heat exchanger into one sub-routine. This eliminates the need for certain approximations and assumptions that were being used in the previous IBACOS model as a means of calculating realistic ground temperatures around the heat exchanger. Simulation results indicated that the annual energy usage is only 4% more than that of a comparable system using two 50-meter vertical wells. Combined annual energy use is 3,802 kWh/yr. Monthly average temperatures ranged from 42°F to 73°F for bottom-of-slab temperatures *(see Figure 10)* and from 39°F to 76°F for outlet fluid temperatures *(see Figure 11)* from the sub-slab heat exchanger. Inlet fluid temperatures were slightly lower, which may still make antifreeze a requirement, but a freeze stat could be used to avoid frost heave damage to the foundation.

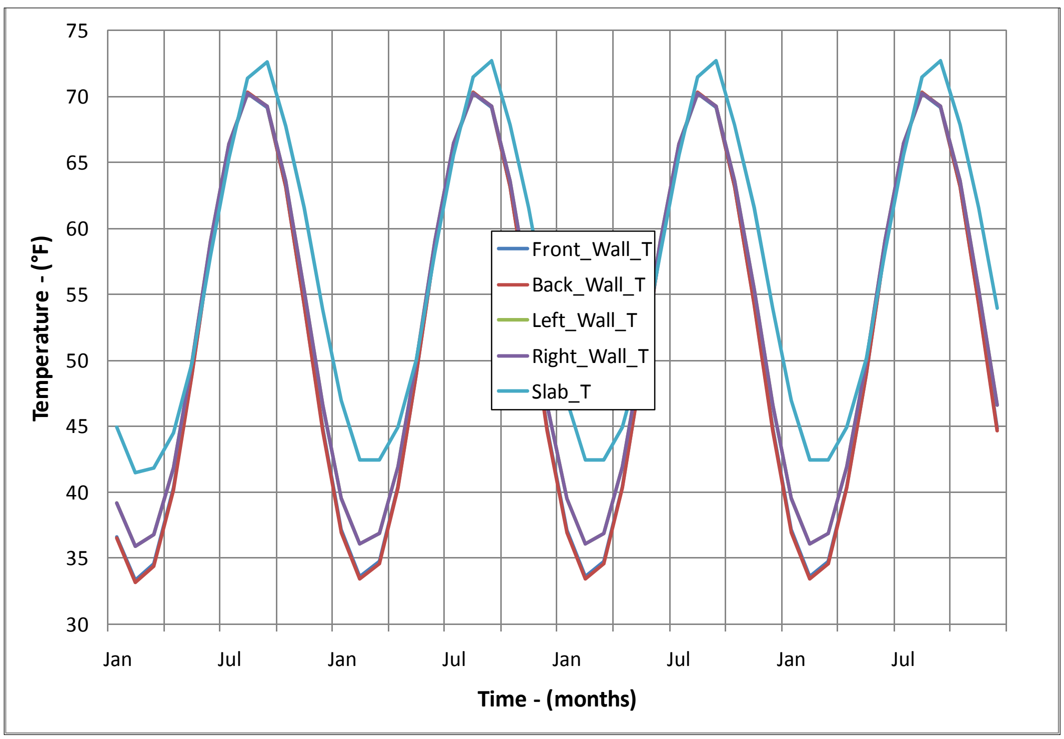

Figure 10: Foundation temperatures - horizontal ground heat exchanger (GHX)

