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INTERIM REPORT

Radiant Heating Field Test Report

October 2012

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Abstract

This report covers the field testing of two prototype hydronic radiant heating and cooling systems operating in heating mode. The testing was performed in two research houses in Sacramento over the 2011-2012 heating season. Both systems were operated under thermostat control with a fixed setting chosen by the occupants. A high-efficiency storage water heater with a closed secondary heating loop was chosen as the heat source. In the Grandstaff house, testing went smoothly and savings of 34% were demonstrated for the heating season. In the 6th Avenue house, the savings was 57% for the heating season. The results show that the hydronic distribution loop, control system, and the radiant panels worked as expected. Comfort was improved from the traditional warm air system in the Grandstaff house – the homeowner reduced the thermostat setpoint from 70°F to 68°F during the first month of operation.

Keywords: Residential, radiant heating, hydronic systems, radiant panels, high-efficiency, Measured Home Performance, retrofit, comfort

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Executive Summary

The objective of this project is to develop and demonstrate a residential radiant heating and cooling system with high efficiency heating and peak load shifting on the cooling system. The major components of the system include radiant panels, water chiller, water heater, pumps and controls, and the hydronic distribution system. This report covers the field testing of the heating system in two houses located in California Building Climate Zone 12 in Sacramento during the 2011-2012 heating season. This climate zone is characterized by a summer 2.5% design temperature of 97° F and a winter 97.5% design temperature of 30° F. There are 1470 cooling degree days and 2702 heating degree days.

The radiant heating system performed very well in the heating season tests. The A. O. Smith Vertex 76,000 Btu/hr input capacity water heater with 96% thermal efficiency was sufficient to meet the load of the Grandstaff and the 6th Avenue houses during the winter, although the 6th Avenue house had evidence of supplemental heating. The radiant panels performed well in both houses. The design conditions of 15 Btu/hr/sf of radiant heat from the panels at 120°F and 0.01 gpm of hot water per square ft. of panel are confirmed in these studies.

Gas energy savings from Grandstaff was 34% compared to its baseline performance, determined by a utility bill analysis. In Grandstaff, the thermostat setpoint was lowered from 70°F to 68°F in the first month of testing by the homeowner due to the improved thermal environment. If the setting would have been left at 70°F for the entire heating season, energy savings from natural gas would have been slightly lower.

In the 6th Avenue house, energy savings from natural gas was 57% when compared to the average of the two prior years as a baseline consumption data point. The occupant interacted frequently with the heating system, so savings are based on an assumption of consistent interaction with the system over the three year period examined in the study.

The conclusions from the heating season test of the two houses is that the energy reduction associated with the radiant heating system and the Measured Home Performance improvements produced an average savings of 45% for the two houses in the Sacramento area with improved comfort. It is not possible to separate the effects of the two factors in this study, however a predicted savings for the increase in efficiency of the heating plant alone would yield a 15% savings for Grandstaff (vs. 80% AFUE furnace) and 30% savings for 6th Avenue (vs. 65% efficient heating system), leaving approximately 25% savings to be spread between thermal envelope improvements, the performance of the radiant heating system and the use of a lower thermostat setpoint.

Field Test Plan Updated

The original field test plan for the project was submitted in February of 2011. Since that time, several changes have been made to the number and types of houses used in the test and the general approach to the system design. The remainder of this section provides the updated field test plan that was used for this project.

Purpose

The purpose of the field tests is twofold:

1. To demonstrate the viability of the combined heating/cooling radiant system in residential applications in order to further the project goal of bringing the system to market.
2. To gather detailed information on the performance of all aspects of the system under 'normal' use conditions. Performance of the panel design, chilled water storage system, off-peak vapor compression cooling system, gas-fired hot water heating system, and associated pumps, valves, and controls will be investigated. The complete design is provided in the System Design report.

The field test will allow the research team to assess the suitability and operation of the various components, as well as of the system as a whole, and to determine what modifications may be needed to move forward into a commercial phase of the project.

Location

Two systems were installed. Due to the downturn in the residential building industry, both systems were installed as retrofits. This will affect the installation costs of the test systems compared to installation in new construction, but the information gathered allows a determination of the additional costs or savings that would be incurred in new construction.

Both locations were in SMUD territory in Sacramento and in California Building Zone 12 (see Figure 1).

The first site is on Grandstaff Drive (will be referred to as "Grandstaff") and has the following characteristics:

- Single story
- Slab on grade construction
- Three bedrooms
- 1 ½ baths
- Two car attached garage

- Built in 1972
- Approximately 1000 square ft.

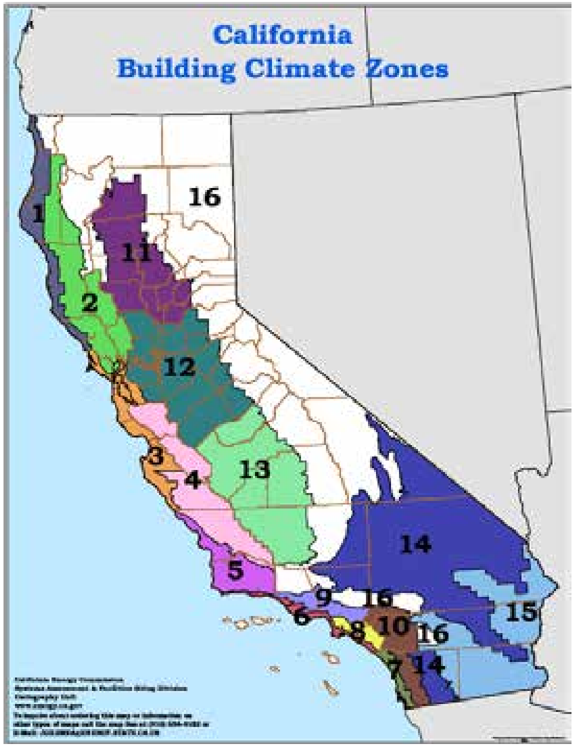

Figure 1 California building climate zones

Figure 2, below, shows the Grandstaff site.


Figure 2 Grandstaff field test house

Figure 3, below, shows the Grandstaff house floor plan.

