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Exterior Insulation Implications for Heating and Cooling Systems in Cold Climates

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Exterior Insulation Implications for Heating and Cooling Systems in Cold Climates

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Office of Energy Efficiency and Renewable Energy

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

Acknowledgments

The authors acknowledge the New York State Energy Research and Development Authority for awarding IBACOS the contract for deep energy retrofits in the area of Syracuse, New York. The authors also acknowledge GreenHomes America, Inc. as the contractor for this project and for its contribution to this report.

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Definitions

ABP	NYSERDA Advanced Buildings Program
ACCA	Air Conditioning Contractors of America
AFUE	Annual Fuel Utilization Efficiency
BEopt™	Building Energy Optimization (software)
Btu	British Thermal Unit
Btuh	British Thermal Units per Hour
CFM	Cubic Feet per Minute
DER	Deep Energy Retrofit
EF	Energy Factor
FPM	Feet per Minute
GG	Gravity Grille
GHA	GreenHomes America, Inc.
HPwES	Home Performance with ENERGY STAR®
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
NYSERDA	New York State Energy Research and Development Authority
OSB	Oriented Strand Board
RH	Relative Humidity
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SSF	Shell Square Foot
SSG	Stamped Steel Grille

Executive Summary

The New York State Energy Research and Development Authority (NYSERDA) is interested in finding cost-effective solutions for deep energy retrofits (DERs) related to exterior wall insulation in a cold climate, with targets of 50% peak load reduction and 50% space conditioning energy savings. The U.S. Department of Energy Building America team, IBACOS, in collaboration with GreenHomes America, Inc. (GHA), was contracted by NYSERDA to research exterior wall insulation solutions. In addition to exterior wall insulation, the strategies included energy upgrades where needed in the attic, mechanical and ventilation systems, basement, band joist, walls, and floors. Under Building America, IBACOS is studying the impact of a "thermal enclosure" DER on the sizing of the space conditioning system and the occupant comfort if the thermal capacity of the heating and cooling system is dramatically downsized without any change in the existing heating and cooling distribution system (e.g., size, tightness and supply outlet configurations).

IBACOS and GHA investigated three separate strategies in three test houses in the area of Syracuse, New York:

- Test House 1: Foam board—Exterior rigid foam board insulation (building on the experiences gained by IBACOS at a cold-climate, new construction, unoccupied test house located in Pittsburgh, Pennsylvania)
- Test House 2: Spray foam—An exterior standoff furring system with polyurethane spray foam
- Test House 3 (the control test house): Dense pack/high R-value windows—A more conventional insulation retrofit approach that achieves an R-15 wall cavity insulation level but uses other whole-house strategies to achieve the overall NYSERDA energy savings and load reduction targets (i.e., 50% peak reduction, 50% space conditioning energy savings).

Although this project relates specifically to cold climates, the results in the long term may identify gaps and barriers relative to space conditioning upgrades in all climate zones. The monitored results indicate that changes to the building shell and thermal capacity of the heating, ventilation, and air conditioning system without changes to the ductwork and balancing can result in frequent temperature excursions in the conditioned zones, as seen in at least one zone in each test house. This leaves contractors at risk for callbacks because of comfort complaints. Also, improvements to the overall shell may isolate the thermostat from the magnitude of load variations seen by individual rooms. However, pre-upgrade data are not available to confirm this.

IBACOS drew the following conclusions about these strategies:

- For the most cost-effective solution, homeowners who are interested in DERs must already be interested in replacing the siding—and possibly the windows—on their homes.
- Ledger boards may need to be installed to allow for deflection between the top and bottom of the siding.

- A spray foam technique called *picture framing* is needed to reduce bowing between 2 × 4 framing members. This technique involves spraying the perimeter of the framed section and then filling the rest with foam.
- Preparatory work to protect the windows and exposed foundation from overspray is required before spray foam insulation is applied.
- Windows should be installed at the same time as the wall framing. This allowed full sections of the envelope to be completed at one time and minimized disruptions.

1 Introduction and Background

According to Harvard (2010), “Lower household mobility in the wake of the housing market crash could also mean that homeowners will focus on upgrades with longer paybacks, particularly energy-efficient retrofits.” That report also shows that homeowners are investing in new siding ($4.847 billion in 2009) and new windows and doors ($11.448 billion in 2009). The decisions to make these improvements frequently are made without consideration of energy improvement opportunities, and research is needed to determine additional measures that could be taken to improve the energy efficiency of the home and the impact of the various opportunities.

1.1 Project Goals and Objectives

The New York State Energy Research and Development Authority’s (NYSERDA) Advanced Buildings Program (ABP) has proven the economic need for, and significant energy-saving benefits of, residential retrofitting strategies based on its deep energy retrofit (DER) pilot project. However, DER activities can be cost prohibitive. This research was conducted to investigate cost-effective DER solutions for improving the building shell exterior while achieving a cost-reduction goal to approximately $12–$18 per shell square foot (SSF), including reducing labor costs considerably, to reach a balanced, 50/50 split between material and labor. The strategy is designed to integrate with other home improvement projects such as siding or window replacement, with both energy and appraisal value attributes, so DER solutions gain market acceptance.

The U.S. Department of Energy Building America team, IBACOS, in collaboration with GreenHomes America (GHA), was contracted by NYSERDA to research exterior wall insulation solutions. In addition to the exterior wall insulation, the strategies included energy upgrades where needed in the attic, mechanical and ventilation systems, basement, band joist, walls, and floors. Specifically, Test House 1 received a rigid foam insulation DER strategy, and Test House 2 received the spray foam insulation DER. Test House 3 was the control test house that received the Home Performance with ENERGY STAR® (HPwES) strategies. Each test house is located near Syracuse, New York, which is in the International Energy Conservation Code (IECC) climate zone 5, as shown in Figure 1.

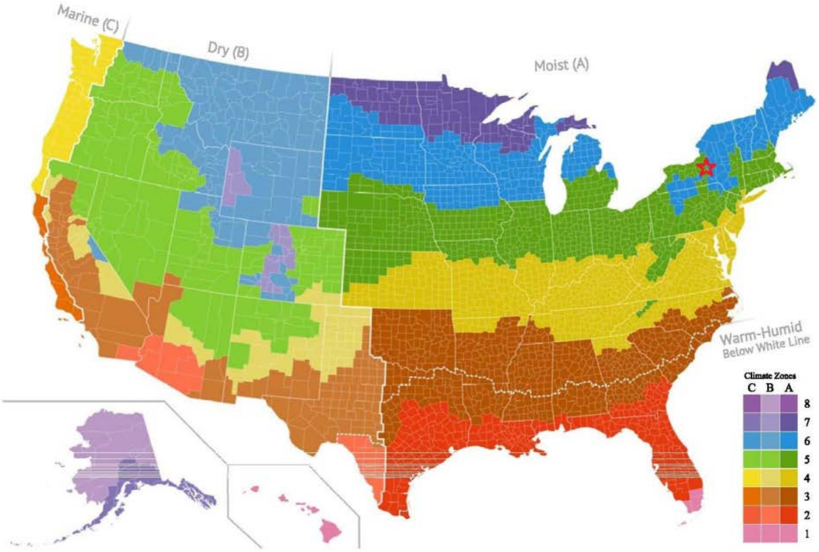

Figure 1. Syracuse is located in central New York in climate zone 5 on the IECC climate zone map

Many cold-climate houses have existing sheet-metal-ducted space conditioning systems that are located primarily, if not entirely, within conditioned space. Provided the house is reasonably well air sealed, there is little energy benefit to significantly sealing the duct systems. These systems also were sized for the relatively inefficient shell of the building (e.g., high air infiltration, low levels of insulation, single-glazed windows). When a whole-house energy upgrade or DER is undertaken to improve the thermal enclosure, these existing space conditioning systems are oversized. Although the heating and air conditioning unit can be downsized to the new peak load of the overall house, the existing duct system remains oversized, which results in slower air velocities at supply outlets. In turn, lower air velocity results in worse throw and room air mixing. In some cases, severe stratification can occur. Changes in the fraction of supply air needed by each room also can have a significant impact on comfort if the existing ductwork is not balanced. Because each test house has a forced-air system, IBACOS will investigate these concerns in this report.

In houses with hydronic heat emitters (e.g., radiators, fin tube) piped in series from a boiler, downsizing the boiler output and keeping the same supply water temperature may lead to rooms closest to the boiler extracting more heat than those farther from the boiler. This, in turn, could lead to room-to-room temperature variations. Additionally, it is not clear if the heat emitter sizing (if done at all) for the original system has any correlation to the actual room-by-room loads in the house after a comprehensive energy upgrade.

1.2 Research Questions

In this project, three test houses in the cold climate of Syracuse, New York, received various upgrade strategies to achieve approximately 50% whole-house energy savings with no significant modification to the existing space conditioning distribution system. This project answers the following research questions for these three houses in a cold climate:

1. What are the differences between the pre- and post-upgrade room-by-room loads, and how do these vary from the capacity of the installed space conditioning equipment and distribution system?
2. Over the course of a year, when do temperature and relative humidity (RH) excursions happen that exceed Air Conditioning Contractors of America (ACCA) Manual RS (Rutkowski 1997) and ASHRAE Standard 55 (ASHRAE 2010) recommendations?
3. What is the heating or cooling equipment runtime associated with the outdoor and indoor temperatures, and how does that compare to the room-by-room temperatures?

2 Mathematical and Modeling Methods

During the renovation phase of the three test houses, IBACOS used Building Energy Optimization (BEopt™) software (BEopt 2013) and ACCA methodologies to complete the final design package.

2.1 BEopt Modeling

IBACOS performed BEopt modeling for each of the three test houses, using BEopt version 2.0.0.6 (BEopt 2013) to calculate the projected whole-house annual energy savings. The team also used BEopt for optimizing the thermal enclosure and mechanical system specifications and for predicting the energy use and energy savings. Appendix A provides more details from the BEopt input and output reports.

2.2 ACCA Manual J and ACCA Manual D

For each of the three test houses, IBACOS followed ACCA Manual J (Rutkowski 2006) and ACCA Manual D (Rutkowski 2009) methodologies to calculate the peak heating and cooling loads and the associated design airflows on a room-by-room basis. Wrightsoft Right-Suite Universal (Wrightsoft 2013) is an ACCA-approved software program for applying ACCA Manual J and ACCA Manual D methodologies. IBACOS used Wrightsoft in the design of the heating, ventilation, and air conditioning (HVAC) system for these test houses.

2.3 ACCA Manual RS

ACCA Manual RS (Rutkowski 1997) requires the dry bulb temperature measured within any room of the thermostatically controlled zone to be within ±3°F of the thermostat setting during the cooling season. Similarly, the temperature during the heating season in any room must be within ±2°F of the thermostat set point temperature. The temperature difference measured between any two rooms in the zone (also known as the room-to-room temperature difference) should be no greater than 4°F in the heating season and no greater than 6°F in the cooling season. For this study, the measured temperature at the thermostat was used as the assumed set point because the user-selected value was not known.

2.4 Analysis and Plotting

To facilitate efficient data analysis and plotting, the team used several open-source software packages based on the Python programming language.[1] The pandas package[2] was used to accurately handle and easily manipulate the data. Matplotlib[3] was used for visualization and proved to be a flexible tool for creating custom and reproducible graphics.

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[1] Python programming language. https://www.python.org/.

[2] pandas package. http://pandas.pydata.org/.

[3] Matplotlib. http://matplotlib.org/.

3 Research/Experimental Methods and Results

To validate the performance of the three test houses, IBACOS conducted short-term performance tests following the upgrade of each test house and installed long-term monitoring systems to collect performance data on the test houses throughout one year. Long-term monitoring equipment was installed in the houses in September 2013, and the monitoring was completed in September 2014.

3.1 Overview of Pre-Deep Energy Retrofit Conditions for All Three Test Houses

The three test houses that were selected for this project were similar in volume. Test House 1 (rigid foam DER) and Test House 3 (the HPwES strategy) were similar in square footage, whereas Test House 2 (spray foam DER) was almost half the square footage of the other two test houses.

Table 1 lists the conditions of the three test houses prior to the DERs.

Table 1. Pre-DER Conditions of the Three Test Homes

Parameters	Test House 1	Test House 2	Test House 3
Square Feet of Conditioned Space	1,682 ft^2	972 ft^2	1,676 ft^2
Perimeter of House	100 ft	124 ft	154 ft
DER Insulated Wall Height	18 ft	10 ft	18 ft*
SSF	1,800 SSF	1,240 SSF	2,772 SSF

*Average height due to roof slopes.

3.1.1 Rigid Foam Deep Energy Retrofit Test House (Test House 1)

In its pre-DER state, Test House 1 had window air conditioning units, used natural gas with metal ducts for heating, and appeared to have no leaks in the roof. The interior included approximately 19 double-hung windows that were in poor condition. The attic was partially conditioned space. It had about 3 in. of fiberglass insulation on the ceiling of the conditioned space and no insulation on the sloped ceiling. The unfinished basement was dry and accessible, with a poured foundation. The water heater, which was located in the basement, had been replaced in 2010 and was in good condition. There also was an 80% annual fuel utilization efficiency (AFUE) heating system in the basement, which was from 1994 and was in poor condition. Neither the water heater nor the furnace had a direct vent to the outdoors. Some existing exterior conditions of the home included a fireplace in the living room (which meant a chimney on the exterior of the home), wooden clapboard siding that was in poor condition, a front porch with two exterior lights, and some exterior lighting at the rear of the home. Figure 2 shows the front exterior of Test House 1 prior to its DER.