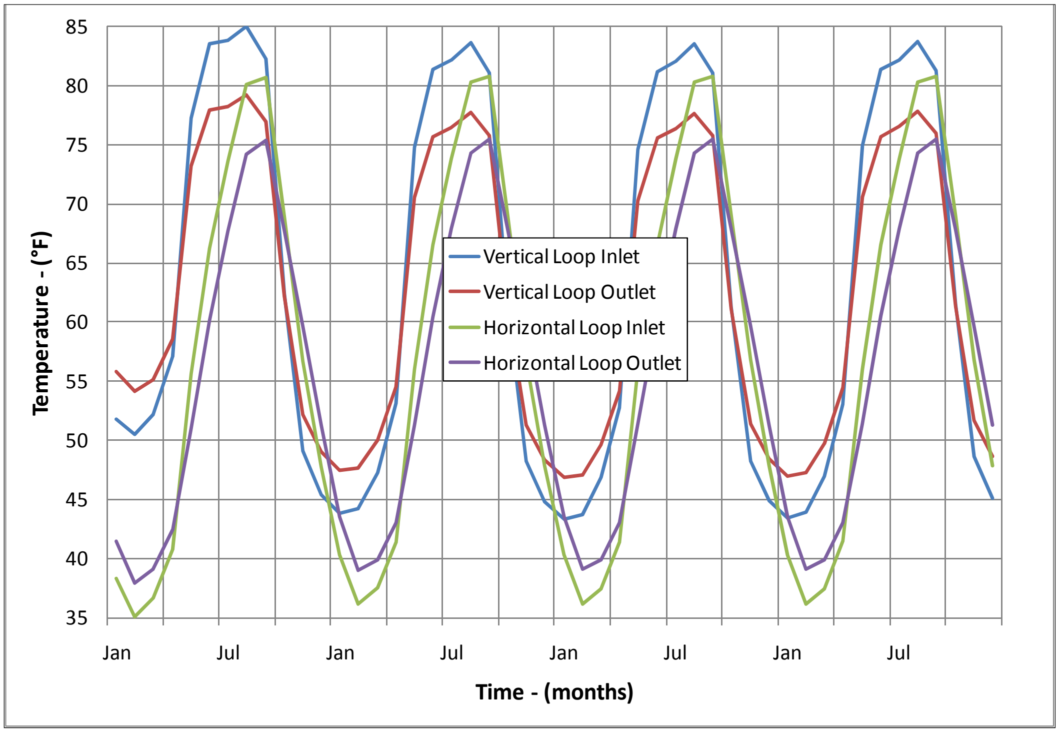

Figure 11: Heat pump ground loop temperatures

IBACOS completed further simulations to evaluate the energy impact due to changes in the proximity of the heat exchanger to the slab. Results illustrated in **Figure 12** indicate that the horizontal heat exchanger piping actual performs better at shallower depths beneath the slab, which will help limit the amount of over-excavation and reduce costs.

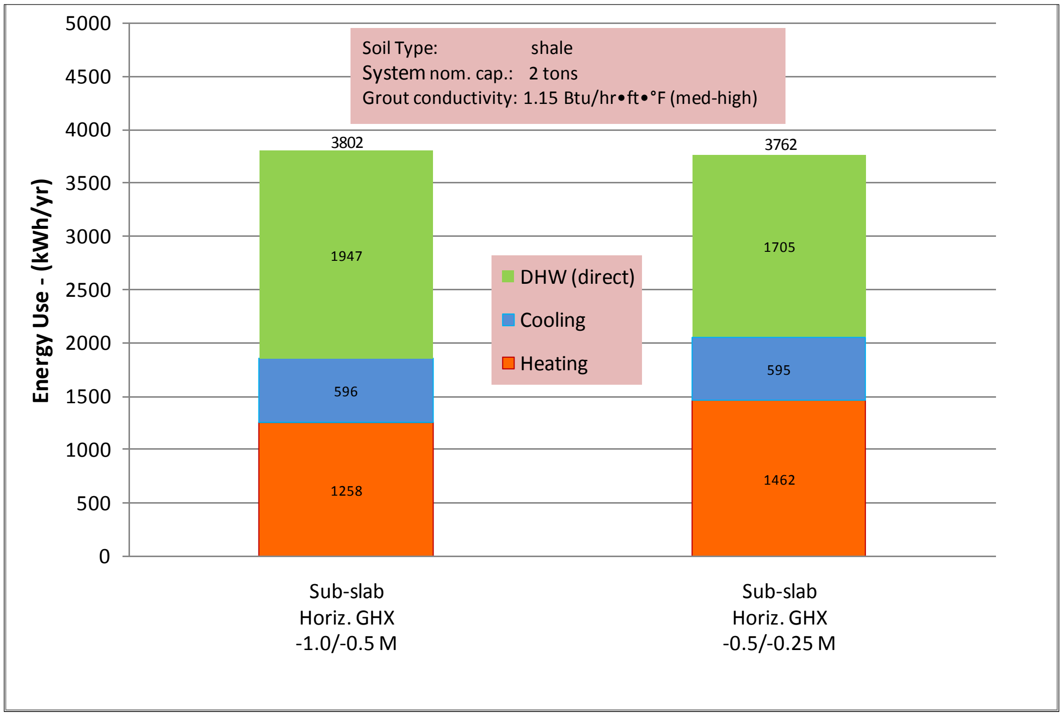

Figure 12: Energy impact of GHX proximity to slab (3-bedroom occupancy)

Dehumidifier performance

IBACOS assembled a TRNSYS model to simulate the performance of a stand-alone dehumidifier over a wide range of inlet air conditions. The model relies on an empirically-based performance map provided by the manufacturer and can be used to evaluate the necessity, energy consumption, and annual efficiency of a high performance dehumidifier used with typical heating and cooling systems in the context of a high performance home. IBACOS evaluated the performance as a function of infiltration, latent loads, and maximum humidity set points.

IBACOS evaluated the impacts of infiltration and humidity capacitance using basic constant-volume and linear models and then using more enhanced models. The enhanced infiltration model was adapted to TRNSYS from chapter 27 of the *ASHRAE Handbook of Fundamentals* and the enhanced humidity capacitance model was already an integral part of TRNSYS. The models were used to evaluate a home built to the 30% energy savings level. In almost all cases, annual heating energy for the enhanced models *(see Figure 13)* was slightly higher than that of the same cases using the basic models *(see Figure 14),* while cooling energy needs were much lower. With dehumidification energy, the results were split, showing energy increases for the cases with high infiltration rates and no dehumidification energy use at all for the enhanced model cases with low infiltration rates. Overall energy use, including dehumidification, was lower using the enhanced models for every case; the largest differences occurred in the cases with lower annual infiltration rates, lower internal latent gains, and higher humidity set points. In the cases that most closely represented the lab home, the enhanced models resulted in a total annual space conditioning energy usage approximately 56% less than previously calculated using the basic models.

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