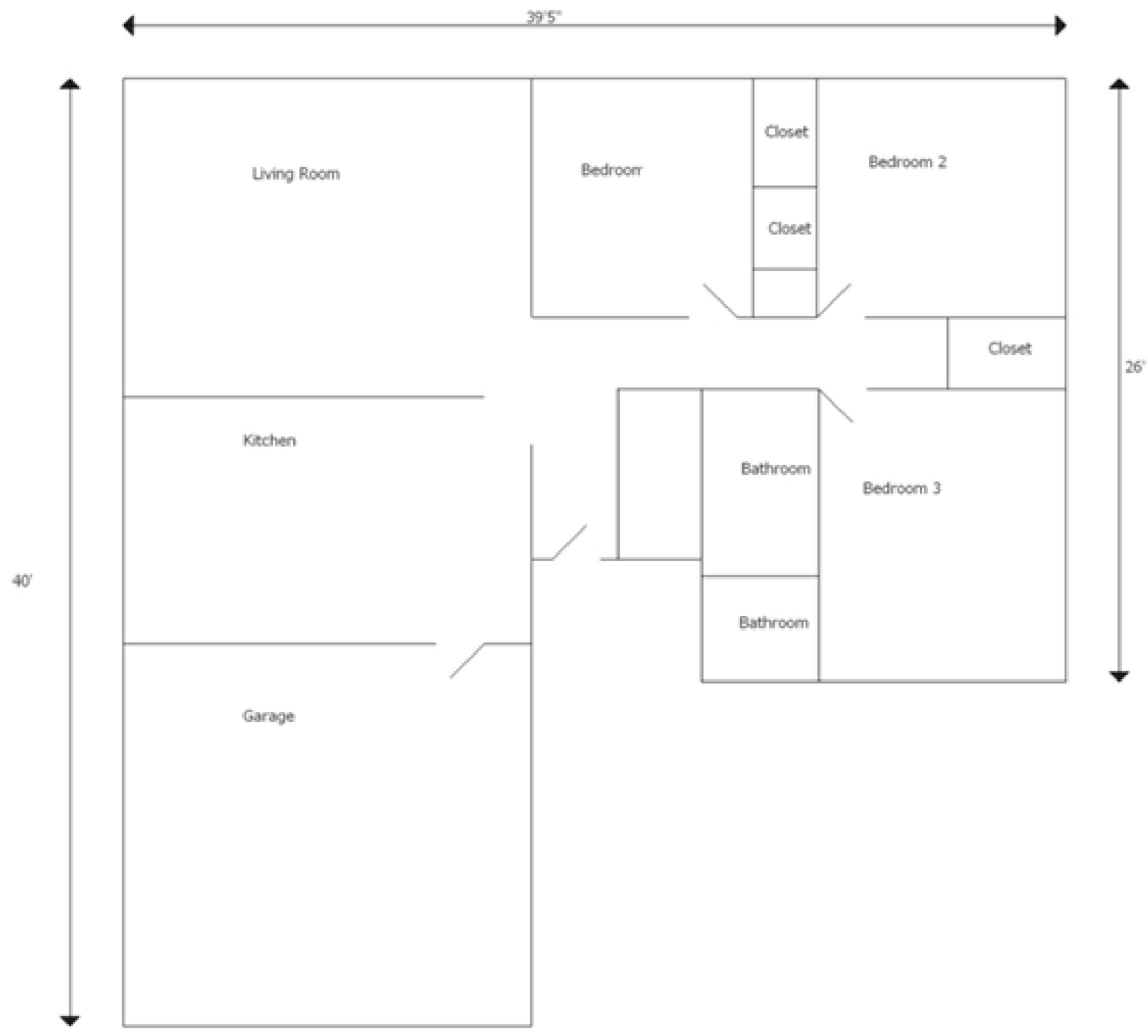

Figure 3 Grandstaff house floor plan

The second field test site is on 6th Avenue ("6th Avenue") and has the following characteristics:

- Single story
- Crawl space construction
- Three bedrooms
- 1 ½ baths
- Detached garage
- Balloon framing

- Built in 1930
- Approximately 1000 square ft.

Figure 4, below, shows the 6th Avenue house.

Figure 4 6th Avenue Field Test House

Figure 5, below, shows the 6th Avenue floor plan.

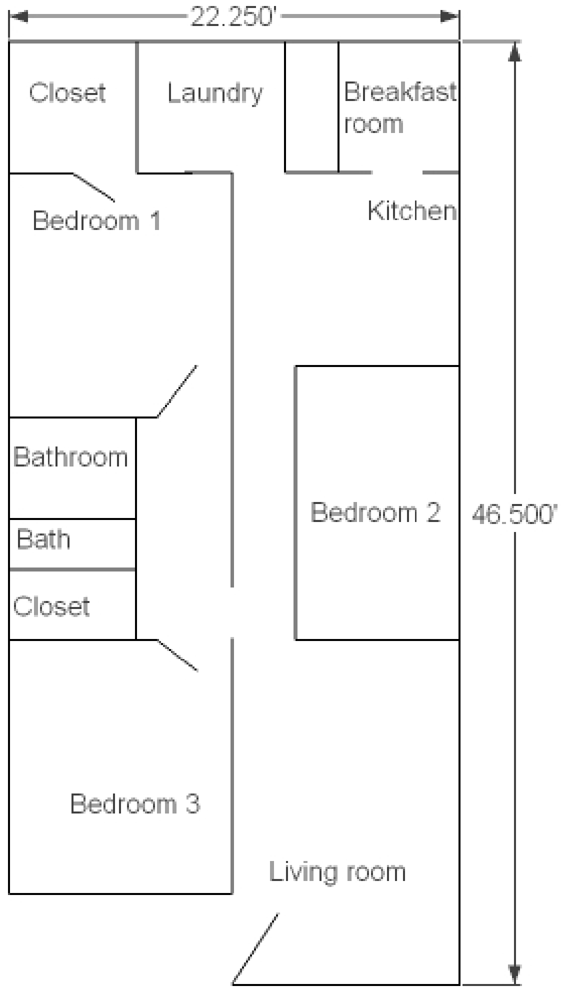

Figure 5 6th Avenue floor plan

Installation

The critical path for installation is:

- Site visit to measure dimensions and plan layout
- Assemble system components
- Install system and controls
- Install sensors and data acquisition hardware
- Commission system

The systems will all be installed by Beutler Heating and Air. The team is working with Beutler on lab testing the storage tank component of the system which will provide continuity between the lab and field tests in addition to ensuring that the install team is familiar with the system.

Monitoring

System performance (measured both in terms of energy use and occupant comfort) will be monitored. Occupant comfort will be self-reported by participants.

Data acquisition will be done using a DataTaker DT85 to log the readings from all the sensors. The DT85 uses a built in cellular modem to allow remote monitoring and downloading of data. The remote monitoring reduces the need for frequent site visits.

Monitoring will be broken down into three areas:

1. Energy: Power consumption will be monitored separately for the compressor and by the water pump. Electrical power is measured using a voltage and current pickups attached to the power cables Power will be monitored using a Dent Powerscout. The Powerscout communicates with the DT85 using the ModBus protocol. We will also be logging the thermostat settings to allow analysis of user behavior. Gas usage will be computed by monitoring using a supplemental gas meter with magnetic pick-up. In addition, the state of the gas valve on the burner will be monitored. Gas consumption will be monitored by a new diaphragm gas meter.
2. Air conditions: Thermocouples will be used to monitor the air temperature, and capacitive sensors will be used to monitor the humidity. There will be one temperature and one humidity sensor in each room of the house, and one on the outside of the house. External sensors will be mounted so as to avoid direct sunlight. All thermocouples and humidity sensors connect directly to the DT85 for logging.
3. Water conditions: Temperature and flow will be monitored. The temperature of the water in the tank and at the inlet and outlet of the panels will be monitored using thermocouples. The flow rate will be monitored using a paddle wheel-type water sensor. As with the thermocouples, the paddle wheel flow sensor is logged using the DT85.

More details are provided in the table below:

Table 1 Details of instrumentation

Measurement	Device	Accuracy
Temperature (air)	Omega EWS-RH	±1.2°F
Relative humidity	Omega EWS-RH	±3% RH
Temperature (water)	Shielded T-Type Thermocouple	±1°F
Water flow rate	Omega FP-5600	±1% FS, 200 pulses/gal.
Gas flow rate	AC-250 Diaphragm Meter	1cuft
Electric power	Dent Powerscout 3	±0.5%

Data acquisition is logged once per minute and stored locally using a DT85 Datataker. Data is uploaded to the WCEC ftp server daily at 6am, and is retained on the Datataker for backup.