Figure 2. Test House 1

3.1.2 Spray Foam Deep Energy Retrofit Test House (Test House 2)

In its pre-DER state, Test House 2 had no air conditioning. The basement was dry and accessible and was half finished. In the basement was a 1991 storage tank water heater in poor condition, as well as a 1983 forced-air gas furnace; neither was directly vented to the outdoors. The house had no leaks in the 5/12 pitched roof. The interior of the home included nine replacement vinyl windows in poor condition, two two-panel sliding windows, and six three-panel sliding windows, as well as a bay window. Urea formaldehyde insulation (which is no longer used because of its harmful levels of formaldehyde gas) was used inconsistently in the existing walls. Insulation in the attic varied from 6 in. of fiberglass batt insulation to no insulation at all. Figure 3 shows the front view of the exterior of Test House 2 prior to its DER.

Figure 3. Test House 2

3.1.3 HPwES Deep Energy Retrofit Test House (Test House 3)

In its pre-DER state, the interior of Test House 3 included ten double-hung windows, six of which were to be replaced in the DER and four that had been replaced recently by the homeowner. It also had R-10 fiberglass insulation in the attic, recessed lighting, and no wall insulation. A water heater located in the unfinished basement had no direct vent to the outdoors and otherwise was vented improperly. Figure 4 shows the front exterior of Test House 3 prior to its DER.

Figure 4. Test House 3

3.2 Overview of Post-Deep Energy Retrofit Conditions for All Three Test Houses

Test House 1, with the rigid foam insulation DER, had an approximate center-of-wall R-value of R-28, including furring strips for siding, with additional systems approach work to supply the complete integrated DER solution. Test House 2, with the spray foam insulation DER, had an approximate center-of-wall R-value of R-30, with additional systems approach work to supply the complete integrated DER solution. The control test house, Test House 3, included criteria from the HPwES program, including dense pack walls and window upgrades for this retrofit strategy.

Table 2 through Table 4 show the pre- and post-upgrade energy features of each of the three test houses.

Table 2. Test House 1: Energy Characteristics

Specifications	Pre-Upgrade Conditions	DER Upgrade Package
Foundation Wall Insulation R-Value	Uninsulated	19.8
Above-Grade Exterior Wall Insulation R-Value	3.9	15.3
Rim/Band/Box Sill Insulation	Uninsulated	Spray foam
Attic Insulation R-Value	22.7	29.9
Window U-Value/SHGC	0.49/0.56	0.2/0.23
Duct Location	Unfinished basement	Finished basement
Heating	Gas, 80% AFUE	Gas, 95% AFUE
Air Conditioning	Single stage, SEER 8	Single stage, SEER 14.5
HVAC Equipment Location	Unfinished basement	Unfinished basement
Whole-House Ventilation Strategy	Exhaust	Exhaust
Water Heater Type/EF	Gas standard	Gas premium

EF is energy factor. SEER is seasonal energy efficiency ratio. SHGC is solar heat gain coefficient.

Table 3. Test House 2: Energy Characteristics

Specifications	Pre-Upgrade Conditions	DER Upgrade Package
Foundation Wall Insulation R-Value	Uninsulated	Uninsulated
Above-Grade Exterior Wall Insulation R-Value	10	21.9
Rim/Band/Box Sill Insulation	Uninsulated	Spray foam
Attic Insulation R-Value	4	52.5
Window U-Value/SHGC	0.49/0.56	0.2/0.23
Duct Location	Unfinished basement	Unfinished basement
Heating	Gas, 80% AFUE	Gas, 98% AFUE
Air Conditioning	None	Single stage, SEER 13
HVAC Equipment Location	Unfinished basement	Unfinished basement
Whole-House Ventilation Strategy	Exhaust	Exhaust
Water Heater Type/EF	Gas standard	Gas premium

Table 4. Test House 3: Energy Characteristics

Specifications	Pre-Upgrade Conditions	DER Upgrade Package
Foundation Wall Insulation R-Value	Uninsulated	20.1
Above-Grade Exterior Wall Insulation R-Value	3.6	12.6
Rim/Band/Box Sill Insulation	Uninsulated	Uninsulated
Attic Insulation R-Value	14.5	71
Window U-Value/SHGC	0.49/0.56	0.2/0.23
Duct Location	In conditioned space	In conditioned space
Heating	Gas, 80% AFUE	Gas, 95.5% AFUE
Air Conditioning	Single stage, SEER 8	Single stage, SEER 13
HVAC Equipment Location	Basement	Basement
Whole-House Ventilation Strategy	Exhaust	Exhaust
Water Heater Type/EF	Gas standard	Gas premium

3.3 Short-Term Test Methods and Results

To characterize the integrity of the thermal enclosure and measure the startup performance of the HVAC system in each test house, IBACOS completed short-term tests after completion of construction of each test house. The following subsections describe the short-term tests that were performed in each test house and the test results.

3.3.1 Room-by-Room Supply Register Airflow

None of the supply outlets was modified as part of the DER upgrade in the three test houses, nor were any modifications made to the return air ducts or registers. This is a typical practice in NYSERDA programs, where work that does not qualify for energy savings usually is not undertaken. In each home, ductwork immediately adjacent to the equipment was modified as needed to accommodate the new furnace and air conditioner, and duct sealing was undertaken on only the new ducts and in easily accessible locations in the basements. Duct sealing is not typically undertaken because the ducts generally are inside conditioned space; thus, no energy savings would be attributed to sealing ducts inside conditioned space.

The measured flow volume from each supply register was determined using a low-flow balometer FlowBlaster[4] with an accuracy of ±3% + 5 CFM. Wray et al. (2002) indicate that the actual in-field error for these devices could be up to 30%. This error could impact the results from this study and the actual real-world installation of HVAC equipment. Because of the lower overall magnitude of the airflow, the risk of measurement error suggesting a dramatically different amount of energy provided to a room is lower than that of a typical house.

The research team compared these measurements to the design airflow values from the ACCA Manual J heating and cooling load calculations (Rutkowski 2006) to determine if adequate

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[4] FlowBlaster Capture Hood Attachment. Minneapolis, MN: The Energy Conservatory. http://products.energyconservatory.com/flowblaster-capture-hood-attachment/.

airflow was reaching each zone of the house. Table 5 through Table 7 show the pre- and post-retrofit Btuh values for the three test houses.

Table 5. Test House 1: Room-by-Room Pre- and Post-Retrofit Btuh Values

Location	Pre-Retrofit Btuh		Post-Retrofit Btuh		% From Pre- to Post-Retrofit	
	Heat	Cool	Heat	Cool	Heat	Cool
Basement	14,495	2,681	13,263	2,026	92%	15%
Living Room	5,829	3,343	1,472	1,423	25%	43%
Dining Room	5,829	2,718	1,472	842	25%	31%
Kitchen	4,875	2,615	1,528	1,490	31%	57%
Entry	8,657	3,072	2,888	974	33%	32%
Study/Office	6,054	2,774	1,525	847	25%	31%
Master Bedroom	23,936	9,087	6,753	2,464	28%	27%
Bedroom 2	3,534	1,575	907	564	26%	36%
Bedroom 3	5,739	2,975	1,451	1,081	25%	36%
Bath	3,454	1,747	864	564	25%	32%
Master Walk-in Closet	N/A	N/A	N/A	N/A		
Totals	**82,402**	**32,587**	**32,123**	**12,275**	**39%**	**38%**
Installed Capacity			**60,000**	**30,000**		

N/A is Not Available.

Table 6. Test House 2: Room-by-Room Pre- and Post-Retrofit Btuh Values

Location	Pre-Retrofit Btuh		Post-Retrofit Btuh		% from Pre- to Post-Retrofit	
	Heat	Cool	Heat	Cool	Heat	Cool
Basement	15,141	2,988	13,890	2,547	92%	18%
Living Room	12,714	6,858	2,998	2,222	24%	32%
Dining Room	3,834	1,899	264	103	7%	5%
Kitchen	6,034	3,691	1,828	1,701	30%	46%
Entry	N/A	N/A	N/A	N/A		
Study/Office	4,322	1,801	726	237	17%	13%
Master Bedroom	7,009	4,097	1,488	1,398	21%	34%
Bedroom 2	5,931	2,546	1,199	502	20%	20%
Bedroom 3	N/A	N/A	N/A	N/A		
Bath	1,187	520	198	29	17%	6%
Master Walk-in Closet	N/A	N/A	N/A	N/A		
Totals	**56,172**	**24,400**	**22,591**	**8,739**	**40%**	**36%**
Installed Capacity			**40,000**	**24,000**		

Table 7. Test House 3: Room-by-Room Pre- and Post-Retrofit Btuh Values

Location	Pre-Retrofit Btuh		Post-Retrofit Btuh		% from Pre- to Post-Retrofit	
	Heat	Cool	Heat	Cool	Heat	Cool
Basement	24,246	4,588	18,927	2,912	78%	15%
Living Room	6,138	2,947	2,609	1,423	43%	48%
Dining Room	7,474	2,546	4,118	1,188	55%	47%
Kitchen	4,333	2,870	1,818	1,791	42%	62%
Entry	N/A	N/A	N/A	N/A		
Study/Office	18,545	12,279	10,645	6,854	57%	56%
Master Bedroom	9,286	4,757	3,061	1,458	33%	31%
Bedroom 2	12,992	4,939	4,638	1,275	36%	26%
Bedroom 3	12,874	6,560	4,045	1,611	31%	25%
Bath	1,672	698	629	186	38%	27%
Master Walk-in Closet	2,537	902	941	198	37%	22%
Totals	**97,560**	**42,184**	**50,490**	**18,698**	**52%**	**44%**
Installed Capacity			**80,000**	**36,000**		

Figure 5 shows the key plan for Test House 1, followed by Table 8 and Table 9, which compare the pre-retrofit design airflows, post-retrofit design airflows, and measured post-retrofit airflows for that test house. Those measured airflows are stated in a percentage of deviation from design. All design and measured airflow values were measured in heating and cooling modes. Airspeed was measured with a TSI VelociCheck 8330 hotwire anemometer[5] with ±5% accuracy.

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[5] TSI VelociCheck Hotwire Anemometer. Shoreview, MN: TSI, Inc. (discontinued).

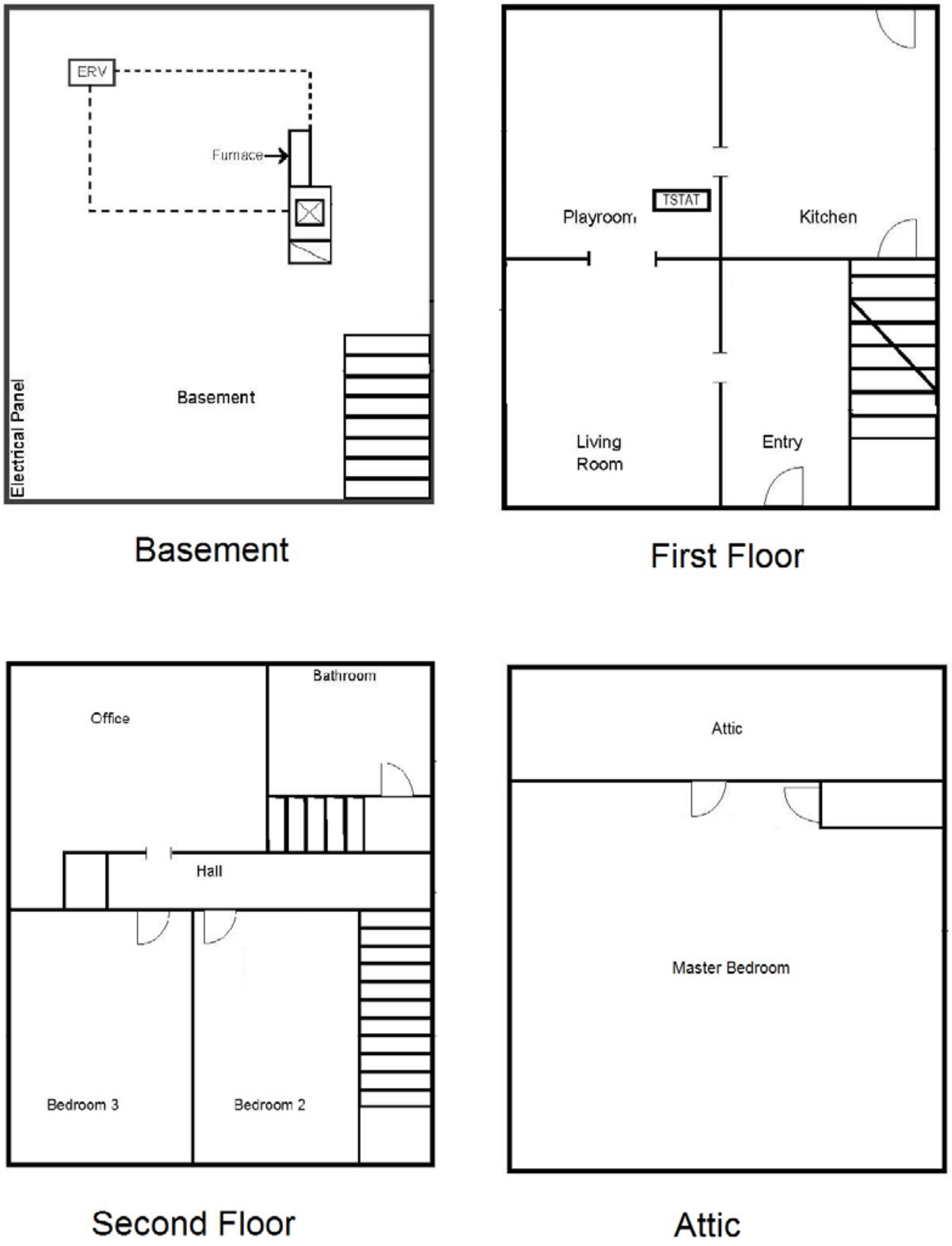

Figure 5. Test House 1 key plan

Table 8. Room-by-Room Pre- and Post-Upgrade Supply Register Airflows for Test House 1

Location	Supply Outlet Post-Retrofit				Pre-Upgrade Design Airflows (CFM)		Post-Upgrade Design Airflows (CFM)		Measured Airflows Post-Upgrade (CFM)		Percentage of Post-Upgrade Airflows Actually Measured (%)	
	Mark	Size	Type	Location	Heat	Cool	Heat	Cool	Heat	Cool	Heat	Cool
Basement	S1	4×14	SSG	Trunk Cut	158	74	140	56	87	100	62%	179%
	S2	4×10	SSG	Trunk Cut	106	50	94	38	44	76	47%	200%
Living Room	S3	10×12	GG	Baseboard	106	154	26	66	48	65	185%	98%
Dining Room	S4	10×14	GG	Baseboard	106	125	26	39	35	35	135%	90%
Kitchen	S5	11×14	GG	Baseboard	89	121	27	69	26	29	96%	42%
Office	S6	8×10	GG	Low Sidewall	110	128	27	39	52	48	193%	123%
Master Bedroom	S7	10×12	GG	Floor	436	419	119	114	65	40	55%	35%
Bedroom 2	S8	8×10	GG	Low Sidewall	66	73	16	26	15	15	94%	58%
Bedroom 3	S9	8×10	GG	Low Sidewall	105	137	26	50	47	47	181%	94%
Bath	S10	4×10	SSG	Low Sidewall	63	81	15	26	26	23	173%	88%
Entry	S11	11×14	GG	Baseboard	158	142	51	45	66	63	129%	140%
Totals					**1,503**	**1,504**	**567**	**568**	**511**	**541**	**90%**	**95%**

SSG is stamped steel grille. GG is gravity grille.

