Demonstration and Performance Monitoring of Foundation Heat Exchangers (FHX) in Ultra-High Energy Efficient Research Homes

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ABSTRACT

The more widespread use of Ground Source Heat Pump (GSHP) systems has been hindered by their high first cost, which is mainly driven by the cost of the drilling and excavation for installation of ground heat exchangers (GHXs). A new foundation heat exchanger (FHX) technology was proposed to reduce first cost by placing the heat exchanger into the excavations made during the course of construction (e.g., the overcut for the basement and/or foundation and run-outs for water supply and the septic field). Since they reduce or eliminate the need for additional drilling or excavation, foundation heat exchangers have the potential to significantly reduce or eliminate the first cost premium associated with GSHPs. Since December 2009, this FHX technology has been demonstrated in two ultra-high energy efficient new research houses in the Tennessee Valley, and the performance data has been closely monitored as well. This paper introduces the FHX technology with the design, construction and demonstration of the FHX and presents performance monitoring results of the FHX after one year of monitoring. The performance monitoring includes hourly maximum and minimum entering water temperature (EWT) in the FHX compared with the typical design range, temperature difference (i.e., Δ T) across the FHX, and hourly heat transfer rate to/from the surrounding soil.

Introduction

Ground source heat pumps (GSHPs) are a promising and proven sustainable technology that can be applied to both residential and commercial buildings. Because the earth provides a more favorable heat source and heat sink than ambient air (i.e., the earth is cooler than outdoor air in summer and warmer in winter), GSHPs are one of the most efficient technologies available for space conditioning and water heating. However, according to a recent study (Liu 2011), less than 1 percent of U.S. houses use GSHP systems. One of the major barriers to more widespread use of GSHPs is high installation cost (Hughes 2008).

Various types of GHXs can be coupled to a GSHP, and the most common GSHP system utilizes a closed-loop ground heat exchanger. The cost premium of closed-loop GSHP systems over conventional space conditioning and water heating systems is primarily associated with drilling boreholes or excavating trenches, installing vertical or horizontal ground heat exchangers, and backfilling excavations.

Hence, a new GHX concept, the Foundation Heat Exchanger (FHX), was proposed as an effort to reduce the GHX installation cost. This concept takes advantage of the fact that in many cases, excavations made during the course of housing construction (e.g., the overcut for the basement and/or foundation and utility trenches for water supply and the septic field) can provide a significant portion of the trenching required for horizontal ground heat exchanger piping. The term foundation heat exchanger (FHX) has been coined to refer exclusively to ground heat exchanger installed in the overcut around basement walls. In general, the total length of the borehole or excavation needed for a building is a function of the building's space conditioning and water heating loads. In the case of ultra-high energy efficient homes, space conditioning and water heating loads may be so low that the excavations required to construct the buildings are sufficient to contain all of the ground heat exchanger necessary. But more generally, even when construction excavations are insufficient to contain the entire ground heat exchanger, there is cost savings associated with using them, and thereby minimizing the length of supplemental excavations. The remaining barrier to more widespread use of this unique heat exchanger concept is a better theoretical understanding of the thermal interaction between pipe, foundation wall, surrounding soil and surface conditions. It is also necessary to prove the concept by implementing the technology in full size houses.

Therefore, the research project described in this paper 1) developed and validated energy performance models and design tools so that FHX or hybrid systems (which include a FHX and supplemental heat rejection/absorption) can be engineered with confidence, enabling this technology to be applied in residential and light commercial buildings, and 2) proved the FHX concept in full size houses. The modeling and validation efforts have been described in several papers (Spitler et al. 2010, Xing et al. 2010, 2011, 2012, Spitler et al. 2010), and this paper describes the design, construction and demonstration of the FHX in two research houses in Oak Ridge, TN. and presents the performance monitoring results of the FHX after one year of operation.

Field Test of the Foundation Heat Exchanger Concept

Description of Two Research Houses

The two side-by-side research houses used for FHX demonstration have identical 3,700 ft^2 floor plans. In these unoccupied research houses, human impact on energy use is simulated, with showers, lights, ovens, washers, and other energy-consuming equipment turned on and off at times that match national average occupancy. Simulating occupancy eliminates a major source of uncertainty in whole-house energy consumption, enabling valid side-by-side experiments even when each "case" has a sample size of one.