Details of the Datataker can be found at http://datataker.com/DT85M.php.

Data analysis

The data collected will be continuously monitored and evaluated on an ongoing basis throughout the field test in order to identify any problems as they arise. Full analysis of all the data collected will be carried out at the end of the test.

Schedule

Installation was scheduled for the summer of 2011, with initial site visits carried out in March and April, with the systems fully commissioned in the summer to allow monitoring throughout the 2011/2012 heating season (through April 15) and the 2012 cooling season until the end of September.

Field Test Site Installation

Two radiant panels were used in the field test. The first was a prototype panel (Tube Panel); and the second was a commercial product sold by Uponor in Europe (Uponor Panel). For the Details of the two panel designs are as follows:

Tube Panel (see Figure 6):

- Size – nominal 4 ft. x 8 ft. (actual 48.25 inches by 104.00 inches)
- Aluminum thickness – 32 mil (.032 inches), painted
- Fiberglass board thickness and density – 1 inch, 7 lb. per cubic ft. density
- Tubing material, size, layout – HDPE, serpentine layout with tubes 6 inches apart
- Mounting method – screw into ceiling joists; small washers may be needed

Figure 6 Tube Panel (photo from the lab)

Figure 7 shows the Uponor Panel. This is a commercial product. The approximate product characteristics are:

- Size – 500 mm x 1200 mm.
- Drywall bottom layer 15 mm thick.
- 10 mm plastic tube (assumed to be PEX) in a channel cut into the drywall
- 27 mm EPS foam insulation on the upper surface
- Mounting method – screw into ceiling joists or furring strips – metric size requires some framing
- Design issues – commercial product in Europe

Figure 7 Uponor Panel

The Grandstaff house was fitted with Uponor Panels in 18 circuits and the 6th Avenue house was fitted with Tube Panels. Figure 8 shows the 6th Avenue house panel layout and Figure 9 shows the Grandstaff house panel layout.

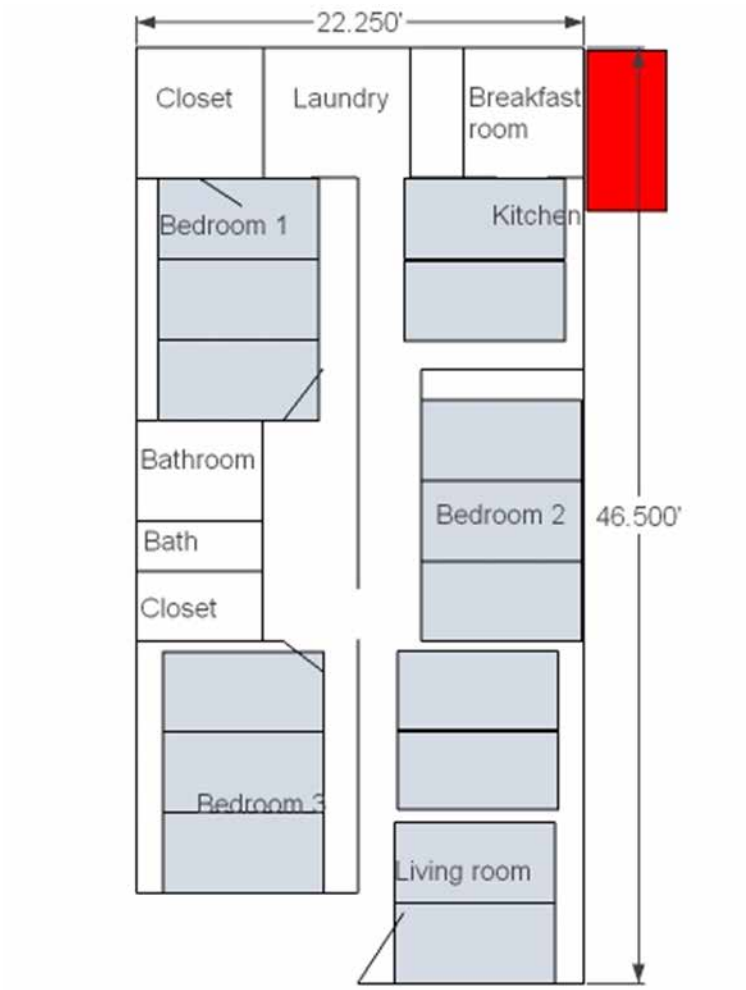

Figure 8 6th Avenue house panel layout

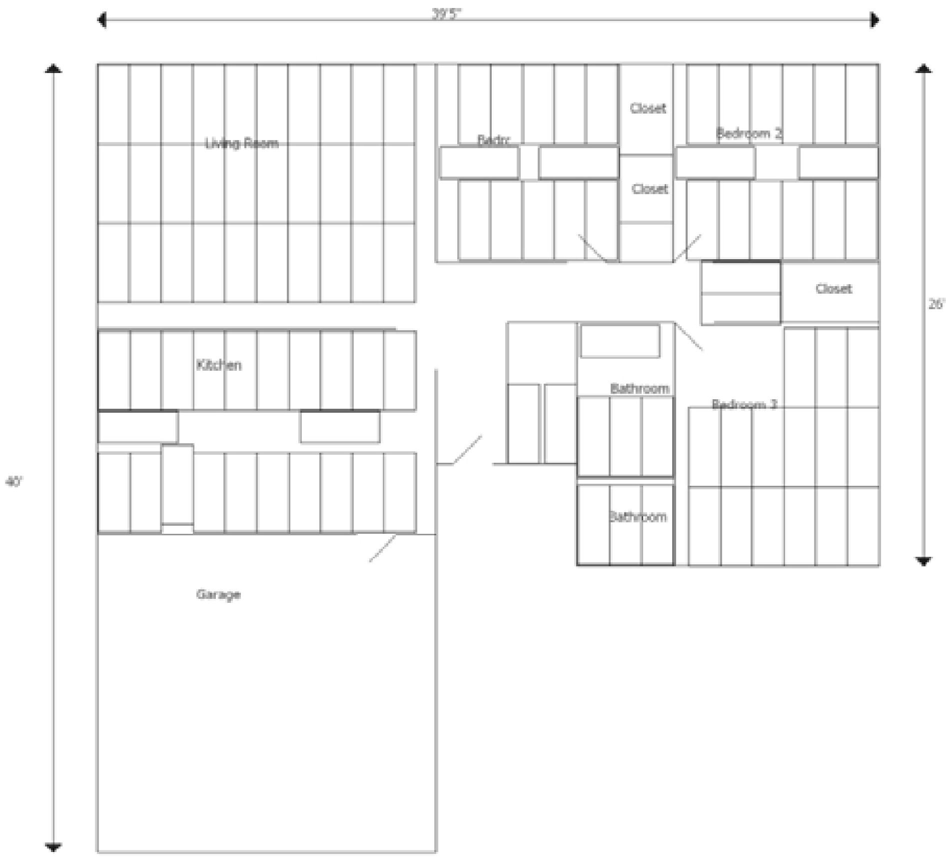

Figure 9 Grandstaff house panel layout

The hydronic system was installed as described in the Test Plan in the section above. For heating, 15 Btu/hr/sf was used for the design conditions of both types of panels. The 6th Avenue heating water flow rate was set at 4.8 gpm for the whole house with 15 panels, or about 0.01 gpm/sq. ft. of panel at 120°F, consistent with the laboratory test results. The flow rate for the Grandstaff house was set at 6.5 gpm for the whole house with 88 panels, also at 0.01 gpm/sq. ft. of panel. The Vertex water heater was set at 120°F to provide the temperature required for the test.