Table 9. Pre- and Post-Upgrade Airspeeds at Registers in Test House 1

Location	Supply Outlet Post-Retrofit				Supply Outlet Calculated Net Free Area (ft^2)	Pre-Upgrade Calculated Airspeed (FPM)		Post-Upgrade Measured Airspeed (FPM)	
	Mark	Size	Type	Location		Heat	Cool	Heat	Cool
Basement	S1	4×14	SSG	Trunk Cut	N/A	–	–	–	–
	S2	4×10	SSG	Trunk Cut	N/A	–	–	–	–
Living Room	S3	10×12	GG	Baseboard	0.58	182	264	28	38
Dining Room	S4	10×14	GG	Baseboard	0.68	156	184	24	24
Kitchen	S5	11×14	GG	Baseboard	0.75	119	162	19	22
Office	S6	8×10	GG	Low Sidewall	0.39	283	329	20	19
Master Bedroom	S7	10×12	GG	Floor	0.58	747	718	38	23
Bedroom 2	S8	8×10	GG	Low Sidewall	0.39	170	188	6	6
Bedroom 3	S9	8×10	GG	Low Sidewall	0.39	270	352	18	18
Bath	S10	4×10	SSG	Low Sidewall	0.00				
Entry	S11	11×14	GG	Baseboard	0.75	211	190	49	47

FPM is feet per minute.

Similarly, Figure 6 shows the key plan for Test House 2, followed by Table 10 and Table 11, which compare the pre-retrofit design airflows, post-retrofit design airflows, and measured post-retrofit airflows for that test house.

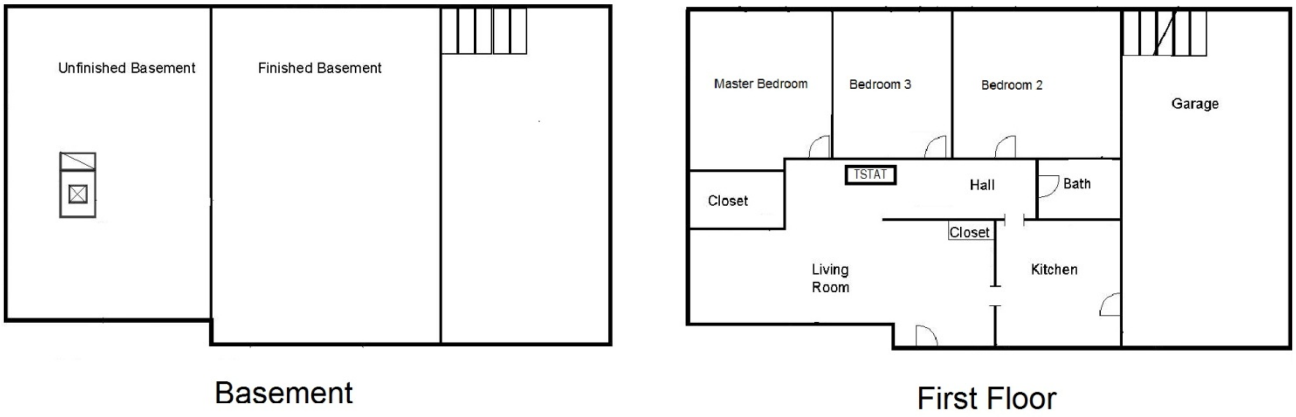

Figure 6. Test House 2 key plan

Table 10. Room-by-Room Pre- and Post-Upgrade Supply Register Airflows for Test House 2

Location	Supply Outlet Post-Retrofit				Pre-Upgrade Design Airflows (CFM)		Post-Upgrade Design Airflows (CFM)		Measured Airflows Post-Upgrade (CFM)		Percentage of Post-Upgrade Airflows Actually Measured (%)	
	Mark	Size	Type	Location	Heat	Cool	Heat	Cool	Heat	Cool	Heat	Cool
Basement	S1	4×10	SSG	Trunk cut	90	41	74	35	18	17	24%	49%
	S2	4×10	SSG	Trunk cut	90	41	74	35	39	40	53%	114%
	S3	8-in. round	SSG	Ceiling	123	56	100	48	60	84	60%	175%
Living Room	S4	6×10	SSG	Baseboard	127	158	27	51	27	34	100%	67%
	S5	6×10	SSG	Baseboard	127	158	27	51	35	40	130%	78%
Dining Room	S6	6×10	SSG	Baseboard	77	87	4	4	34	45	850%	1125%
Kitchen	S7	6×10	SSG	Baseboard	121	170	33	78	17	19	52%	24%
Master Bedroom	S9	6×10	SSG	Baseboard	140	189	27	64	26	29	96%	45%
Bedroom 2	S10	6×10	SSG	Baseboard	119	117	21	23	30	37	143%	161%
Bedroom 3	S8	6×10	SSG	Baseboard	87	83	13	11	36	43	277%	391%
Bath	S11	6×10	SSG	Low sidewall	24	24	4	1	47	56	1,175%	5,600%
Totals					**1,125**	**1,124**	**404**	**401**	**369**	**444**	**91%**	**111%**

Table 11. Post-Retrofit Airspeeds at Registers in Test House 2

Location	Supply Outlet Post-Retrofit				Measured Velocity Post-Upgrade (FPM)	
	Mark	Size	Type	Location	Heat	Cool
Basement	S1	4×10	SSG	Trunk cut	46	215
	S2	4×10	SSG	Trunk cut	435	1,030
	S3	8-in. round	SSG	Ceiling	132	360
Living Room	S4	6×10	SSG	Baseboard	117	395
	S5	6×10	SSG	Baseboard	152	435
Dining Room	S6	6×10	SSG	Baseboard	169	598
Kitchen	S7	6×10	SSG	Baseboard	26	170
Master Bedroom	S9	6×10	SSG	Baseboard	96	255
Bedroom 2	S10	6×10	SSG	Baseboard	205	440
Bedroom 3	S8	6×10	SSG	Baseboard	172	520
Bath	S11	6×10	SSG	Low sidewall	215	375

Finally, Figure 7 shows the key plan for Test House 3, followed by Table 12 and Table 13, which compare the pre-retrofit design airflows, post-retrofit design airflows, and measured post-retrofit airflows in that test house.

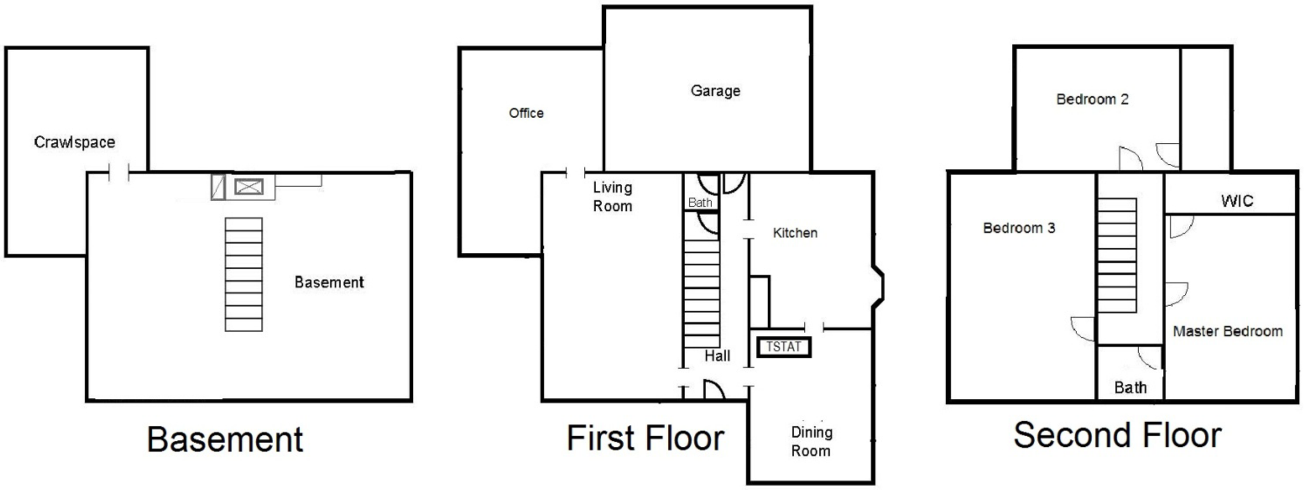

Figure 7. Test House 3 key plan

Table 12. Pre- and Post-Upgrade Room-by-Room Supply Register Airflows for Test House 3

Location	Supply Outlet Post-Retrofit				Pre-Upgrade Design Airflows (CFM)		Post-Upgrade Design Airflows (CFM)		Measured Airflows Post-Upgrade (CFM)		Percentage of Post-Upgrade Airflows Actually Measured (%)	
	Mark	Size	Type	Location	Heat	Cool	Heat	Cool	Heat	Cool	Heat	Cool
Basement	–	–	–	–	481	162	321	134	0	–	NA	–
Living Room	S1	12×14	GG	Floor	61	68	22	33	60	–	273%	–
	S2	12×14	GG	Floor	61	68	22	33	66	–	300%	–
Dining Room	S3	14×16	GG	Floor	148	118	69	55	83	–	120%	–
Kitchen	S4	3×11	SSG	Toe kick	44	66	15	42	0	–	0%	–
	S5	3×11	SSG	Toe kick	44	66	15	42	30	–	200%	–
Office	S6	4×14	SSG	Floor	138	212	67	118	69	–	103%	–
	S7	4×14	SSG	Floor	138	212	67	118	76	–	64%	–
	S8	4×8	SSG	Floor	92	143	46	80	76	–	165%	–
Master Bedroom	S9	11×14	GG	Floor	184	220	52	67	56	–	108%	–
Bedroom 2	S10	12×14	GG	Low sidewall	258	232	79	58	99	–	125%	–
Bedroom 3	S11	11×14	GG	Low sidewall	227	264	66	72	76	–	115%	–
Bath	S12	10×12	GG	Low sidewall	33	32	11	9	32	–	291%	–
Master Walk-in Closet	S13	12×14	GG	Low sidewall	50	42	16	9	98	–	613%	–
Totals					**1,959**	**1,905**	**868**	**870**	**821**			

Table 13. Pre- and Post-Upgrade Airspeeds at Registers in Test House 3

Location	Supply Outlet Post-Retrofit				Supply Outlet Calculated Net Free Area (ft^2)*	Pre-Upgrade Calculated Airspeed (FPM)		Post-Upgrade Measured Airspeed (FPM)	
	Mark	Size	Type	Location		Heat	Cool	Heat	Cool
Basement	–	–	–	–	–	–	–	–	–
Living Room	S1	12×14	GG	Floor	0.82	75	–	73	–
	S2	12×14	GG	Floor	0.82	75	–	81	–
Dining Room	S3	14×16	GG	Floor	1.09	136	–	76	–
Kitchen	S4	3×11	SSG	Toe kick	–	–	–	–	–
	S5	3×11	SSG	Toe kick	–	–	–	–	–
Office	S6	4×14	SSG	Floor	–	–	–	–	–
	S7	4×14	SSG	Floor	–	–	–	–	–
	S8	4×8	SSG	Floor	–	–	–	–	–
Master Bedroom	S9	11×14	GG	Floor	0.75	246	–	75	–
Bedroom 2	S10	12×14	GG	Low sidewall	0.82	316	–	121	–
Bedroom 3	S11	11×14	GG	Low sidewall	0.75	303	–	102	–
Bath	S12	10×12	GG	Low sidewall	0.58	57	–	55	–
Master Walk-in Closet	S13	12×14	GG	Low sidewall	0.82	61	–	120	–

3.3.2 Duct Air Leakage

IBACOS measured the duct air leakage for each of the units by performing tests using a Minneapolis Duct Blaster.[6] Total air leakage through the duct systems of all three test houses was measured, as well as total air leakage to the outside. The amount of air leaking through the duct systems helped to characterize the performance of the air distribution systems' capacity for delivering the proper amount of air to the zones of the houses. Table 14 shows the measured total duct air leakage and leakage to the outside for all three test houses, as well as the percentage of total unit airflow (nominal) represented by each leakage measurement.