The primary experiment using houses 1 and 2 involved testing two different envelope strategies - a structural insulated panel (SIP) envelope in House 1, and an Optimal Value Framing (OVF) envelope in House 2. As implemented, both of these strategies had very low air leakage and high levels of insulation, and thus have very low heat gain and loss through the building envelope, which of course contributes to their very low space conditioning loads. As mentioned earlier, the very low space conditioning loads of these two houses would be ideal for demonstrating FHX concept since the needs for additional conventional horizontal loop could be minimized. Figure 1 shows front views of the houses. The envelope characteristics of House 1 and House 2 are described in detail in a previous paper (Miller et al. 2010). Summary descriptions of the building envelope subsystems are provided in Table 1.

Figure 1. Front View of House 1 (right) and House 2 (left) from the Street

The two houses' cooling and heating design loads were calculated using "Manual J: Residential Load Calculation" method and associated tools developed by the Air Conditioning Contractors of America (ACCA). Space conditioning in houses 1 and 2 is provided by water-to-air heat pumps (WAHPs) connected to ground heat exchangers (combination of FHX and conventional HGHX, as described later). The WAHPs were sized using ACCA's "Manual S: Residential Equipment Selection" methodology as it applies to WAHPs. Based on the calculation, nominal 2 ton capacity units with two-stage compressors were selected for both House 1 and House 2. For comparison, typically in East Tennessee, a house built to code and having 3,700 ft^2 of floor space would require a 4 to 5 ton nominal capacity unit for space conditioning (Im et al., 2011). Supplemental electric resistance heat was also installed.

Description of Ground Heat Exchangers Installed in Houses 1 and 2

In designing the FHX, the team began with a design tool for sizing conventional HGHX loops was used as no FHX design tool was available at that time, and then engineering judgment was applied. The team selected a six-pipe configuration, meaning six ¾ inch diameter high-density polyethylene pipes in the excavations (three fluid circuits – out and back) with a minimum spacing of 1 ft between pipes. The soil thermal conductivity assumed was 0.75 Btu/(hr•ft•°F). Maximum and minimum heat pump entering fluid temperatures (EFTs) of 95°F and 30°F were used as the design constraints for sizing the ground heat exchanger. The necessary design values for heat extraction from the ground during winter and heat rejection to the ground during summer were derived from the space conditioning and water heating loads, and efficiency of equipment satisfying those loads, using a bin analysis. The calculation shows that there would be 300 feet of excavation required for house 1.

Then, the heat exchanger run was laid out over the house plan to see whether the construction excavation and utility trench would be sufficient to provide the required length of

Table 1. Description of House 1 and House 2 Building Envelope Subsystems

Envelope component	House 1 Structural Insulated Panel Strategy	House 2 Optimal Value Framing Strategy
Roof	IRR standing seam metal	IRR standing seam metal
Roof deck	SIPs	Foil facing on phenolic foam
Roof deck ventilation	Open at eave and ridge above sheathing	Open at soffit and ridge below sheathing
Sheathing	DELTA®-TRELA	Felt paper
Attic	R-35 Cathedral (SIPs 10 in.)	R-50 Cathedral (aged phenolic) 24 in. O.C.
Cladding	Hardie® board and stack stone	Hardie® board and stack stone
Exterior paint	CoolWall®	CoolWall®
Wall	R-21 SIPs (6 in. thick)	R-21 2x6 wood frame, 24 in. centers with ½ in. OSB
Wall cavity	SIP (EPS)	Flash & batt (½ in. foam with R-16 batt)
Window	Pella triple pane, third pane removable	Pella triple pane, third pane removable
Floor	20 in. truss between basement & first floor with installed ductwork and 18 in. truss between first and second floor.	20 in. truss between basement & first floor with installed ductwork.
Foundation	Basement	Basement
Weather-resistive barrier	DrainWrap™	Barritech VP Liquid applied
Foundation wall above grade	12 in. poured concrete with exterior 2 3/8 in. fiberglass drainage board insulation; stone facade	10 in. poured concrete with exterior 2 3/8 in. fiberglass drainage board insulation; stone facade
Foundation wall below grade	12 in. poured concrete with exterior 2 3/8 in. fiberglass drainage board	10 in. poured concrete with exterior 2 3/8 in. fiberglass drainage board

heat exchanger pipe, or whether additional conventional horizontal loop would be needed. Since the north and west basement walls provides about 100 feet of excavation length, the remaining 200 feet of excavation is provided in the form of utility or supplemental trenches. Of the remaining 200 ft, 80 feet of excavation is provided by utility trench. The remaining 120 feet of HGHX was installed on the south side of the house. In other words, 60% (180 of 300 ft) of the excavations used for installation of the ground heat exchanger were required anyway to construct the home. Figure 2 presents the final layout of the designed FHX loop over the house 1.