Figure 10 shows the layout of the radiant heating and cooling system in a 3-D sketch. Note the position of the chilled water storage tank next to the A/C condenser and the routing of the plumbing to the hydronic distribution and control system.

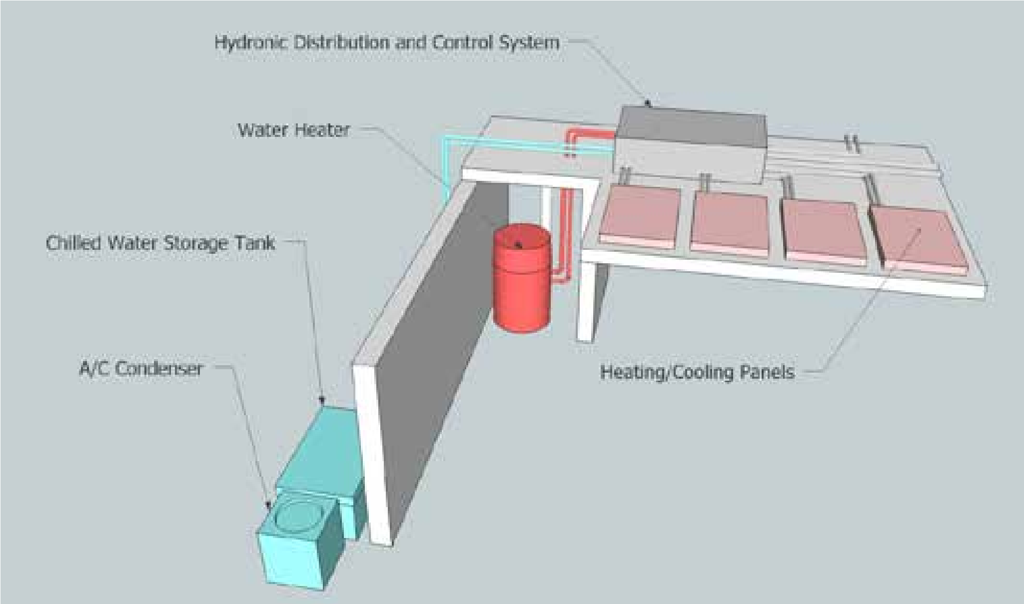

Figure 10 Schematic of radiant heating and cooling system

Figure 11 shows a schematic of the distribution and control system in the Grandstaff house in a 3-D sketch. Note the manifold for the 18 separate hydronic loops and the 3-way valve for switchover from heating to cooling.

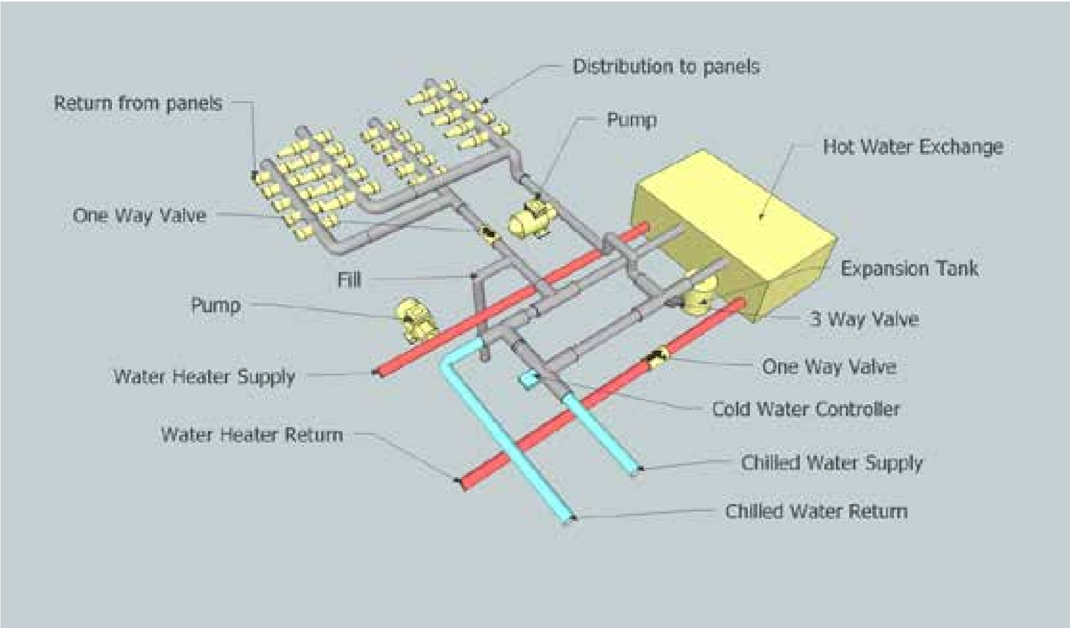

Figure 11 Schematic of hydronic distribution and control system

Figure 12 through Figure 19 show various components of the system before and during installation.

Figure 12 Uponor panels installed in the Grandstaff house

Figure 13 Uponor piping manifold in Grandstaff house

Figure 14 Hydronic system in Grandstaff house

Figure 15 Chilled water storage tank in Grandstaff house

Figure 16 High efficiency water heater installed in Grandstaff house

Figure 17 High efficiency water heater in the lab showing with side mount heat exchanger

Figure 18 Tubing installation in the attic of the 6th Avenue house

Figure 19 Radiant panels installed in the 6th Avenue house

Installation of the panels, hydronic system, and data acquisition system was followed by application of Measured Home Performance thermal envelope improvements by Chitwood and Associates. See Figure 20 and Figure 21 for photos.

Figure 20 Measured Home Performance installation in Grandstaff house

Figure 21 Measured Home Performance installation in 6th Avenue house

Data Collection and Analysis

Data collection for the heating tests followed the test plan. Key test points included:

- Temperature and relative humidity in each room
- Water flow rates for the entire system
- Water heater gas consumption (gas meter)
- Whole house gas consumption (gas meter and utility bills)
- Operating hours
- Pump power consumption

Figure 22, below shows the temperature variation between rooms at Grandstaff on a typical winter day, December 11, 2011. The room temperatures stayed very consistent with each other with about a 4 degree variation, and also stayed consistent over time while the system was operating. Note the kitchen temperature variation caused by the cycling of the refrigerator.