Overall duct leakage values for all three test houses were high as a result of the old duct systems and the frequent use of panned returns in the original designs of the test houses. In addition, the old registers were large, and the duct systems were unsealed, which also contributed to the large values of leakage.

Table 14. Post-Retrofit Duct Air Leakage for All Three Test Houses

Performance Metric	Test House 1	Test House 2	Test House 3	Units
	Values			
Nominal System Size	3	2	3	Tons
Nominal System Airflow	1,200	800	1,200	Cubic feet
Final Duct Leakage	606	564	479	CFM25
	50.5%	70.5%	39.9%	Percent of nominal system flow
Final Duct Leakage to the Outside	12	0	27	CFM25
	1.0%	0%	2.3%	Percent of nominal system flow

3.3.3 Whole-Building Air Leakage

To evaluate the airtightness performance of the building enclosure for each test house, IBACOS conducted tests using a Minneapolis Blower Door[7] after the DER of each test house was completed. The test measures the amount of air leaking through the building enclosure under a known operating pressure differential between the house and the outside. Table 15 shows the test results.

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[6] Minneapolis Duct Blaster. Minneapolis, MN: The Energy Conservatory. http://www.energyconservatory.com/products/duct-blaster%C2%AE-systems-and-accessories.

[7] Minneapolis Blower Door. Minneapolis, MN: The Energy Conservatory. http://products.energyconservatory.com/blower-door-systems/.

Table 15. Whole-House Air Leakage for All Three Test Houses

	Test House 1		Test House 2		Test House 3		
Performance Metric	**Pre-Retrofit**	**Post-Retrofit**	**Pre-Retrofit**	**Post-Retrofit**	**Pre-Retrofit**	**Post-Retrofit**	**Units**
House Size	2,254		1,908		2,316		Square feet of finished floor area
House Volume	18,720		15,552		16,865		Cubic feet
Final Whole-House Air Leakage	2,765 9.1	1,394 4.74	1,790 6.9	881 4.08	4,200 14.8	3,203 11.4	CFM50 ACH50
% from Pre- to Post-Retrofit	52%		59%		77%		

3.4 Long-Term Monitoring and Data Collection

After completion of the DERs for all three test houses, long-term monitoring was performed on each test house for 1 year (September 2013 to September 2014) to collect data on the performance of key subsystems in these occupied test houses. The primary objectives of this monitoring included collection of temperature and RH data from individual rooms and thermal zones in each test house and outdoors, outdoor incident solar radiation, and electricity consumption of the indoor air handling units and outdoor compressor units. A primary data logger was used to take measurements from installed sensors for 1 year and recorded data at 1-minute intervals. Appendix B shows diagrams of the monitoring system design, including sensor locations and data that were collected.

The research team installed monitoring wiring and equipment during and after the DER of each test house. The team used a combination of wired and wireless sensors to capture the needed data and minimize installation labor. Table 16 lists the long-term monitoring equipment installed in the three test houses. Figure 8 through Figure 10 are photos of examples of installed monitoring equipment in Test House 2.

Table 16. Long-Term Monitoring Equipment Installed in the Three Test Houses

Measurement	Equipment Needed	Manufacturer	Part Number	Accuracy
Whole-House Electric	Watt node power meter	Continental Control Systems	WNB-3Y-P 4 HZ Output	±0.5%
Whole-House Electric	Split core current transformer	Continental Control Systems	ACT-0750-150	±0.75%
Compressor Electric	Watt node power meter	Continental Control Systems	WNB-3Y-P 4 HZ Output	±0.5%
Compressor Electric	Split core current transformer	Continental Control Systems	ACT-0750-030	±0.75%
Air Handler Electric	Watt node power meter	Continental Control Systems	WNB-3Y-P 4 HZ Output	±0.5%
Air Handler Electric	Split core current transformer	Continental Control Systems	ACT-0750-015	±0.75%
Data Collection	Main logger	Campbell Scientific	CR1000	±0.06%
Data Collection	Multiplexer	Campbell Scientific	AM 16/32 SDA-SWA8	NA
Supply and Return RH	Humidity sensor	Campbell Scientific	CS210	±3%
Supply and Return Temperature	Type T thermocouple	Omega	FF-T-24S-TWSH-SLE	0.75%
Space Air Temperature and RH	Wireless humidity sensor	Monnit	SCM-91A-0HA	±2%
Data Collection	Wireless Gateway			

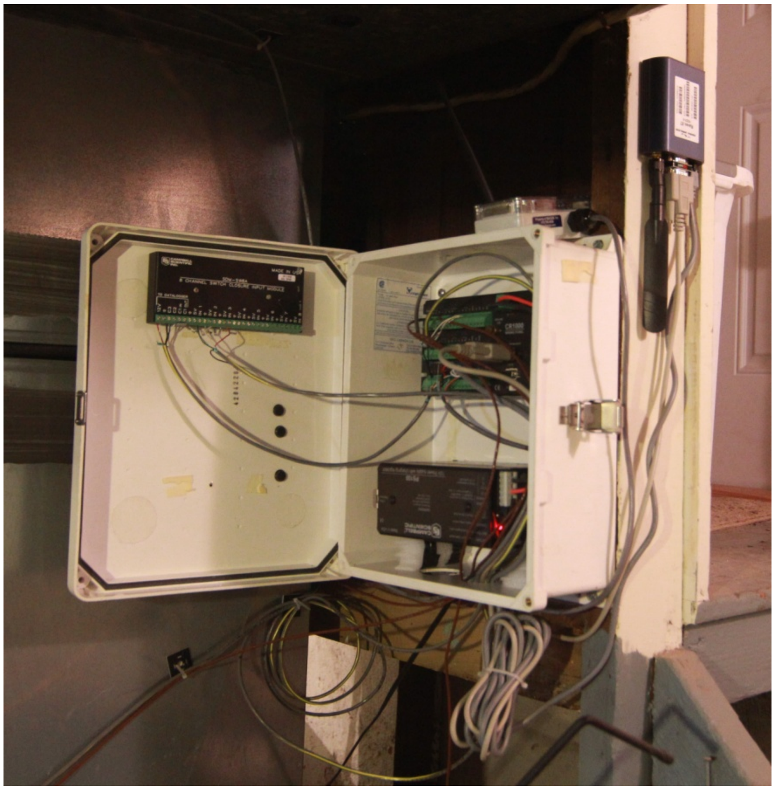

Figure 8. Campbell Scientific data logger and modem in the basement of Test House 2

Figure 9. Wireless temperature and RH sensor at the thermostat in Test House 2

Figure 10. Temperature sensors at the register of the longest duct runs in Test House 2

3.5 Results

In this section, the monitoring results from the three test houses are presented in several summary graphics as a high-level overview. Specific days have been plotted in detail for further review and discussion.

The single point of regular human interface with the HVAC system is the thermostat. To gain a baseline understanding of the operation and performance of the evaluated systems, the average temperature recorded at the thermostat was plotted for the duration of the study, as shown in Figure 11. To capture the detail of system setbacks but to filter individual system cycles, minute data were resampled to 6-hour averages. The average thermostat temperature was plotted as shown in Figure 11.

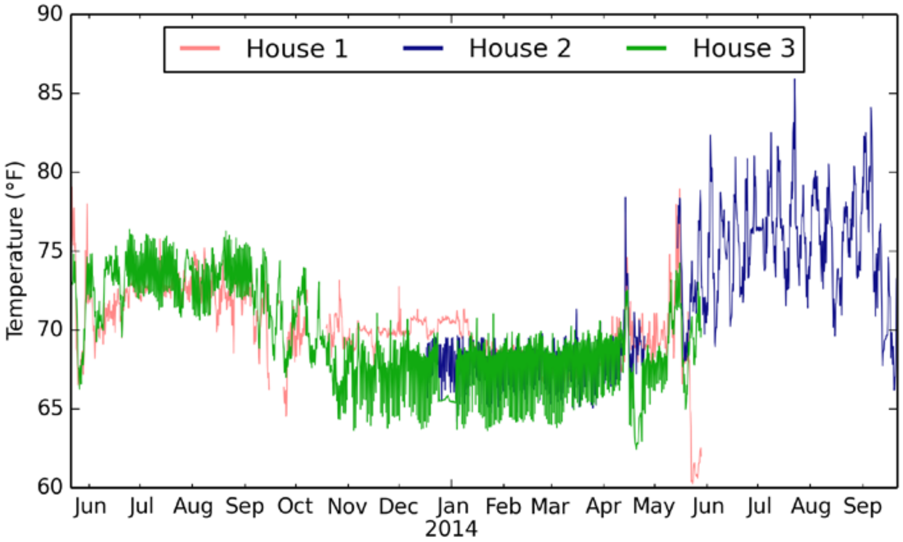

Figure 11. Thermostat temperature averaged every 6 hours for each test house

In the climate zone of the test houses (IECC climate zone 5), humidity control is not as problematic as it is in other climate zones. To determine if any significant humidity excursions warranted further analysis, all humidity values were plotted for each test house. The daily average humidity in each zone was plotted as shown in Figure 12, with all zones in each test house sharing one color. This graphic shows a few excursions above 60% RH; however, these were relatively brief. The basements in Test House 1 and Test House 2 show elevated levels of humidity.

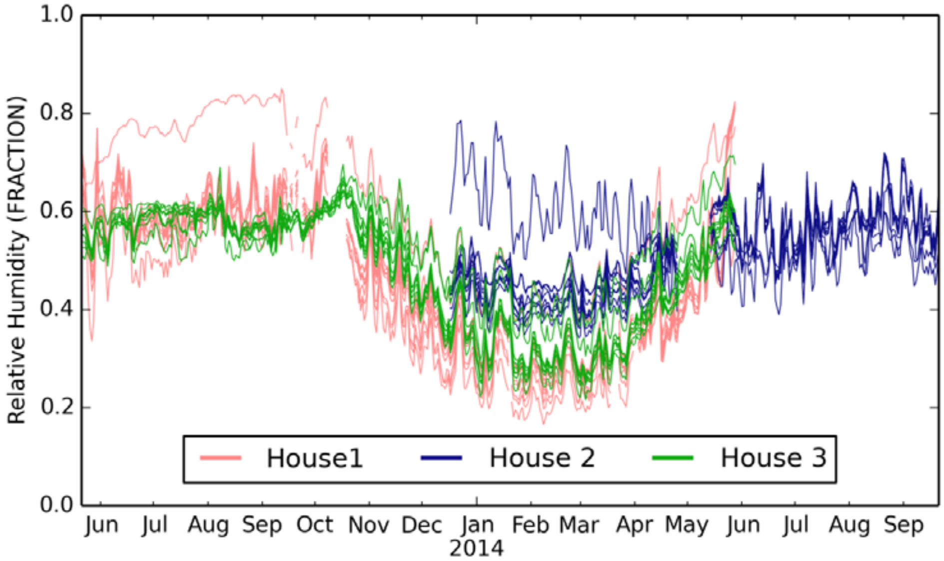

Figure 12. Conditioned space RH averaged every day for each test house

A primary question of the research is to understand the thermostat-to-room temperature variability and its impact on comfort in each of the test houses. Figure 13 through Figure 15 present summaries of the thermostat-to-room temperature variability for each test house.