It was estimated that 360 feet of excavation would be required for House 2. Again, the effective FHX excavation length is approximately 100 ft, so in this case an additional 260 ft is required. The layout of the ground heat exchanger at House 2 (the OVF House) is illustrated in Figure 3. The trench for the buried electrical service entrance (northwest or upper left) provided 50 ft; the trench for the supply water connection (northeast or upper right) provided 30 ft; and the equivalent six-pipe trench (in the rain garden or not) south of the house provides the remaining 180 ft of the 260 ft required. In other words, 50% (180 of 360 ft) of the excavations used for installation of the ground heat exchanger were required anyway to construct the home.

In both houses, the depth of the pipe from the surface to the bottom of the foundation excavation is about 7 – 8 ft, and the distance from the pipe on the excavation wall to foundation wall is about 3 – 4 ft. Figure 4 show the FHX in the construction overcut and the horizontal ground heat exchanger (HGHX) in the utility trench.

Ground Heat Exchanger Performance Measurements

Measurement Setup

Measurements taken to establish FHX/HGHX performance and enable model validation included the thermal loads (heat rejection and extraction) to the FHX/HGHX imposed by the heat pump, undisturbed far field temperature of the soil at various depths, numerous temperatures on the outside surface of the pipes, basement wall heat flux, drainage board and near-wall soil temperatures in a few locations, soil thermal conductivity, and weather data at the demonstration site. There are approximately 70 thermistors installed per house for temperature measurements at various points, and the data has been measured at 15-minutes intervals since December 2009.

The manufacturer of the WAHP and WWHP units installed a differential pressure transducer across the fluid side of the internal fluid-to-refrigerant heat exchanger and used factory turbine flow meter measurements to generate calibration curves for heat exchanger pressure drop vs. ground heat exchanger flow rate at several entering fluid temperature (EFT) values. These software-implemented calibration curves enabled fluid flow rate through the unit to be deduced from the pressure drop measurement during the field experiment. The valve modulating the fluid flow through the WWHP unit can result in very low flows under some operating conditions and insufficient measurement accuracy of the flow rate using the calibration curve approach. Therefore a redundant turbine flow meter measurement was included in the field experiment. Since the WAHP and WWHP were plumbed in parallel, the total FHX/HGHX fluid flow rate equaled the sum of the fluid flow rates through the separate units.

The manufacturer also installed thermal wells on the inlet and outlet of the fluid side of the internal fluid-to-refrigerant heat exchanger. The thermal wells were used for fluid temperature measurements during the field experiment. Heat rejection to, or extraction from, the FHX/HGHX was deduced from the measurements of fluid flow rate and inlet and outlet fluid temperatures whenever the WAHP and WWHP compressors were operating. Appropriate corrections were applied during calculation to account for the working fluid being 20% propylene glycol by weight in water, rather than pure water.

Undisturbed far field soil temperature measurements were taken at two different locations at 3, 4, and 5 ft depths at houses 1 and 2. The locations of these measurements are shown in figures 2 and 3. The temperature measurements were made with thermistors that were carefully calibrated prior to installation.

Figure 2. Layout of the FHX and HGHX at House 1 (Numbers show measurement points)