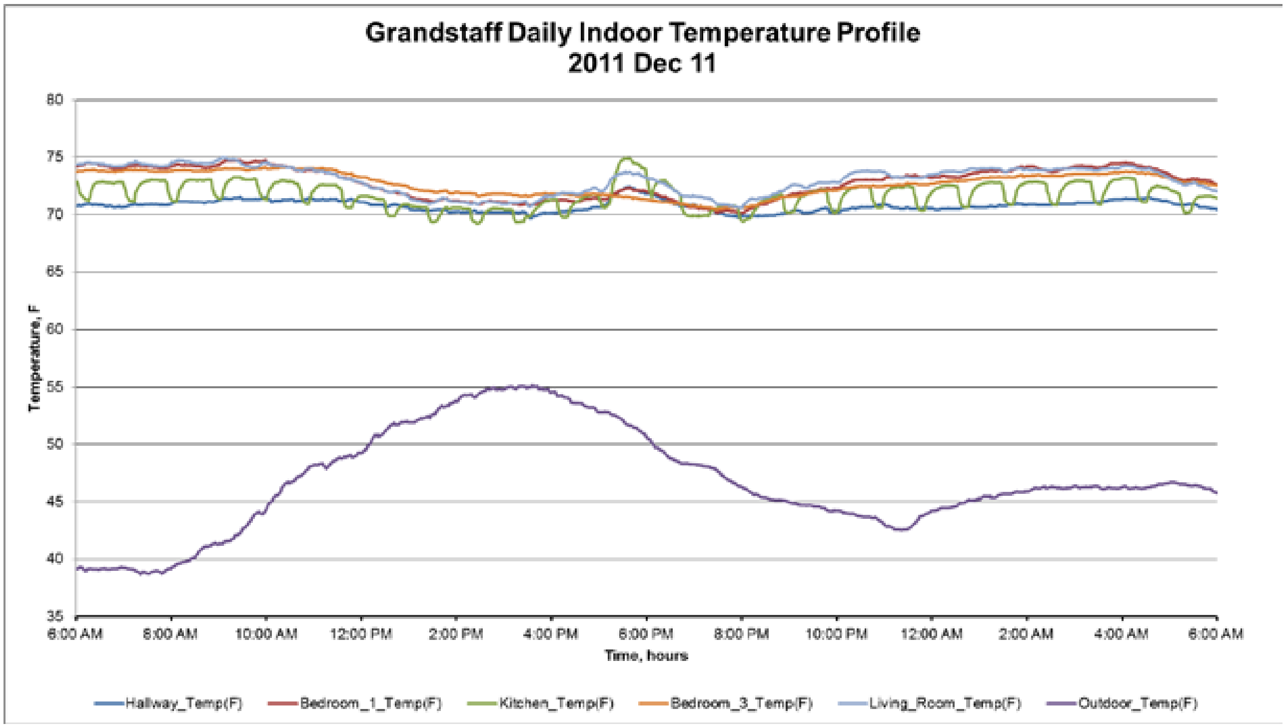

Figure 22 Grandstaff temperature profile

Figure 23 shows equipment cycling over the same test period. The pink line shows the water pump operation caused by regular thermostat cycling at about 6 cycles per hour until increasing outdoor temperature reduce the demand on the system. The supply water temperature cycles between 100°F and 120°F as the hot water tank thermostat responds to the energy being withdrawn for space heating. The gas meter (dark blue spikes) reads the gas consumption caused by the water heater thermostat cycling and calling for heat. Finally, the living room temperature varies only a few degrees during this process, indicating that comfort in the space is being maintained.

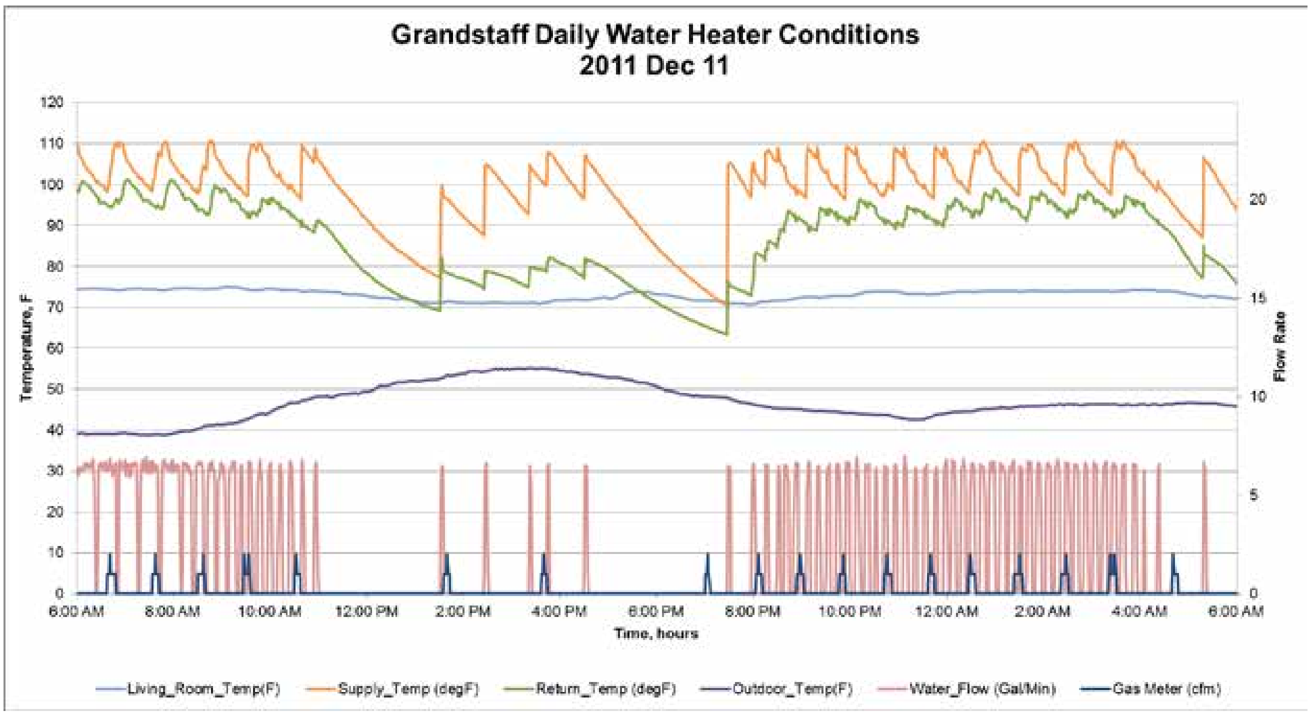

Figure 23 Grandstaff equipment cycling

Figure 24, below shows the utility bill therms per month for the Grandstaff site over the 2009-2012 billing periods. Heating therms were determined by subtracting the summer monthly average gas usage over the period, in this case 7.8 therms per month.