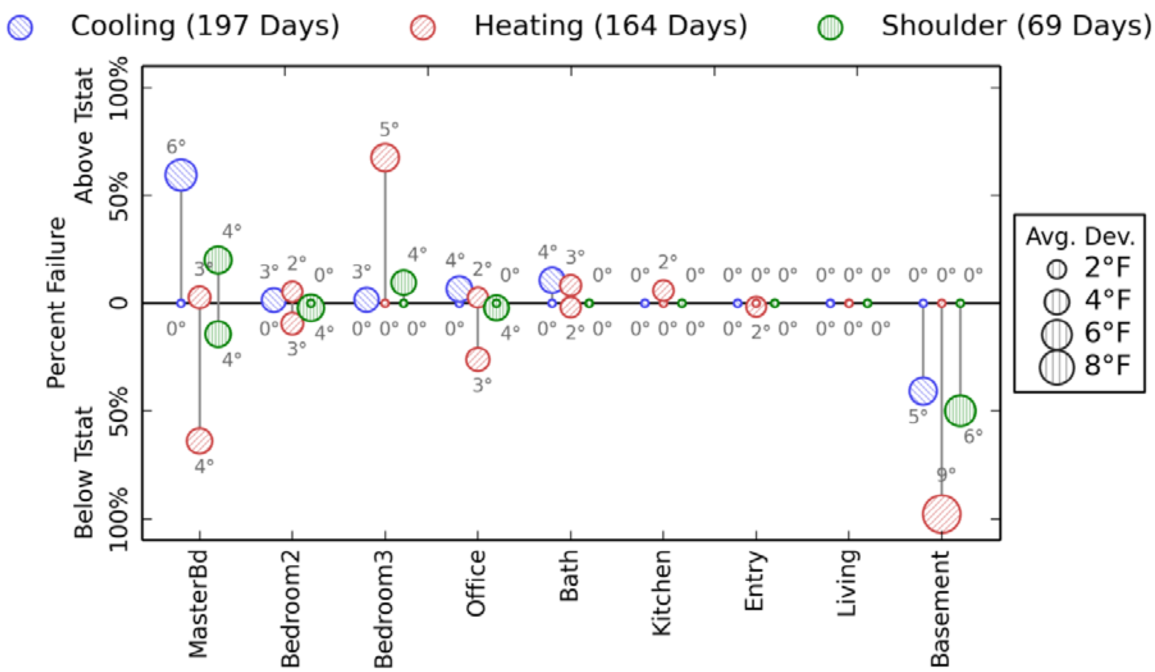

Figure 13. House 1: Room-to-thermostat temperature variability

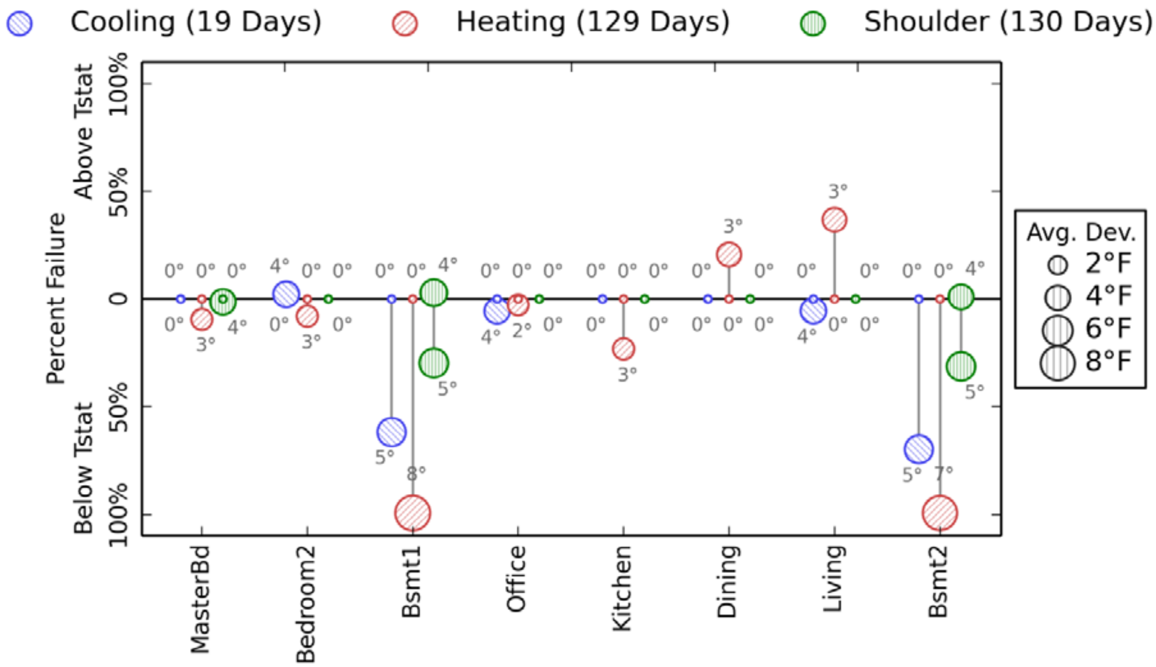

Figure 14. House 2: Room-to-thermostat temperature variability

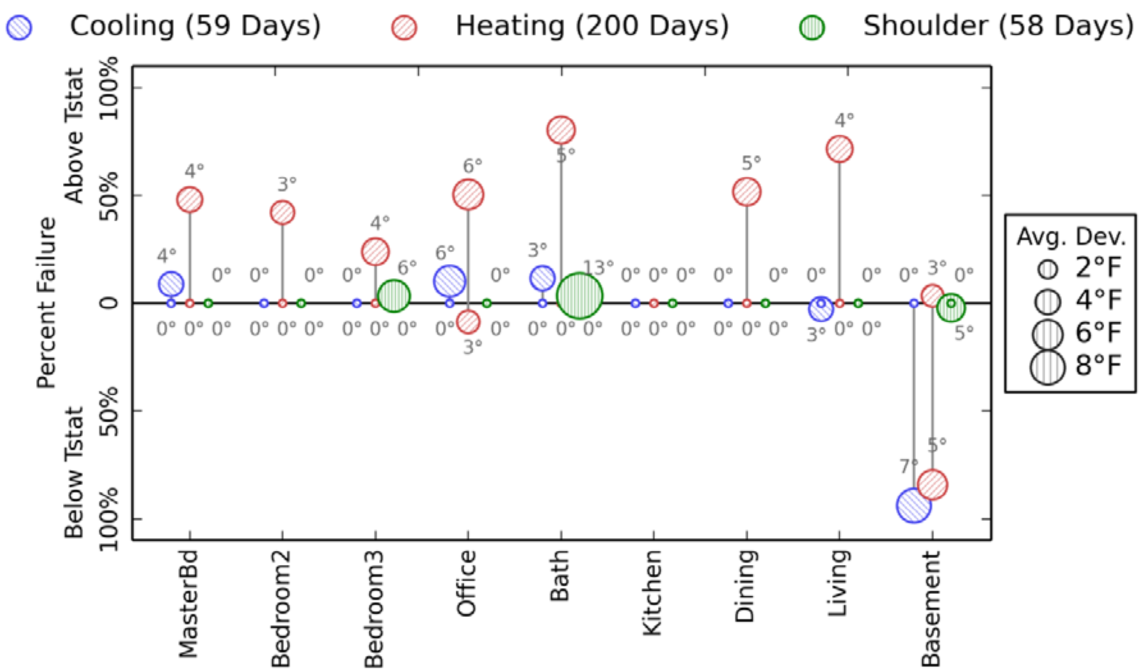

Figure 15. House 3: Room-to-thermostat temperature variability

In Figure 13 through Figure 15, several pieces of information are encoded for each test house. The most important number is the percentage of time a room is outside the comfort band as defined by ACCA Manual RS (±2°F in heating mode and ±3°F in cooling mode) (Rutkowski 1997). The positive Y-axis represents the percentage of time the room was above the comfort band; the negative Y-axis represents the percentage of time the room was below the comfort band. Days were broken down into heating mode, cooling mode, and shoulder days when the air handler did not operate. The number of days fitting into each category is listed beside the mode. The total number of days in each category was calculated based on actual system operation. As a result, the number of days varied among test cases.

For each test house, the area of each room's set of circles is scaled according to the average magnitude of failures, and a label specifies the numeric value of the average deviation during failure. The color of the dot and the direction of the hatch lines indicate whether the system was in cooling mode, heating mode, or shoulder days with no system operation.

To dig deeper, the team plotted temperature and system operation data during peak load conditions for each test house. These data are shown in Figure 16 through Figure 21. Three consecutive days were selected, which contained the top and bottom five outdoor temperature percentiles for hot and cold days, respectively. Each graphic contains several subplots: the temperature difference between each room and the thermostat, the outdoor temperature, the thermostat temperature, the design temperature, and finally the percentage runtime and outdoor temperature as a percentage of design temperature. The team calculated the outdoor temperature as a percentage of design temperature by dividing the instantaneous indoor-to-outdoor temperature difference by the design indoor-to-outdoor temperature difference. Temperatures are represented as hourly averages of minute data, plotted with linear interpolation; percentages are represented as stepped hourly averages. This graphic allows direct comparison between the outdoor temperature and system runtime and the effect of system runtime on room-to-room temperature differentials. A system designed to perfectly match the load should run 100% of the time when the outdoor temperature is 100% design conditions. In Figure 16 through Figure 21, the "design" label is the outdoor temperature as a percentage of design.