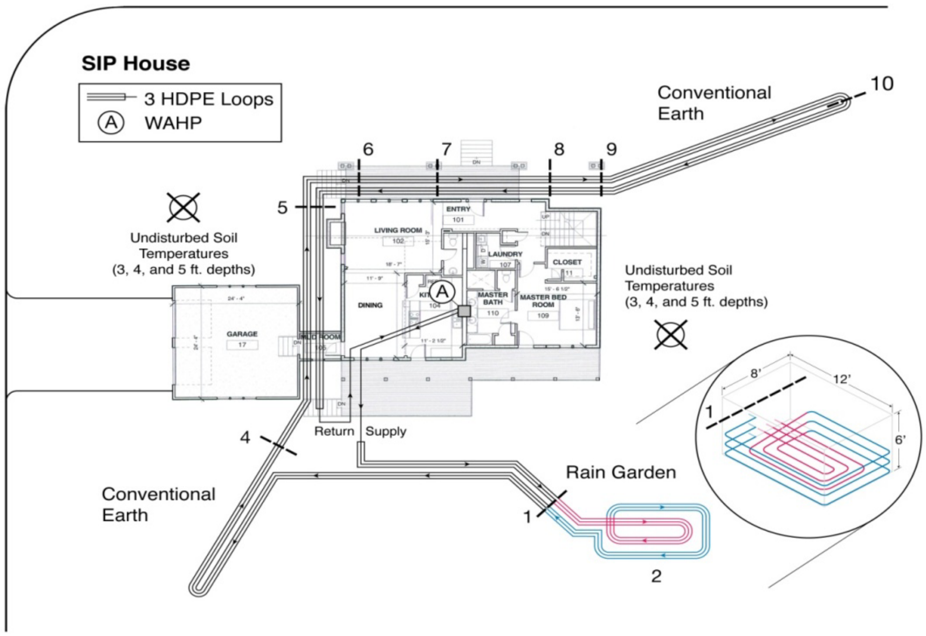


Figure 3. Layout of the FHX and HGHX at House 2 (Numbers show measurement points)

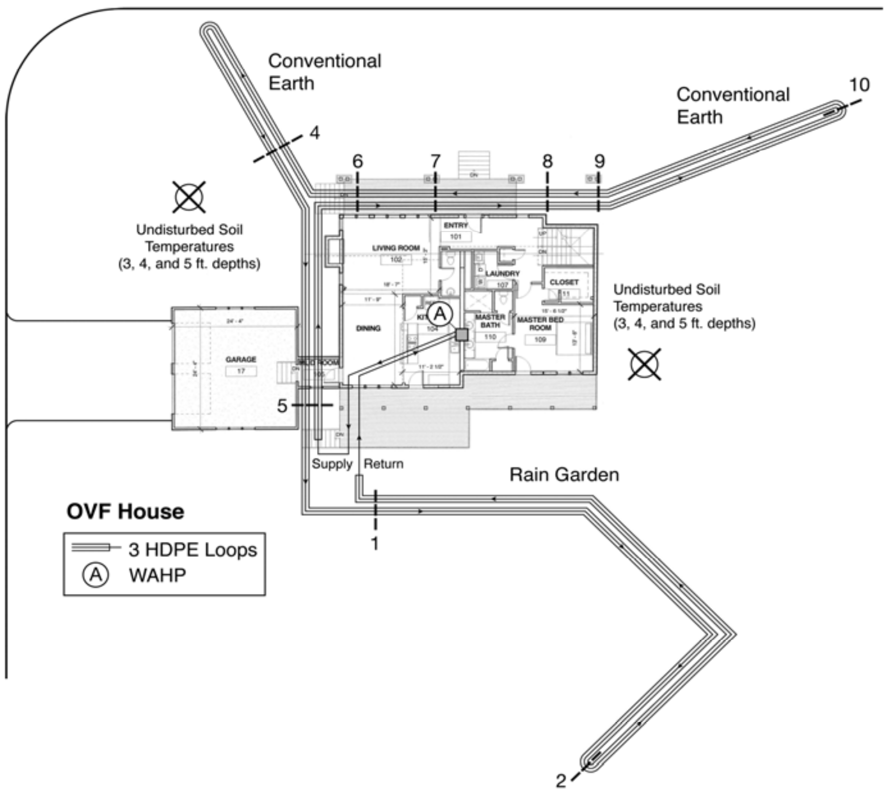
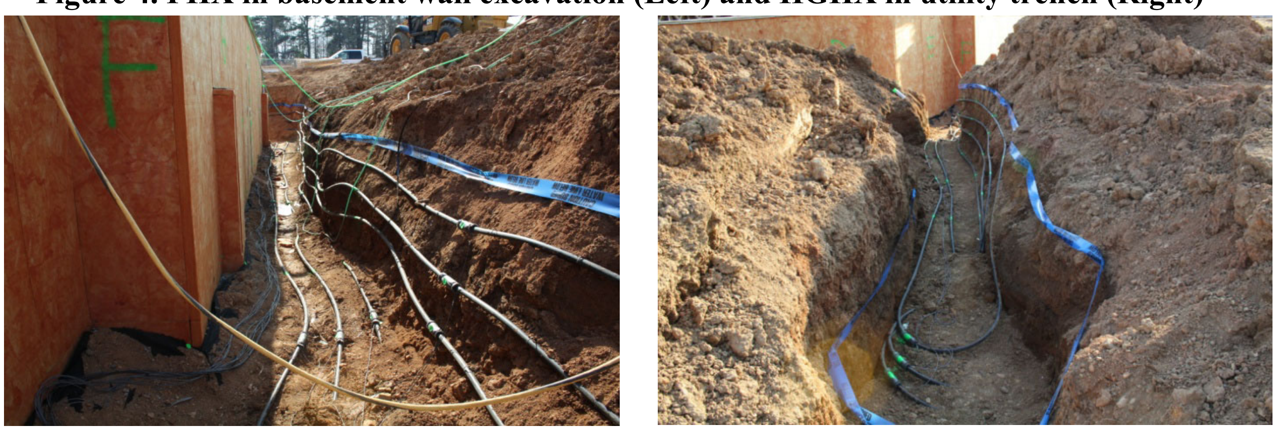