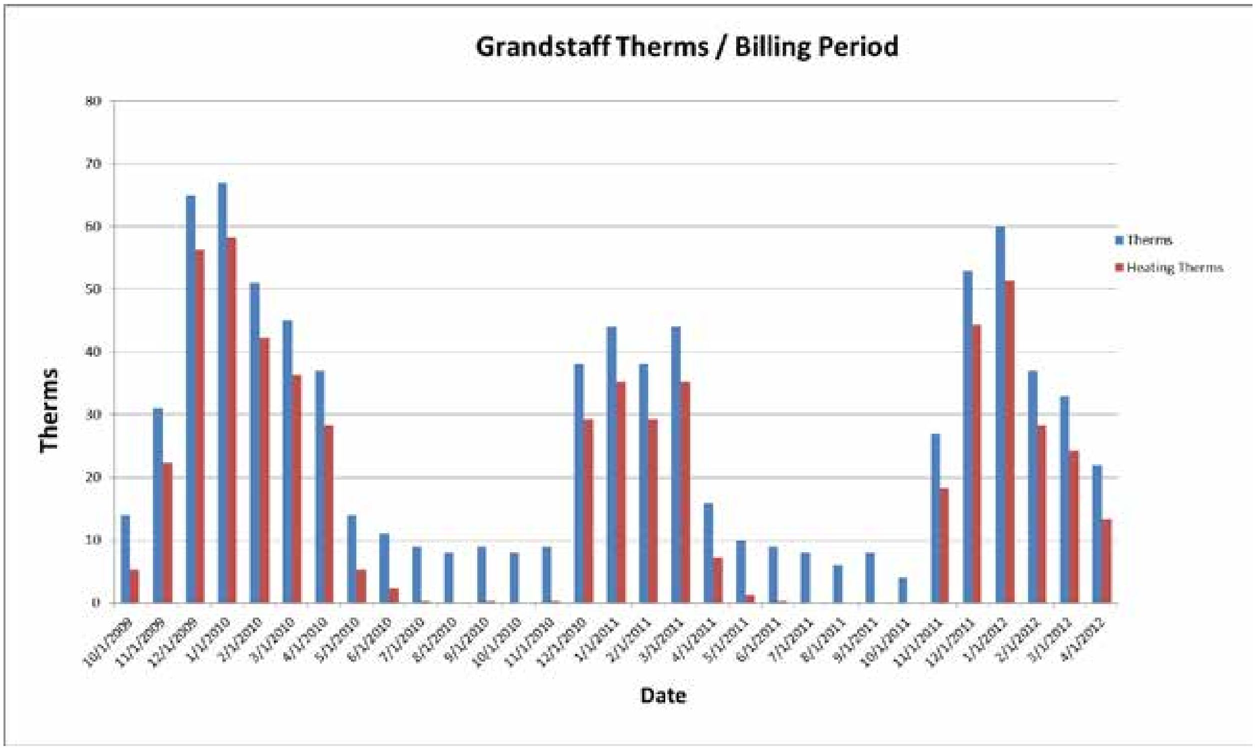

Figure 24 Grandstaff house therms per billing period

In Figure 25, the monthly heating therms over the same period are plotted and the system installation period is identified. In this figure, the post-retrofit actual therms (blue line) are weather normalized to compare consumption with the 2009-2010 heating season (red line). Note that the consumption patterns for the 2010-2011 heating season show a significant anomaly in January that was not related to the weather. For this reason the 2009-2010 heating season was chosen for the comparison. The balance point for this house was determined to be 59°F using an r-squared analysis of the energy usage with several balance point options. Heating Degree Days were then determined using the 59°F balance point.

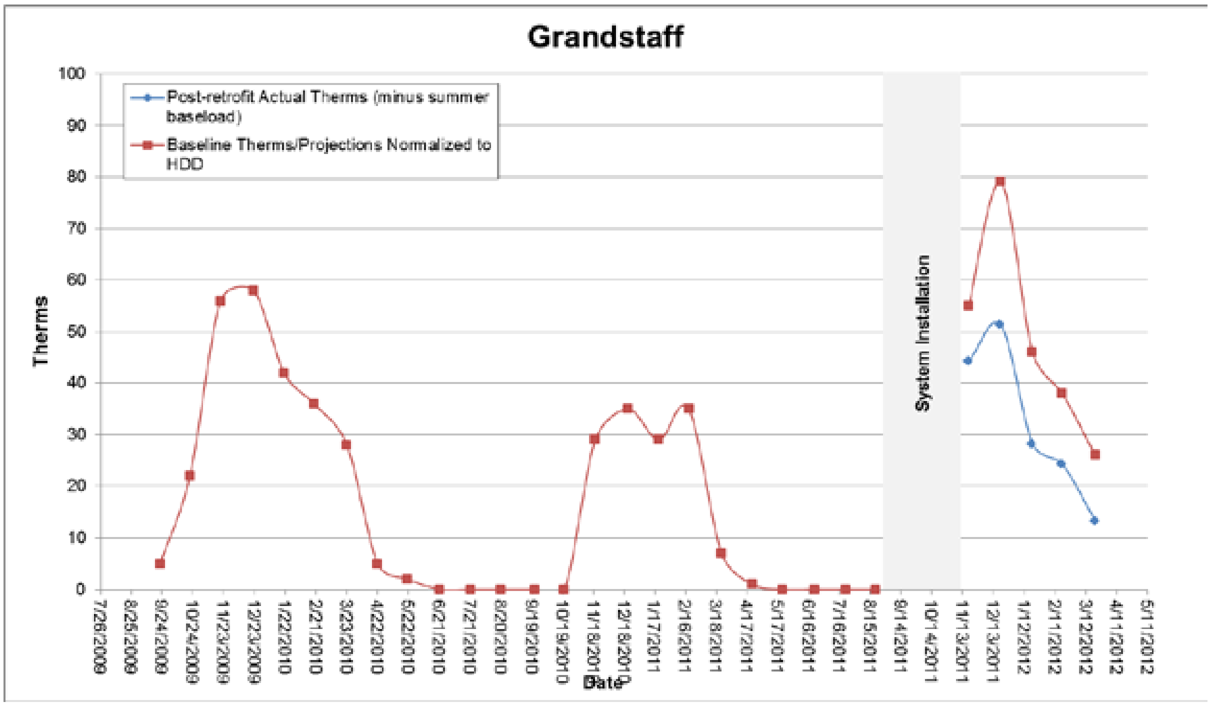

Figure 25 Grandstaff house monthly energy consumption with savings

In Table 2, below, the heating degree days for the three periods, the projected therm usage, the actual therm usage and the savings is shown. Note that the heating degree days for the three periods is steadily increasing, further highlighting the anomaly in the 2010-2011 heating season. Based on this analysis, the weather-adjusted annual savings for the Grandstaff house is 34%. If an average of the 2009-2010 and 2010-2011 winters are used as the baseline, the savings is 16%.

Table 2 Grandstaff house energy savings calculation

Grandstaff		Actual Space Heat Therms	HDD_59	Projected Therms	Annual Savings	Therms Saved
Pre/Baseline	2009/10 Winter	222	1433			
Pre/Baseline	2010/11 Winter	137	1497			

Post-retrofit	**2011/12 Winter**	**162**	**1581**	**244**	**34%**	**83**

A similar analysis was performed for the 6th Avenue house. Figure 26, below shows the temperature variation between rooms at 6th Avenue on a typical winter day, December 10, 2011. The room temperatures were not very consistent with each other with about an 8 degree variation, but stayed fairly consistent over time while the system was operating. Note the 3rd bedroom temperature variation - this spike and drop in temperature are likely caused by occupant behavior.