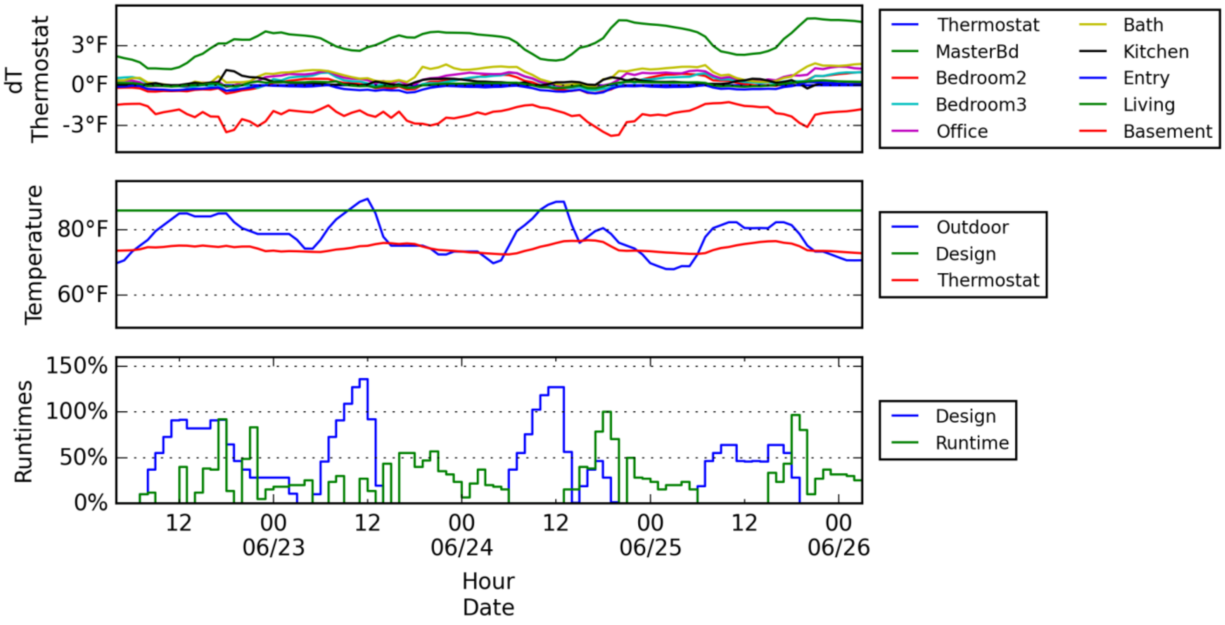

Figure 16. Test House 1: Operation during peak summer conditions

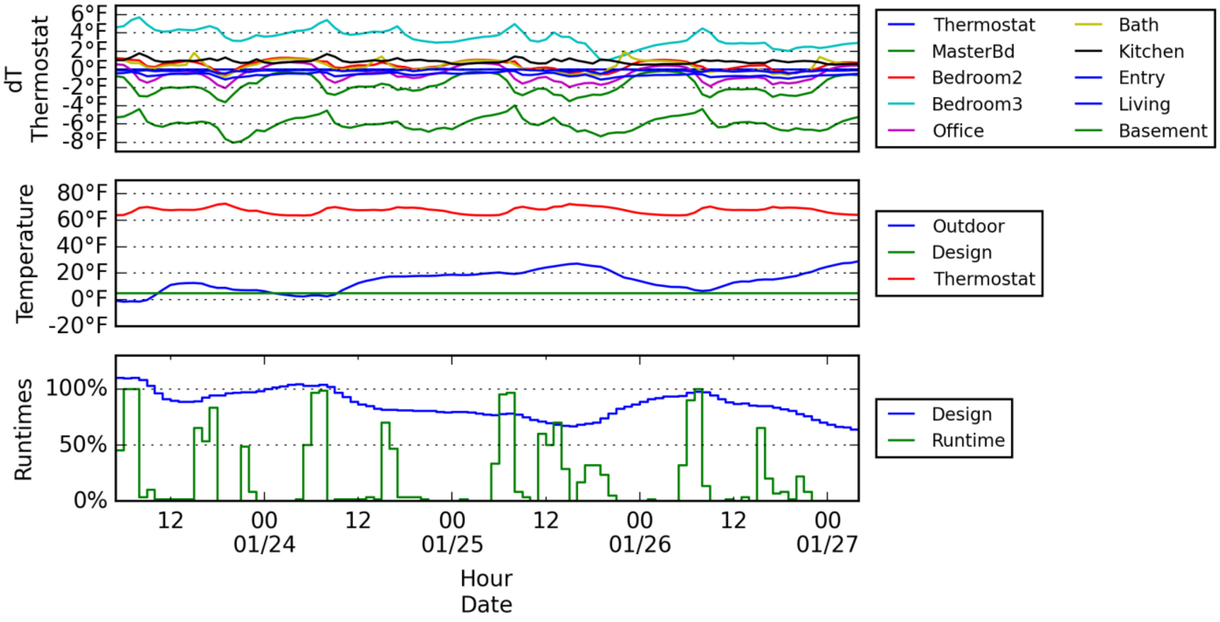

Figure 17. Test House 1: Operation during peak winter conditions

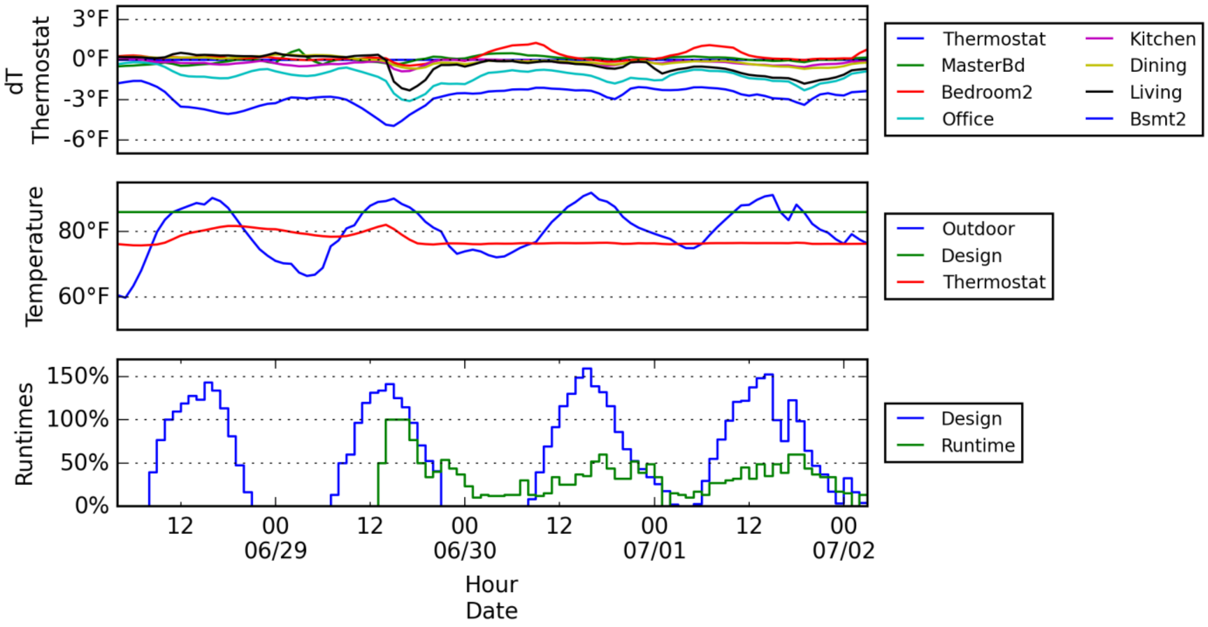

Figure 18. Test House 2: Operation during peak summer conditions

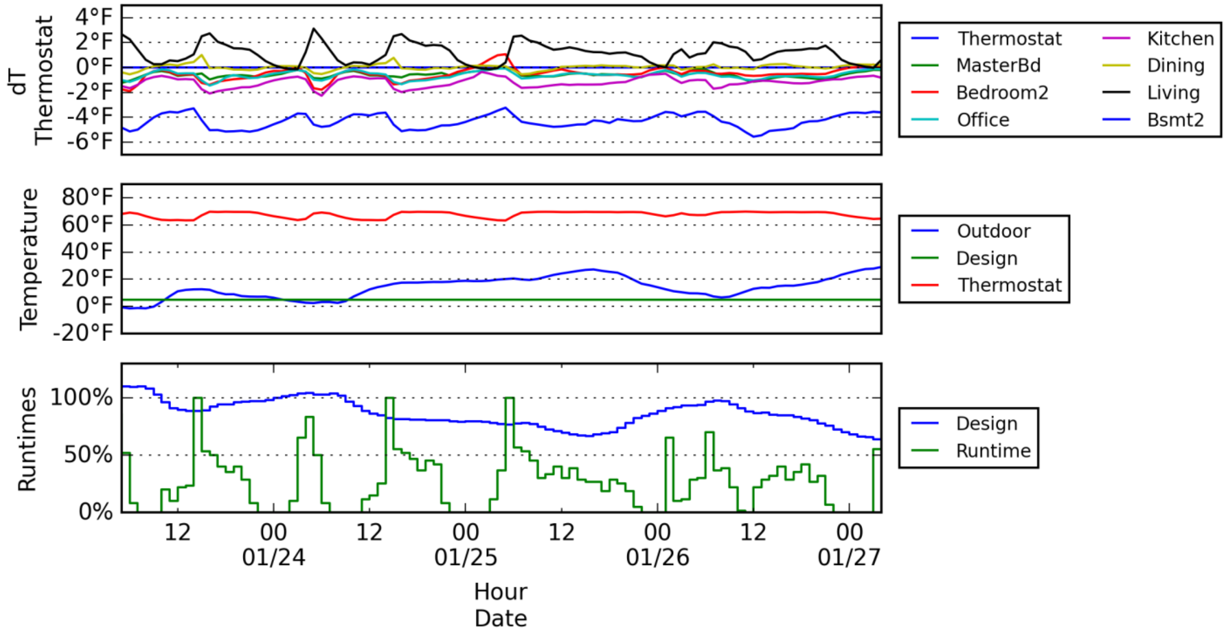

Figure 19. Test House 2: Operation during peak winter conditions

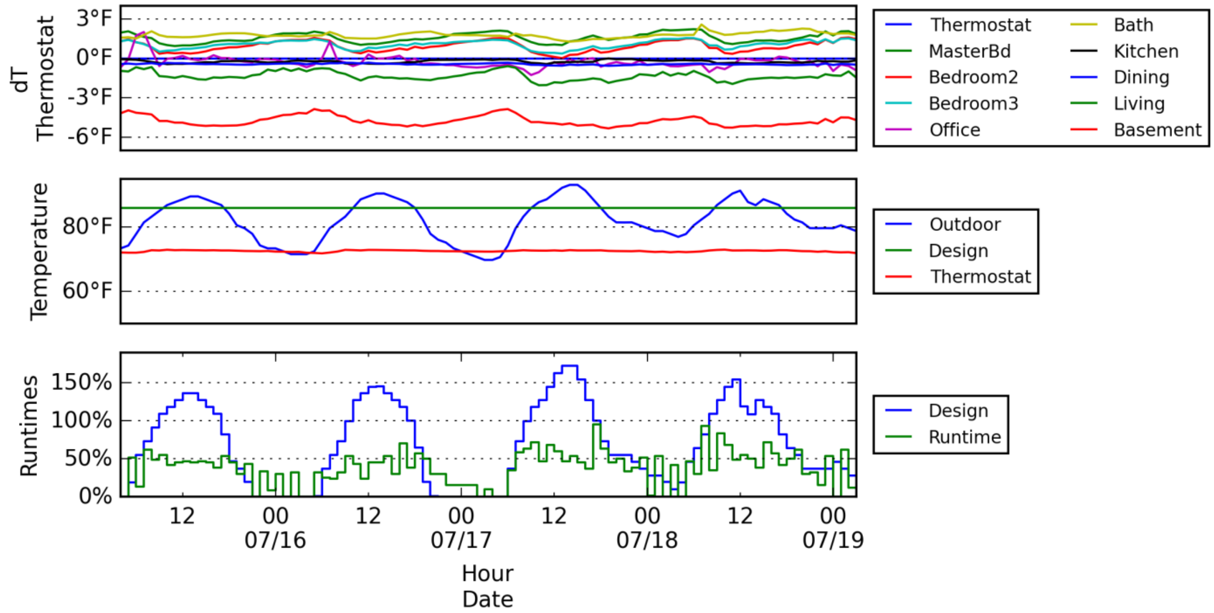

Figure 20. Test House 3: Operation during peak summer conditions

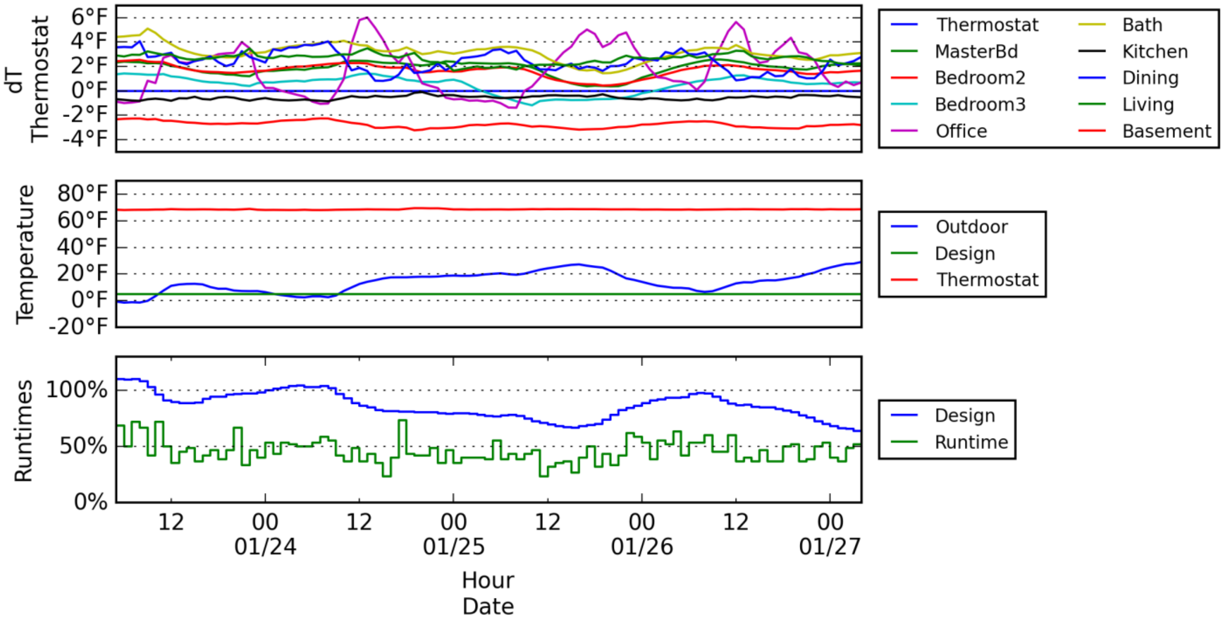

Figure 21. Test House 3: Operation during peak winter conditions

4 Discussion

4.1 Lessons Learned

From the three different DER strategies, there were some key "lessons learned", as described in the following paragraphs.

In Test House 1, when the ledger boards were installed over existing siding, the inconsistent surface created additional layout work. The distance of the ledger boards from the walls varied, depending on where these ledger boards fell. The siding was a wide shingle that left significant variation. This led to creating a new wall surface that did not follow the existing wall and rough openings. The team resolved this issue by planning for the inconsistencies from the beginning and measuring out how far the boards needed to be placed from the existing wall or by shimming the ledger to a consistent distance from the existing wall framing.

In Test House 2, a side-to-side bowing occurred on some 2 × 4s when spray foam was being applied. At first, the research team thought it might be necessary to place a bracket at the midpoint of the wall. This could be an inexpensive, nonstructural bracket that would simply provide the rigidity needed while spraying the insulation. This deflection also caused additional "detail" work in installing the windows. Some rough openings were moved out of plumb, which affected the trim work and, in turn, affected the timing of the project. The research team determined that if you "picture frame" the 2 × 4s with spray foam, less deflection will occur. This "picture frame" technique involves spraying the perimeter of the framed section and then filling the rest with foam.

When using spray foam, preparatory work is needed. The preparatory work for the DERs in Test House 2 included placing plastic over the windows and exposed foundation to protect them from overspray. The subcontractor also built a portable "tent" that propped against the house to minimize overspray onto plantings or other areas adjacent to the house.

The decision to change the original plan of installing the windows after the exterior wall construction to doing the two installations simultaneously in Test House 2 allowed for entire sections of wall to be completed; however, this change also left a gap between the old and new walls that had to be addressed. Instead of using a temporary enclosure with tape or oriented strand board (OSB) to handle foam expansion, the research team decided to install the extension jambs along the way as well. This minimized disruptions on the inside because more work was done all at once in a particular area. It is recommended that contractors plan for pulling and replacing the windows at the same time as the exterior wall framing is being built.

4.2 Peak Load and Airflow Reductions

Table 5 through Table 7 show that the retrofits undertaken in the three test houses resulted in 48% to 64% peak heating and cooling load reductions. Table 8, Table 10, and Table 12 show similar reductions in whole-house design airflows. The room-by-room measured airflows for the main living spaces in these houses showed reductions from 100% to increases of 96% from the pre-retrofit condition. The reduction from 100% was in the kitchen of Test House 3. In Test House 3, some of the ductwork was updated, and the supply to the kitchen register was removed during that renovation. The increase of 96% was in the bathroom of Test House 3. The contractors replaced ductwork in the basement of that test house, and it was not properly commissioned for this room. The installed dampers were not used to choke down the airflows.

Basement supply outlets were left in the pre-retrofit locations in all three test houses, most of which were cut directly into the side of the trunk ducts. Basement supplies showed significant variation in pre-upgrade design airflows and post-upgrade measured airflows.

Because of the significantly reduced loads, the installed HVAC systems were oversized in each test house in both heating and cooling capacities. In Test House 1, the heating capacity was oversized by a factor of 1.9 and the cooling capacity by a factor of 2.4. In Test House 2, the heating capacity was oversized by a factor of 1.8 and the cooling capacity by a factor of 2.75. In Test House 3, the heating capacity was oversized by a factor of 1.6 and the cooling capacity by a factor of 1.9. Typical recommendations suggest a system oversize factor of no more than 1.2, or 20%. The oversized systems resulted in frequent short cycling, reducing the overall efficiency of the systems. Additionally, short cycling can negatively impact zone stratification and mixing. It is interesting to note that if the system were sized smaller, the total CFM would be reduced, and the supply velocities would be further reduced.

None of the test houses had appropriately sized HVAC systems based on ACCA Manual J recommendations (Rutkowski 2006). This is apparent in the runtime calculations presented in Figure 16 through Figure 21. Test House 1 had regular thermostat setbacks; considering this, the only time the system ran 100% of an hour was during a return from setback. Otherwise, the system typically ran less than 50% of the time in heating and cooling modes. The data presented in Figure 18 from Test House 2 contained a period of two peak cooling days with no apparent modifications to the thermostat setting. During excursions of 150% of the design temperature, the system ran 50% of an hour. This runtime aligns well with the design capacity being only 36% of the installed capacity. The installed capacity of the systems in Test House 3 was closest to the design capacity. Figure 20 and Figure 21 do not show a user-controlled thermostat setback. Through the peak summer conditions, the system runtime in Test House 3 was typically 50% to 60% of an hour. Similar runtime was seen during peak winter conditions.

4.3 Supply Outlet Type and Airspeed Implications

Test House 1 and Test House 3 appear to have been designed for gravity warm-air furnaces. This conclusion was reached based primarily on the register locations and configurations. The left side of Figure 10 shows a typical gravity furnace grille. Test House 2 has SSGs that indicate the original system in the house was designed for forced air.

Konzo and MacDonald (1992) summarize much of the original research conducted on the performance of gravity furnaces, and several key points must be emphasized that are fundamentally different from those of traditional forced-air system design.

First, gravity furnaces rely on the buoyancy of the air for the motive force to deliver the air. There is no fan. As such, the duct design and outlet location and sizing are based more on stack effect and the relative movement of warm air by gravity than on the friction of the duct.

Willard (1919) found that taller duct runs in a gravity system delivered a greater volume of airflow through the duct compared to shorter vertical ducts or minimally pitched horizontal duct runs. This led to a sizing and design strategy where the ducts to the second floor of the house are actually smaller than the ducts to the first floor, as a function of the Btu output per square inch of duct cross-sectional area. This difference in size also applies to the net free area of the outlet, where a proper system design would have a similar net free area as the cross-sectional area of the duct.