Figure 4. FHX in basement wall excavation (Left) and HGHX in utility trench (Right)



Fluid temperatures along the FHX/HGHX pipes were approximated by measuring the outside pipe surface temperature of all six pipes at nine different locations, numbered as 1, 2, 4, 5, 6, 7, 8, 9, and 10 (the number 3 was not used) in figures 2 and 3. All temperature measurements were made with thermistors that were carefully calibrated prior to installation. The thermistors were applied directly to the outside of the pipes and then wrapped with insulation. For clarity on what was done, Figure 5 identifies for House 1 the nine pipe measurement locations and two undisturbed soil temperature measurement locations. At both houses, six heat flux transducers were installed to measure heat flux through the basement wall. Three of the wall heat flux transducers were located at pipe temperature location 6, and the remaining three at pipe temperature location 7. Center lines of the transducers were approximately 1, 4, and 7 ft below grade at both locations. Also at locations 6 and 7, temperatures were measured at the outside of the drainage board insulation at 1, 4, and 7 ft below grade, and in the soil 2 ft from the basement wall at 1 and 3 ft below grade.

Measured Performance

Measured performance for the space conditioning systems at houses 1 and 2 is summarized in tables 2 and 3. In both houses the heating and cooling thermostat set points in all four zones were maintained throughout the year at 71 and 76°F. It appears that the hybrid FHX/HGHX systems were reasonably well sized at both houses. Annual maximum EFTs measured at houses 1 and 2 were 93.2°F and 90.3°F, and minimums were 33.4°F and 33.7°F, respectively. These values compare well with the design values for maximum and minimum EFT of 95°F and 30°F used to size the FHX/HGHX. The measured WAHP heating and cooling COPs are also about what would be expected for a GSHP system with a properly sized ground heat exchanger. Data analysis beyond what is shown in the tables indicated that heating and cooling set points maintained throughout the year were 71°F and 76°F, respectively, and the supplemental electric resistance heating elements were never activated at House 1 and consumed only 66 kWh at House 2, which verifies that the WAHPs were appropriately sized at 2 tons nominal capacity.

Measured performances (annual COPs) of the water heating systems at houses 1 and 2 were 3.1 and 2.6, respectively. Although the water heating COPs observed at House 1 were as expected, the water heating COPs at House 2 were considerably lower. The lower than expected water heating efficiency at House 2 was attributable to a smaller source-side pump than in House 1. As a result the WWHP experienced lower loop flow, especially when it had to compete with the larger pump in the WAHP when both were operating simultaneously. Due to these unexpected results from house 2, the data set from House 1 was used to validate the FHX/HGHX models and design tool.

Figure 6 shows hourly trend plots for several variables for the period January through November 2010 for House 1. The figure shows the entering and leaving fluid temperature for the WAHP, outside air temperature, undisturbed (far field) and disturbed (in excavation)