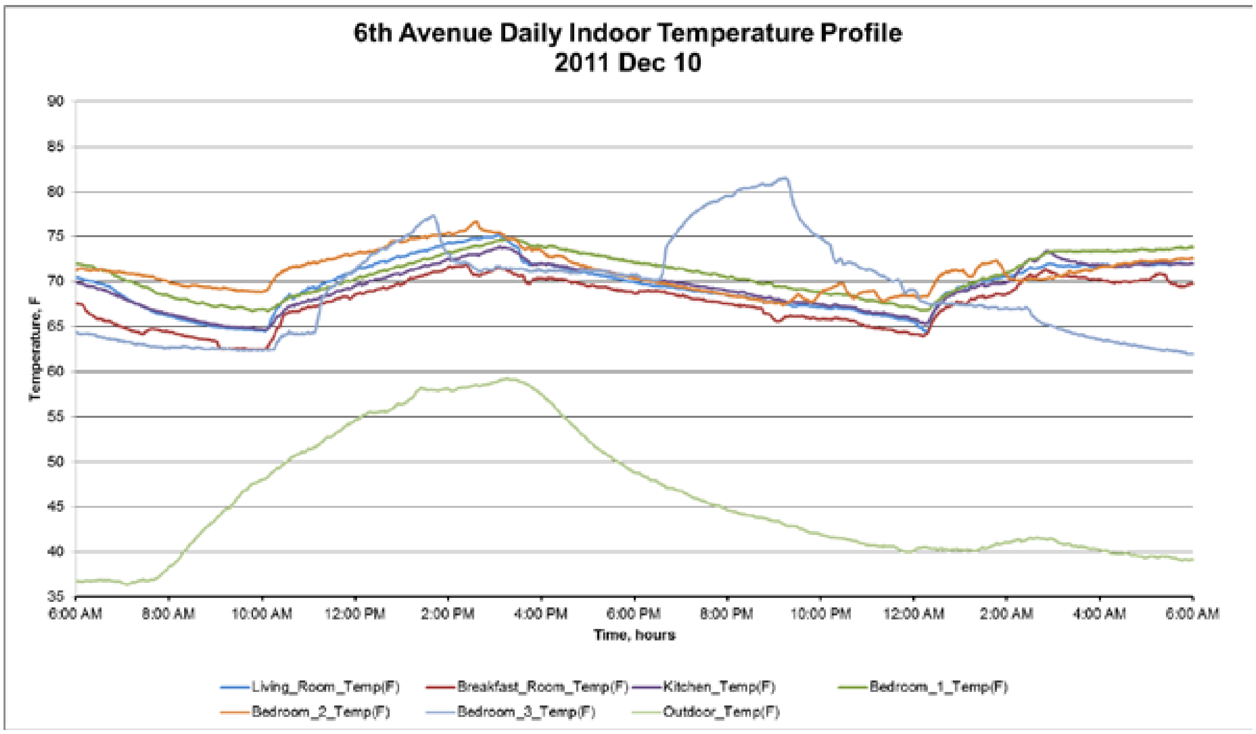

Figure 26 6th Avenue temperature profile

Figure 27 shows equipment cycling over the same test period. The red line shows the water pump operation. Note that in this case, the thermostat called for heat continuously over a 5 hour period starting at 10 a.m. and then again at midnight. The thermostat in the water heater reacted to the continuous draw by firing at regular intervals to keep the tank warm. Both the outdoor temperature and living room temperature was rising during the morning period and the outdoor temperature was level while the living room temperature was rising in the period starting at midnight. It appears that the house was responding to a change in the thermostat setpoint during these periods, possibly caused by a setback program. Since space temperatures are rising the capacity of the heating system seems adequate for the house. As in the Grandstaff case, the supply water temperature cycles between 110°F and 120°F as the hot water tank thermostat responds to the energy being withdrawn for space heating. The gas meter (dark blue spikes) reads the gas consumption caused by the water heater thermostat cycling and calling for heat.

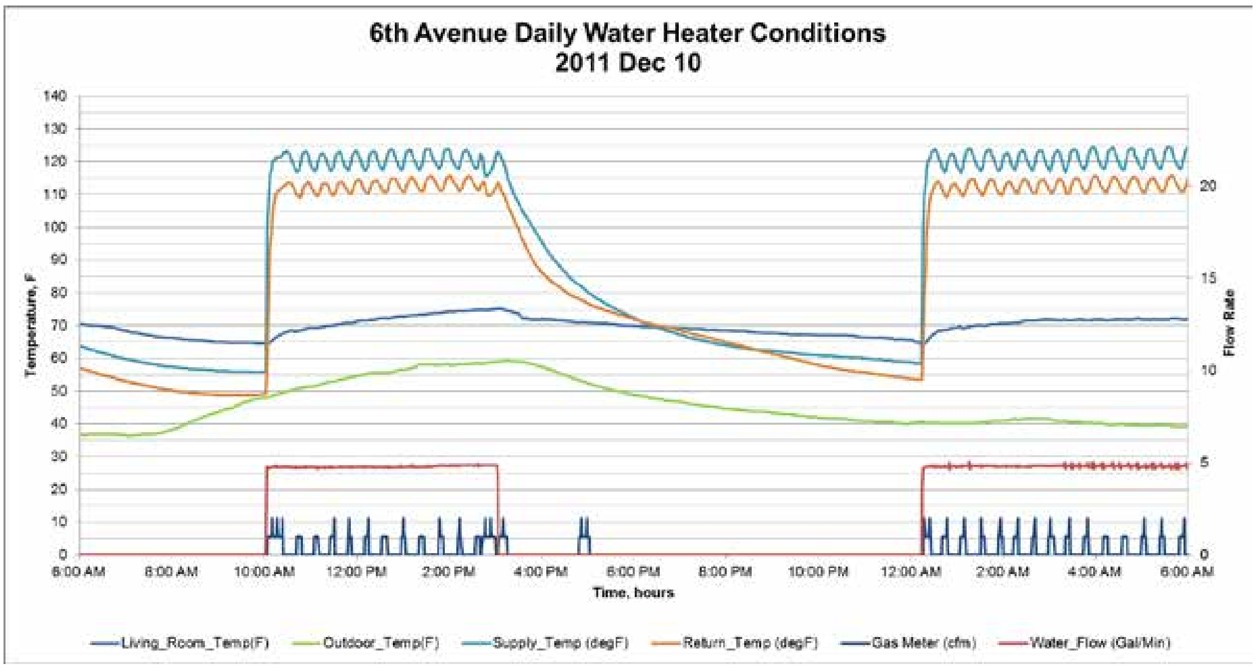

Figure 27 6th Avenue equipment cycling

Figure 28, below shows the utility bill therms per month for the 6th Avenue site over the 2009-2012 billing periods. Heating therms were determined by subtracting the summer monthly average gas usage over the period, in this case 33.8 therms per month. The 6th Avenue house had a family of 4, so baseline usage for water heating, cooking, and other uses is higher.