Second, gravity systems were never envisioned or designed to supply cooling to the rooms served. Konzo and MacDonald (1992) document research showing that low sidewall location provided better mixing of air temperature for space heating than high sidewall outlets. Again, this is due to the fact that a warm-air system relies entirely on the buoyancy of the air in the space. Supplying the air low in the room gives it a chance to move and mix with the entire volume of room air, rather than stagnate at the ceiling of the room, outside the occupied zone. This mixing function also is enhanced by the general stack effect of the house, which is assumed to be very leaky because gravity furnaces were installed in the early 1900s, when little attention was paid to air sealing of buildings.

The IBACOS team measured the airspeed of each diffuser whenever possible. Table 9 and Table 13 show the measured face velocities of 6 FPM to 38 FPM in Test House 1 and 73 FPM to 121 FPM in Test House 3, respectively. Note that Kratz and Konzo (1939) found approximately 8°F floor-to-ceiling temperature differences in a cold-climate research house with baseboard grilles at approximately 120 FPM airspeeds. Kratz et al. (1938) found that low sidewall outlets with straight louvers (presumably similar to a gravity system grille) were not ideal for forced-air cooling with 450-FPM face velocities. ACCA Manual RS (Rutkowski 1997) suggests supply registers have a face velocity of 600 FPM to 700 FPM to provide adequate mixing in each zone. The low supply velocity leads the team to believe there may be concerns with adequate zone mixing and stratification. IBACOS recommends strategies should be used to improve throw and mixing whenever the total system airflow has been reduced on a legacy duct system (Burdick 2014). These strategies could include reducing the area of the register to increase face velocity.

4.4 Data Monitoring Discussion

The results of the monitoring activity indicate each test home had zones with significant excursions outside the ACCA Manual RS comfort bands (Rutkowski 1997).

Test House 1 had significant excursions in the third-floor master bedroom, which are evident in Figure 13. These excursions occurred during both heating and cooling modes. The master bedroom was underheated during winter and undercooled during summer. The most significant cause of this problem is the insufficient CFM of air supplied to the room. As specified in Table 8, the bedroom should have received 119 CFM during heating but received only 65 CFM; it should have received 114 CFM during cooling but received only 40 CFM. Low airflow, coupled with the fact that this room is the most removed from the rest of the house, resulted in many extended periods of temperature measured beyond the comfort zones. Bedroom 3 showed frequent overheating during the winter. During the installation of monitoring equipment, the team noted a portable space heater in this room, which may have been the cause.

Through the peak summer conditions and as shown in Figure 16, the HVAC system rarely ran 100% of the time, even during design conditions, indicating the cooling capacity to be significantly oversized. The periods of 100% operation are during return from thermostat setback. Humidity control is not a primary concern in the test climate; however, for energy retrofit projects in other climates, correct cooling sizing is critical to provide adequate dehumidification. Through the winter peak conditions, system operation peaked only during return from thermostat setback, again indicating the system was oversized.

One of the key reasons the homeowners underwent the DER in Test House 1 was for improved comfort, specifically in the master bedroom. The homeowners' overall satisfaction with the DER has been hampered by a lack of balancing of the HVAC system. Decreasing the load by improving the shell alone is not enough to ensure occupant comfort. The HVAC system also must be redesigned and correctly balanced. The airspeed out of the master bedroom's supply register was measured at 38 FPM and 23 FPM in heating mode and cooling mode, respectively. ACCA Manual RS (Rutkowski 1997) suggests supply register velocities of 600 FPM to 700 FPM. To achieve an average airspeed of 600 FPM with the measured cooling airflow volume of 40 CFM, the master bedroom register area should be 0.066 ft^2, which is equal to a 3-½-in.-diameter circle. The actual register size is 0.83 ft^2.

Test House 2 showed significant excursions in only the basement zones. These zones were removed from the home, with no connecting staircase in conditioned space. If the basement is to be considered conditioned and occupied space, increased heating airflow would be needed. The other zones generally kept within ±2°F of the thermostat. Test House 2 is a single-story ranch-style house, and the simple floor plan contributed to the consistent thermostat-to-room temperature. The occupant in Test House 2 operated the cooling system only when the home became uncomfortable; as such, the system ran only 19 days in the summer during the long-term monitoring period. During the peak load conditions plotted in Figure 18, the system saw an hour with 100% utilization; however, this was the result of a return from setback. Subsequent days show the system runtime peaking at 50% during an hour, with outdoor temperatures at 150% of the design temperature. This suggests the cooling capacity for Test House 2 is oversized by a factor of 3. Peak winter operation, as plotted in Figure 19, again shows that the system is oversized.

Test House 3 showed significant overheating occurrences in Figure 15, with consistent comfort during cooling operation.

5 Conclusions

This project was intended to answer three research questions.

The first research question asked, “What are the differences between the pre- and post-upgrade room-by-room loads, and how do these vary from the capacity of the installed space conditioning equipment and distribution system?”

IBACOS found that pre- and post-upgrade house and room loads for the three test houses with DERs ranged from 48% to 64% peak heating and cooling load reductions. The resulting reductions in room loads, measured airflows, and measured and calculated airspeeds at supply outlets indicated that, even if total delivered energy to each room may be adequate, it is not clear if the room mixing and stratification will maintain comfort for occupants. Furthermore, in Test House 1, only six of 22 supply registers were within 20 percentage points of the specified airflow. Test House 2 had three of 22, and Test House 3 had four of 12 register airflows within bounds. With wildly varying airflows, it takes no stretch of the imagination to realize why some rooms exhibited occupant discomfort. Two of the test houses (Test House 1 and Test House 3) apparently were originally designed for gravity warm-air systems. The measured post-retrofit airspeeds in these two houses ranged from 6 FPM to 121 FPM. Test House 2, which was originally designed for a forced-air system, had measured post-upgrade airspeeds of 26 FPM to 598 FPM. Although the focus of this study was primarily on heating season performance, low supply outlet airspeeds and existing floor return locations may not enable enough mixing to maintain the desired occupant comfort on second floors in cooling.

The second research question asked, “Over the course of a year, when do temperature and RH excursions happen that exceed ACCA Manual RS (Rutkowski 1997) and ASHRAE Standard 55 (ASHRAE 2010) recommendations?”

Each test house showed some excursions during various conditions. The excursions had several potential causes: insufficient or excessive airflow, significant solar gains, significant internal gains, or the zone was located below grade. Test House 1 had a third-floor bedroom that consistently overheated in the summer and did not maintain temperature in the winter because of insufficient airflow. Test House 2 exhibited adequate performance during cooling and shoulder days, with the basement zones significantly cooler than the rest of the house. During heating mode, the open and connected south-facing dining and living areas tended to overheat 20% to 40% of the time; these zones also were collectively supplied with 160% of the design airflow. Conversely, the south-facing kitchen was underheated 25% of the time, with only 53% of the design airflow. The results from Test House 3 show that the only comfort concern is consistent overheating in each zone except the basement. This may be due to the placement of the thermostat.

It can be concluded that not balancing the HVAC system has a greater impact on thermal comfort and room-to-room temperature uniformity in these retrofit cases than the environmental conditions. Something to be considered in the future is the impact of nonenergy savings measures such as design and balancing of the HVAC system on the overall success of the retrofit project.

The third research question asked, “What is the heating or cooling equipment runtime associated with the outdoor and indoor temperatures, and how does that compare to the room-by-room temperatures?”

Each test house showed a system runtime response that varied with the indoor and outdoor temperature difference. The data also showed that the only periods in which the system ran 100% of the time in a given hour was during a return from setback. Otherwise, the systems typically ran at most 60% of the time during peak outdoor conditions, which is consistent with an oversized system.

Room-by-room temperature uniformity varied among the test houses with respect to system runtime. At times, the test houses showed worse thermal uniformity during increased system operation; however, there may be no causality. Test House 1 typically exhibited worse uniformity during periods of extended system runtime and improved uniformity when the system did not operate for a period. The cause of this may be load imbalances during peak conditions or poor balancing of the HVAC system. Test House 2 also showed worse uniformity during periods of increased system operation, specifically during the heating season. Test House 3 did not appear to have any thermostat setback; as such, the system runtime did not vary as significantly hour to hour. In Test House 3, the room-by-room temperatures varied most significantly based on the diurnal temperature swing and solar loads.

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Appendix A: Input Parameters for BEopt and Results

The following charts show the information that was input into the BEopt models for each of the three test houses. The graphs in Figure 22 through Figure 33 show the differences between the pre- and post-retrofit models.