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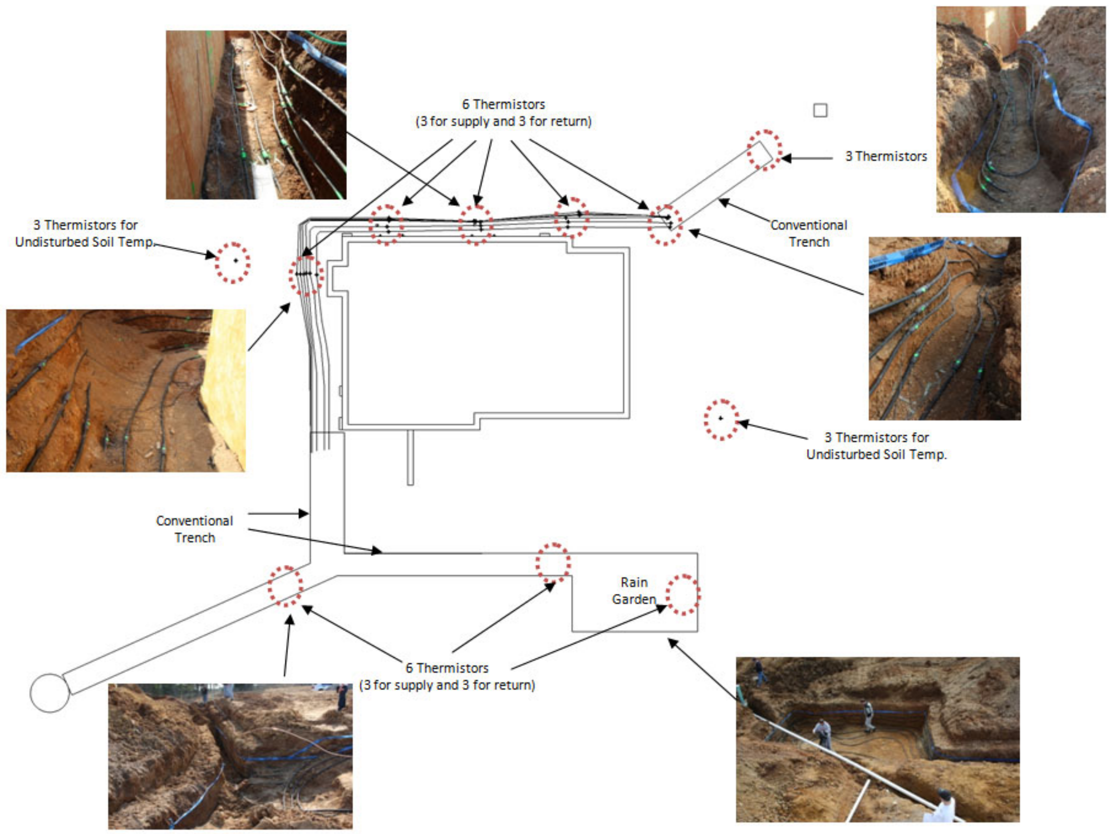
Figure 5. Location of Pipe and Undisturbed Far Field Soil Temperature Sensors at House 1



underground temperature, and delta T (i.e., entering fluid temperature minus leaving fluid temperature). The periods of cooling only, heating only, and mixed cooling/heating are also noted. Outdoor air temperature ranges from 8 to 96°F, while the undisturbed underground temperature at a 5 ft depth ranges from 45 to 78°F, which explains the potential for horizontal GSHP systems to perform better than air-source heat pumps. Also note that outdoor air temperature can fluctuate by over 20°F in a day, while soil temperature at a 5 ft depth changes very little in any given day. As expected, the absolute value of delta T across the FHX/HGHX in cooling mode of 5.7°F exceeds the heating mode value of 3.7°F, because in cooling mode heat

Table 2. Summary of measured performance of space conditioning system at House 1[a]

Month	*Electric Consumption*		*Energy Delivered/Removed (Loads Met)*		*Coefficient of Performance (COP) (Includes Pumping)*		*"On" Entering Fluid Temp. (EFT)*			*"On" Average Outdoor Air Temp. (OAT)*	
	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating	Cooling	Min (°F)	Avg. (°F)	Max. (°F)	Heat (°F)	Cool (°F)
10-Jan	856.1	0	3051	0	3.6		36.6	40.3	45.8	31.7	
10-Feb	823.9	0	2829.9	0	3.4		33.4	37	40.9	33.3	
10-Mar	565.8	0	1987.1	0	3.5		33.6	38.7	44.5	44.5	
10-Apr	61.8	36.3	252.9	218.3	4.1	6	41.9	51.2	58.4	51.9	76.3
10-May	0.5	158.7	2.2	857.1	4.6	5.4	55.2	63.8	70.1	53.8	75.9
10-Jun	0	387	0	1789.1		4.6	65.6	75.8	84.8		81.4
10-Jul	0	532.5	0	2182		4.1	75.6	83.8	89.5		82
10-Aug	0	635.1	0	2394.1		3.8	81.7	89	93.2		81.7
10-Sep	0	384.3	0	1508		3.9	78.8	86.2	93.2		77.4
10-Oct	2.9	46.9	14.2	211.5	4.9	4.5	65.1	76.1	83.6	38.7	69.8
10-Nov	137.4	0	625.2	0	4.6		55.2	60.9	67.8	39.5	
10-Dec	842.4	0	2973.3	0	3.5		-	44.8	-	31.3	
Total	**3,290.8**	**2,180.8**	**11,735.8**	**9,160.1**	**3.6**	**4.2**	**33.4**	**59.8**	**93.2**	**35.4**	**80.1**

[a] December values are estimated.