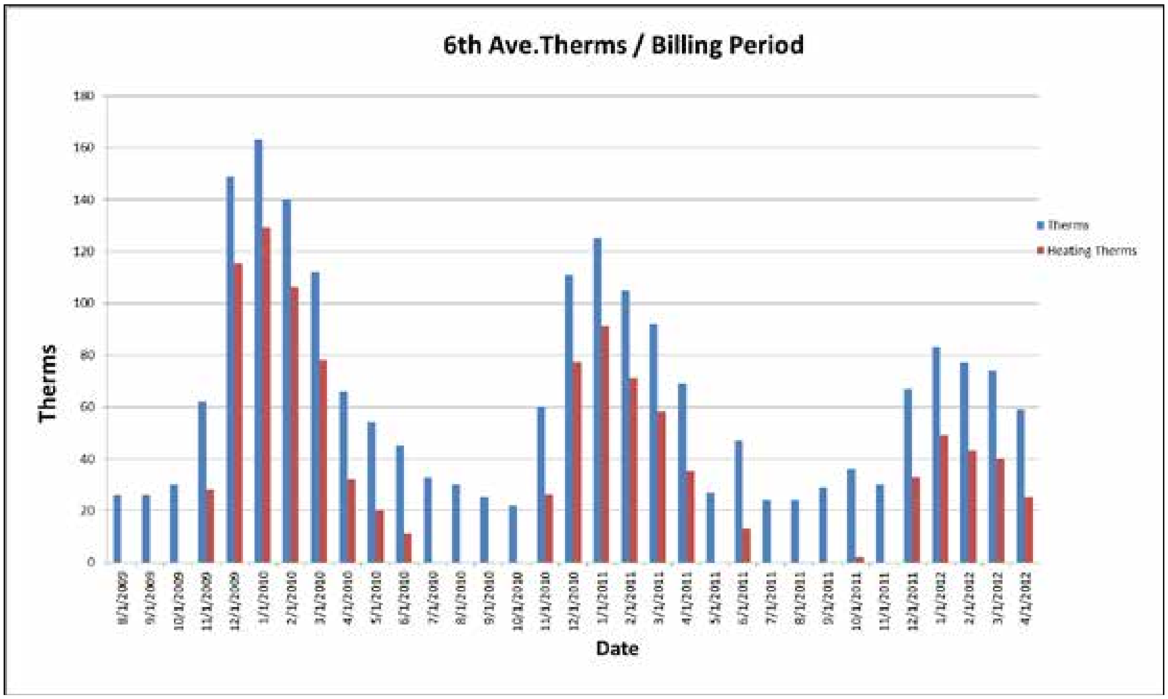

Figure 28 6th Avenue house therms per billing period

In Figure 29, the monthly heating therms over the same period are plotted and the system installation period is identified. Unlike the Grandstaff case, the post-retrofit actual therms from Figure 29 (blue line) are weather normalized to compare consumption with an average of the 2009-2010 heating season and the 2010-2011 heating season (red line). Note that the consumption patterns for the 2010-2011 heating season are significantly lower despite having the same heating degree days as the 2009-2010 heating season. However the anomaly seen in Grandstaff is not seen here, so the 2010-2011 heating season data was used in the analysis. The balance point for this house was determined to be 63°F using an r-squared analysis of the energy usage with several balance point options. Heating Degree Days were then determined using the 63°F balance point. Note that for this house, the balance point is 4 degrees higher even with more occupants, evidence of a poorer thermal envelope than Grandstaff.

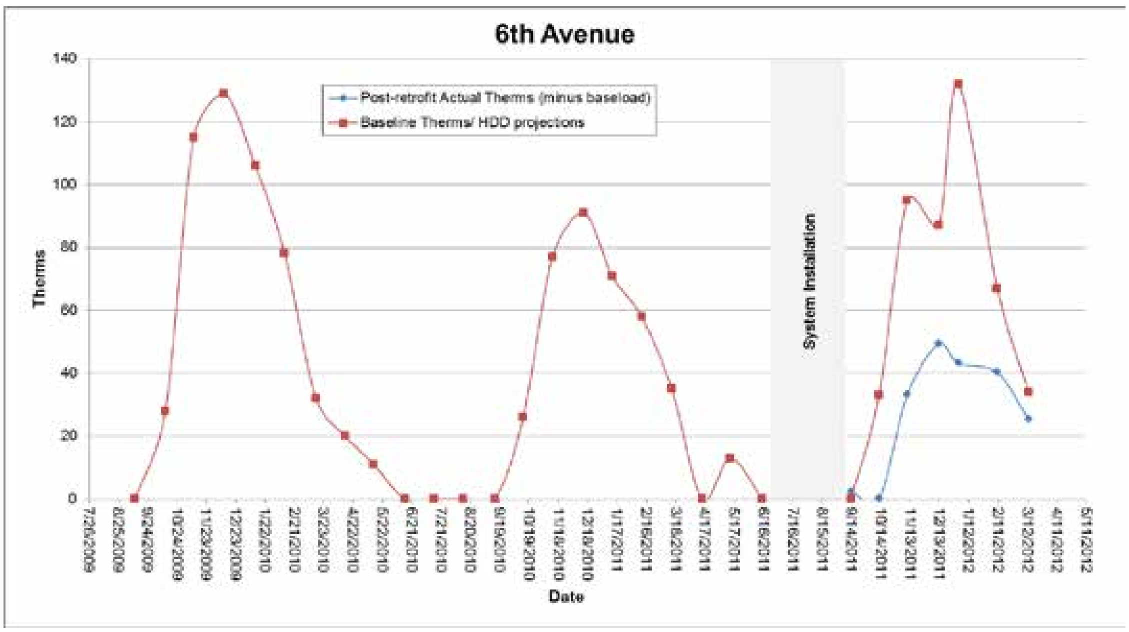

Figure 29 6th Avenue house monthly energy consumption with savings

In Table 3, below, the heating degree days for the three periods, the projected therm usage, the actual therm usage and the savings is shown. Note that the heating degree days have less variation at the 63°F balance point than at the 59°F balance point used for Grandstaff. Based on this analysis, the weather-adjusted annual savings for the 6th Avenue house is 57%.

Table 3 6th Avenue house energy savings calculation

6th Avenue		Actual Space Heating Therms	HDD_63	Projected Therms	Annual Savings	Therms Saved
Pre/Baseline	2009/10 Winter	489	2367			
Pre/Baseline	2010/11 Winter	359	2376			
Post-retrofit	2011/12 Winter	193	2506	448	57%	255

Results and Conclusions

The radiant heating system performed very well in the heating season tests. The A. O. Smith Vertex 76,000 Btu/hr input capacity water heater with 96% thermal efficiency was sufficient to meet the load of the Grandstaff and the 6th Avenue houses during the winter, although the 6th Avenue house had evidence of supplemental heating. The radiant panels performed well in both houses. The design conditions of 15 Btu/hr/sf of radiant heat from the panels at 120°F and at 0.01 gpm of hot water per square ft. of panel are confirmed in these studies.

Gas energy savings from Grandstaff was 34% compared to its baseline performance, determined by a utility bill analysis. In Grandstaff, the thermostat setpoint was lowered from 70°F to 68°F in the first month of testing by the homeowner due to the improved thermal environment. If the setting would have been left at 70°F for the entire heating season, energy savings from natural gas would have been slightly lower.

In the 6th Avenue house, energy savings from natural gas was 57% when compared to the average of the two prior years as a baseline consumption data point. In this house the thermostat setpoint varied significantly at the hands of the occupant, so the assumption is made that the same patterns were used over the three heating seasons. In this house, there was some evidence that the occupant used the oven for space heating. The occupant was warned of the dangers of doing so; however there was some evidence that the practice continued during part of the testing period (a CO detector had been installed). Again, the results are based on the assumption here is that the use of the oven for space heating did not change during the three heating seasons used in the study.

The conclusions from the heating season test of the two houses is that the energy reduction associated with the radiant heating system and the Measured Home Performance improvements produced an average savings of 45% for the two houses in the Sacramento area with improved comfort. It is not possible to separate the effects of the two factors in this study, however a predicted savings for the increase in efficiency of the heating plant alone would yield a 15% savings for Grandstaff (vs. 80% AFUE furnace) and 30% savings for 6th Avenue (vs. 65% efficient heating system), leaving approximately 25% savings to be spread between thermal envelope improvements, the performance of the radiant heating system and the use of a lower thermostat setpoint.