Table 3. Summary of measured performance of space conditioning system at House 2[b]

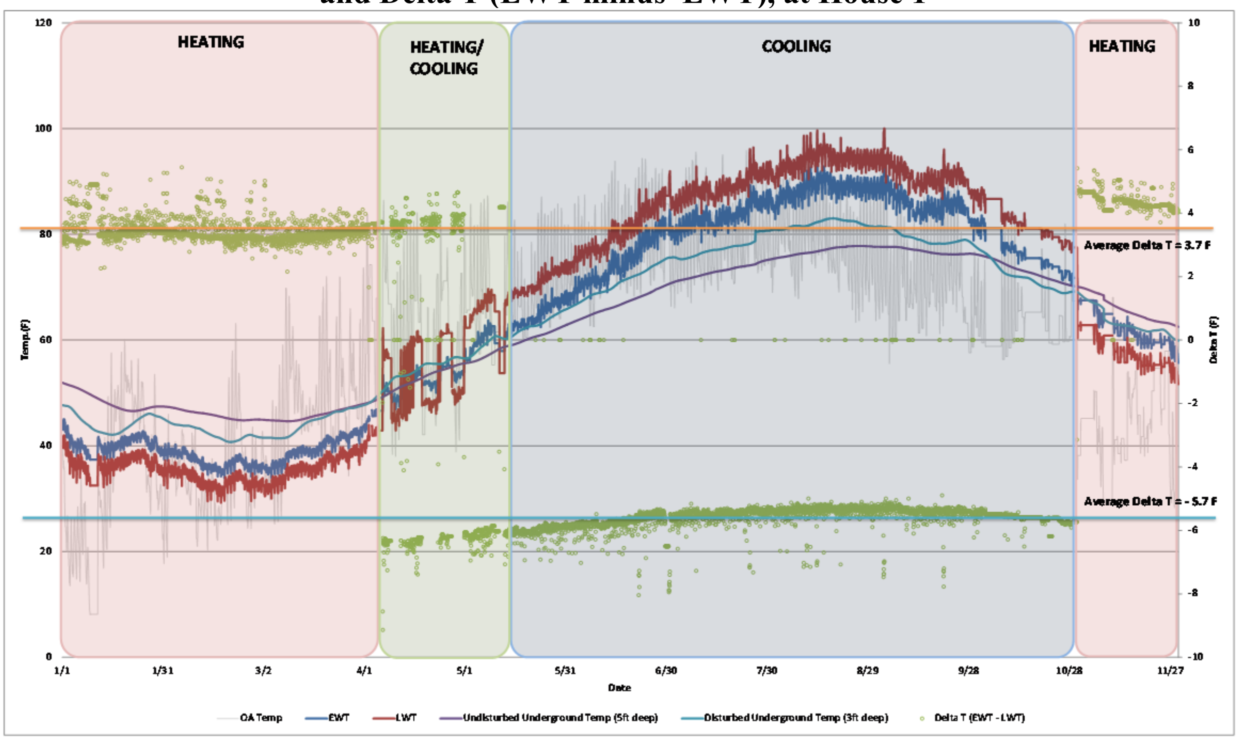
Month	*Electric Consumption*		*Energy Delivered/Removed (Loads Met)*		*Coefficient of Performance (COP) (Includes Pumping)*		*"On" Entering Fluid Temp. (EFT)*			*"On" Average Outdoor Air Temp. (OAT)*	
	Heating (kWh)	Cooling (kWh)	Heating (kWh)	Cooling (kWh)	Heating	Cooling	Min (°F)	Avg. (°F)	Max. (°F)	Heat (°F)	Cool (°F)
10-Jan	1084.4	0	3801.1	0	3.5		36.8	39.8	47.3	32.1	
10-Feb	1028.6	0	3495.6	0	3.4		33.7	36.2	39.4	33.9	
10-Mar	684.8	0	2399.4	0	3.5		34.3	38.9	43.9	45.1	
10-Apr	126.9	37.6	531.3	235.8	4.2	6.3	42.5	51.3	56.3	55	77.3
10-May	7.3	157.1	33.4	841.8	4.6	5.4	54.8	63.3	68.9	55.5	77.6
10-Jun	0	442.5	0	1967.1		4.4	66.2	75.1	80.8		82.3
10-Jul	0	610.9	0	2403.7		3.9	75.8	82.6	87.3		82.3
10-Aug	0	667.1	0	2437.5		3.7	81.9	87.2	90.3		82.1
10-Sep	0	352.2	0	1353		3.8	78.2	84	88.1		78.6
10-Oct	8.3	17.9	41.1	79.5	5	4.4	66.8	73.6	79.9	39.4	73.3
10-Nov	210	0	956.4	0	4.6		55.5	60.3	68.2	42.8	
10-Dec	1,056.7	0	3,689.5	0	3.5		-	43.1	-	31.9	
Total	**4,207.0**	**2,285.3**	**14,947.8**	**9,318.4**	**3.6**	**4.1**	**33.7**	**55.0**	**90.3**	**36.4**	**81.5**

[b] December values are estimated.

rejection includes the load met plus WAHP power consumption, whereas in heating mode the heat extraction equals the load met less the WAHP power consumption.

Monthly heat transfer between the WAHP and WWHP and the ground (rejection or extraction) at houses 1 and 2 is summarized in tables 4 and 5. Net heat transfer to the ground on an annual basis was nearly zero (well balanced) at House 1, and showed a modest net extraction at House 2. If the ground heat exchangers served only space conditioning (rather than also serving water heating), both houses would have had a modest annual net heat rejection. This infers that there will be no significant long term operation penalty that can be found in a GSHP system with unbalanced heat rejection and extraction.

Figure 6. Hourly Trends for Outdoor Air (OA), Entering and Leaving Water/Fluid Temperature (EWT or LWT), Undisturbed Ground and Disturbed Ground Temperatures, and Delta T (EWT minus LWT), at House 1



Summary

This project investigated reducing the cost of horizontal closed-loop ground heat exchangers through the use of construction excavations augmented when necessary with supplemental trenches. Two side-by-side, three-level, unoccupied research houses with walkout basements, identical 3,700 ft^2 floor plans, and hybrid FHX/HGHX systems were constructed to demonstrate and monitor the performance of the system in full size houses. The project shows that around 50% to 60% of the total ground loop can be installed in existing construction excavation or utility trenches that were required anyway to construct the home, which will significantly reduce the excavation cost for GHX.

Table 4. Monthly Heat Transfer Between Heat Pumps and the Ground at House 1 (kBtu/month)[c]

	WAHP heat rejection	WAHP heat extraction	WWHP heat extraction	Sum of extraction/rejection
Jan	0	6,504	986	7,490
Feb	0	6,578	870	7,448
Mar	0	4,688	963	5,651
Apr	-866	650	802	586
May	-3,445	6	853	-2,586
Jun	-7,123	0	833	-6,290
Jul	-9,220	0	739	-8,481
Aug	-10,278	0	902	-9,376
Sep	-6,422	0	997	-5,425
Oct	-880	46	1,046	213
Nov	0	1,379	994	2,372
Dec	0	7,261	1,019	8,280
Total	**-38,233**	**27,112**	**11,003**	**-118**

[c]December values are estimated.

Table 5. Monthly Heat Transfer Between Heat Pumps and the Ground at House 2 (kBtu/month)[d]

	WAHP heat rejection	WAHP heat extraction	WWHP heat extraction	Sum of extraction/rejection
Jan	0	8,925	714	9,639
Feb	0	8,014	723	8,736
Mar	0	5,658	916	6,575
Apr	-930	1,376	754	1,200
May	-3,395	89	807	-2,499
Jun	-5,753	0	700	-5,052
Jul	-9,961	0	663	-9,298
Aug	-10,491	0	561	-9,930
Sep	-5,797	0	709	-5,088
Oct	-330	112	755	537
Nov	0	2,496	841	3,337
Dec	0	9,335	845	10,180
Total	**-36,658**	**36,005**	**8,989**	**8,336**

[d]December values are estimated.

The 1 year monitored datasets shows that measured equipment performance at houses 1 and 2 were as expected in GSHP systems with a properly sized ground heat exchanger. The measured performance data included WAHP heating season COPs of 3.6 and 3.6, WAHP cooling season COPs of 4.2 and 4.1, respectively. WWHP annual COPs for House 1 and 2 were 3.1 and 2.6, respectively. Annual maximum heat pump EFTs measured at houses 1 and 2 were 93.2°F and 90.3°F, and minimums were 33.4°F and 33.7°F, which can be compared well with the design values for maximum and minimum EFT of 95°F and 30°F used to size the FHX/HGHX. Heating and cooling set points maintained throughout the year were 71°F and 76°F, respectively, and the supplemental electric resistance heating elements were never activated at House 1 and consumed only 66 kWh at House 2, which verifies that the WAHPs were appropriately sized at 2 tons nominal capacity.

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