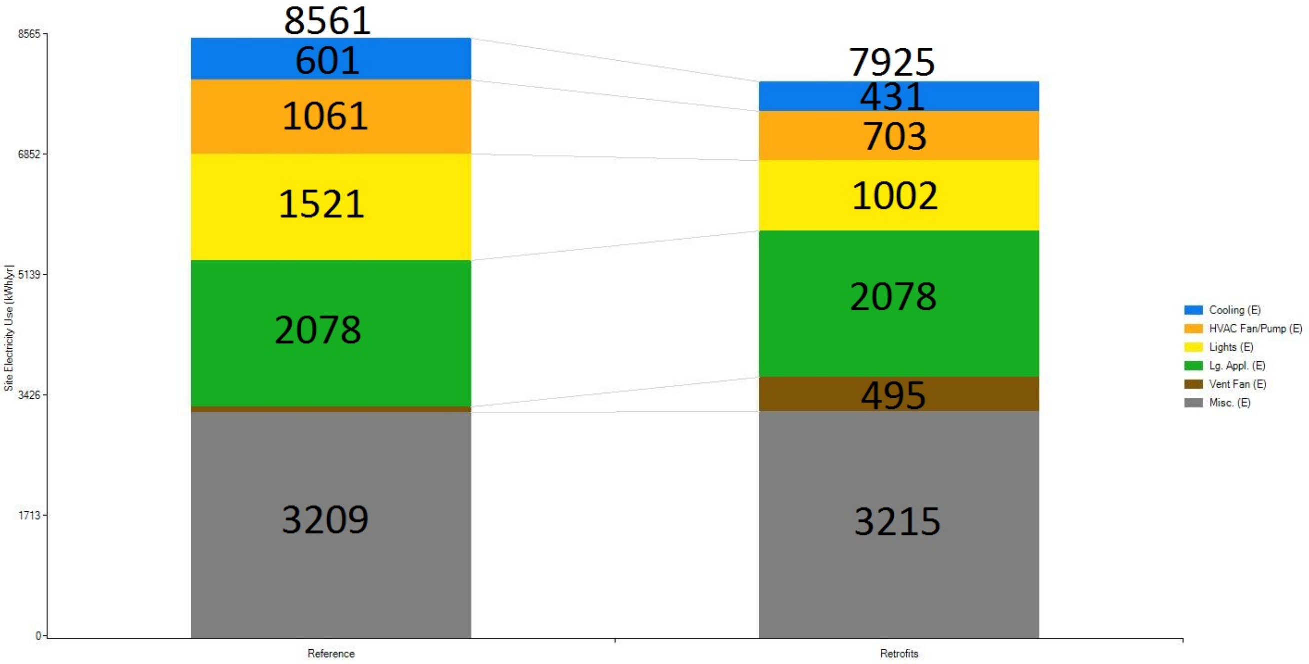


Figure 22. Test House 1: Electricity

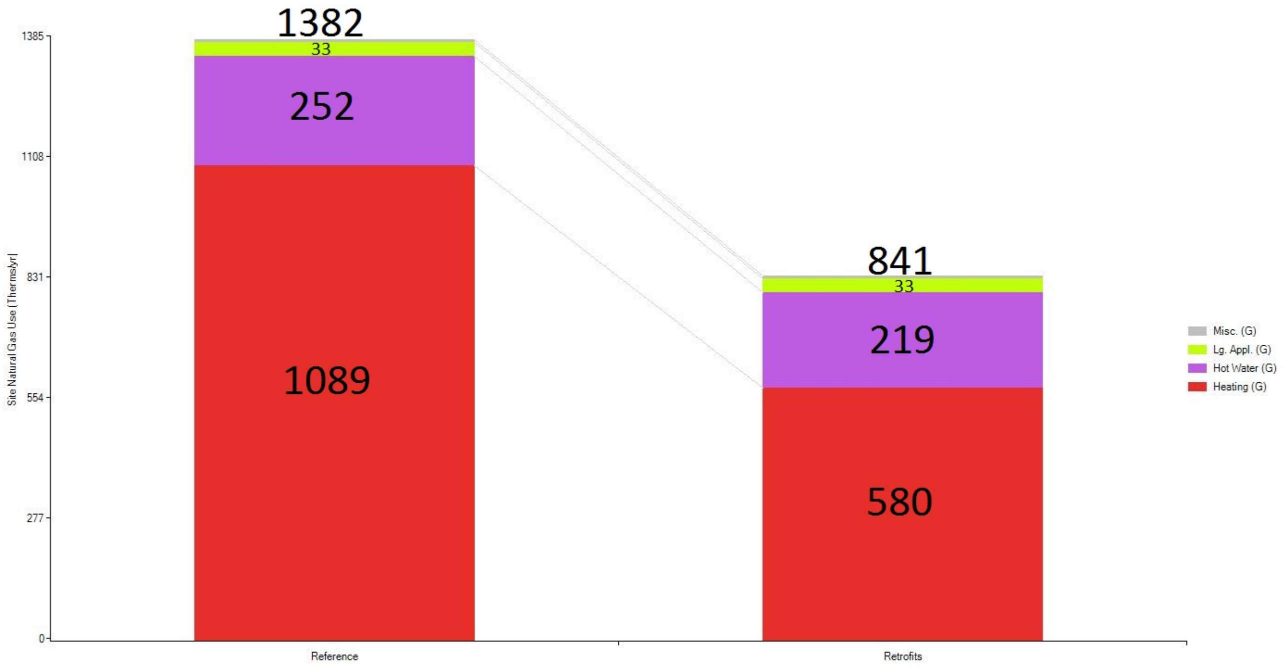


Figure 23. Test House 1: Natural gas

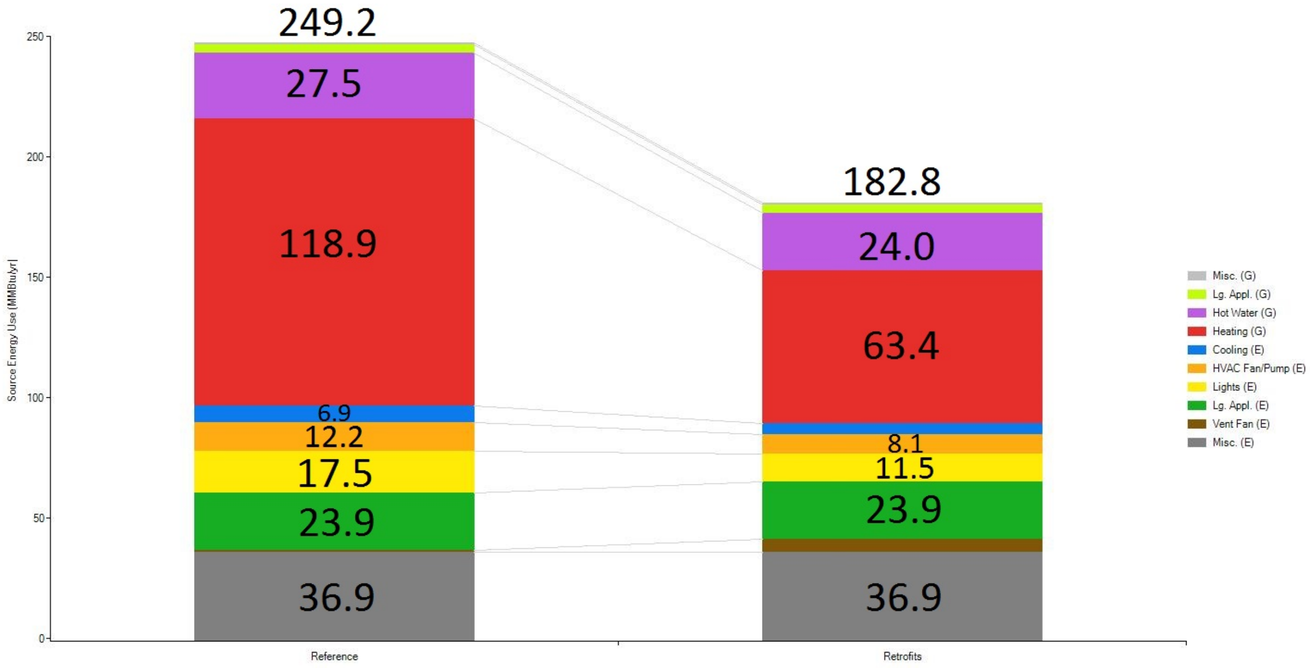


Figure 24. Test House 1: Source energy

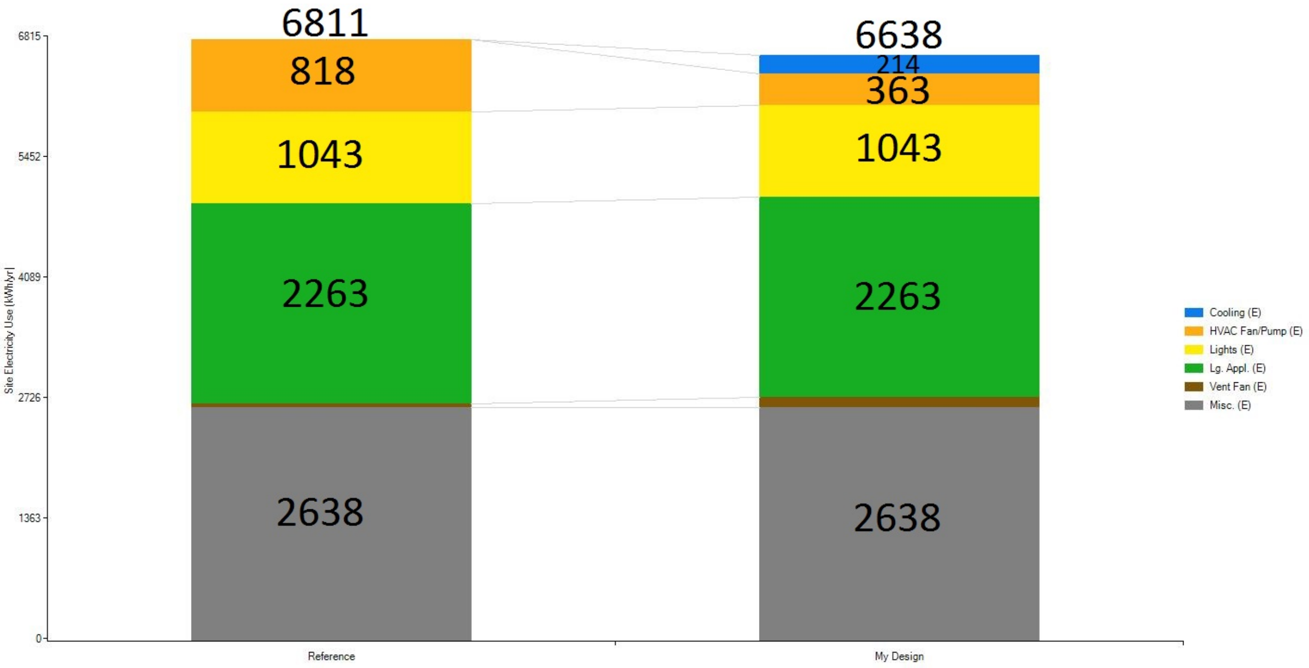


Figure 25. Test House 2: Electricity

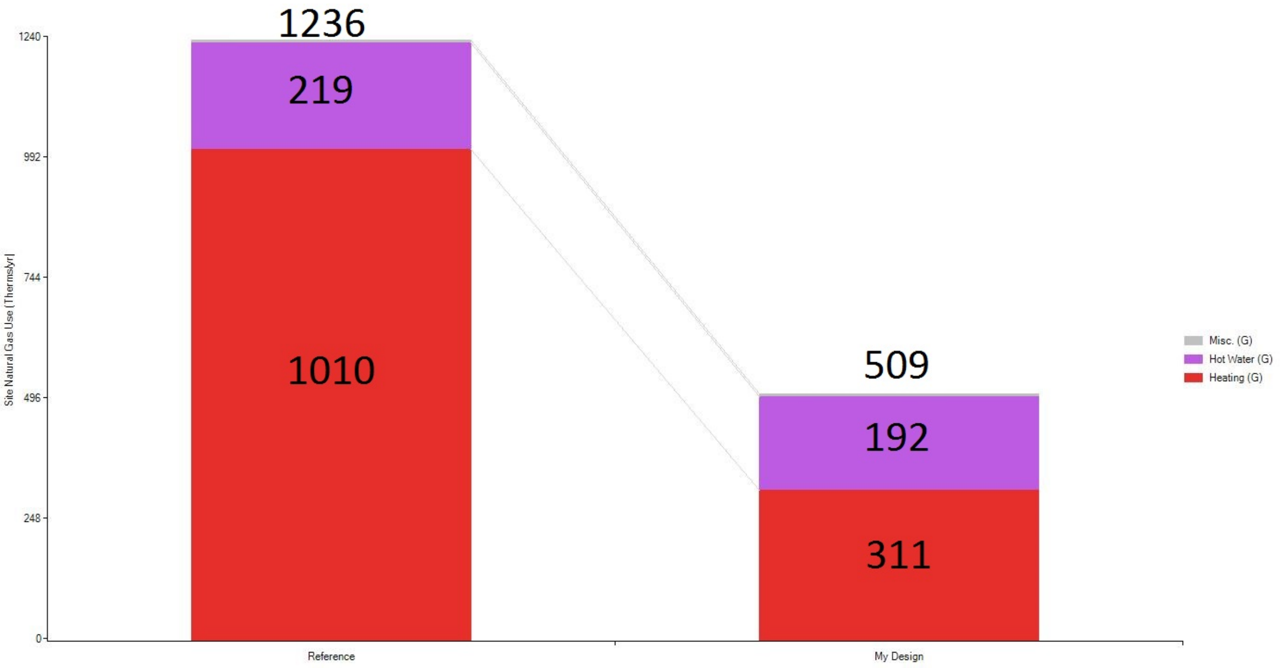


Figure 26. Test House 2: Natural gas

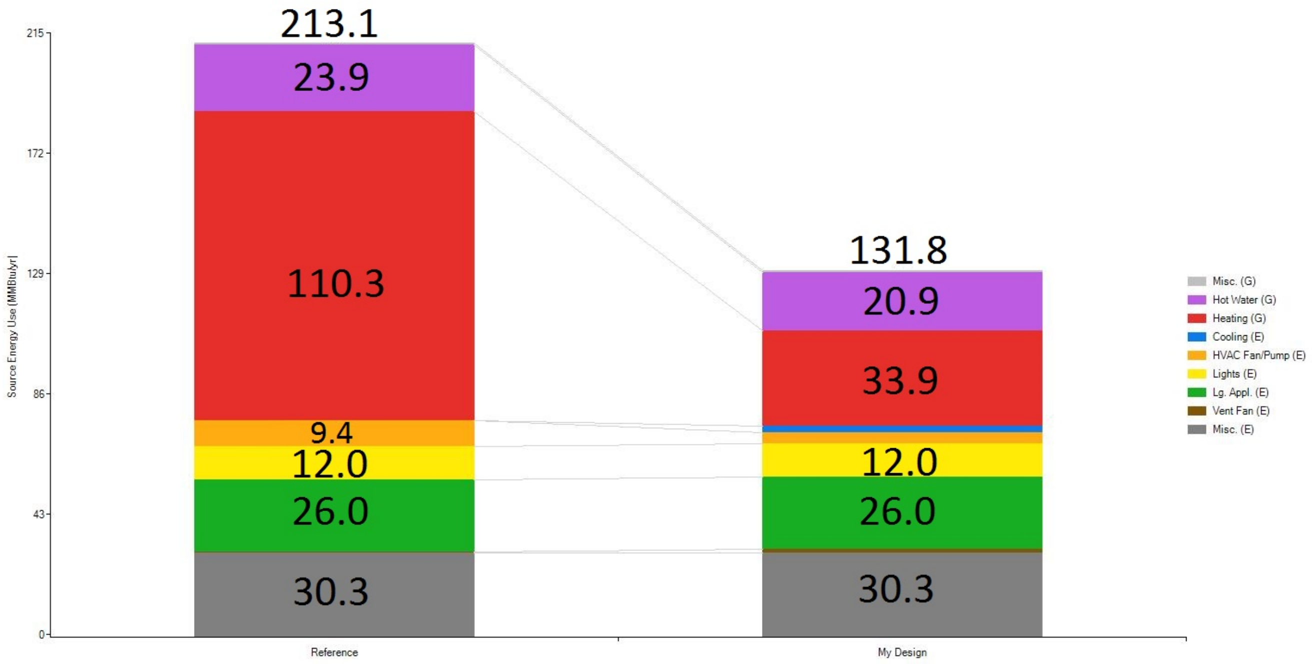


Figure 27. Test House 2: Source energy

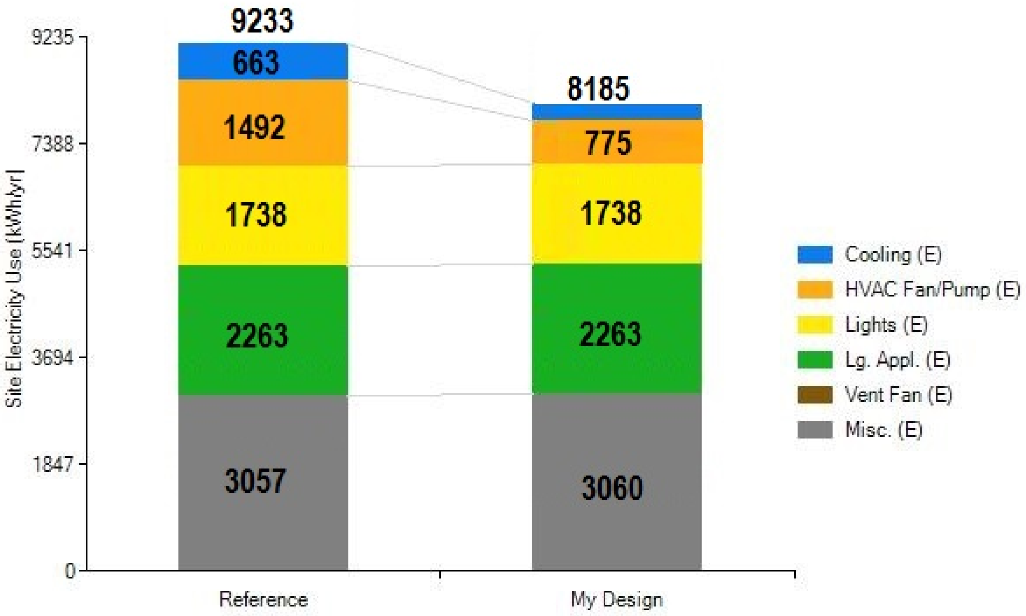


Figure 28. Test House 3: Electricity

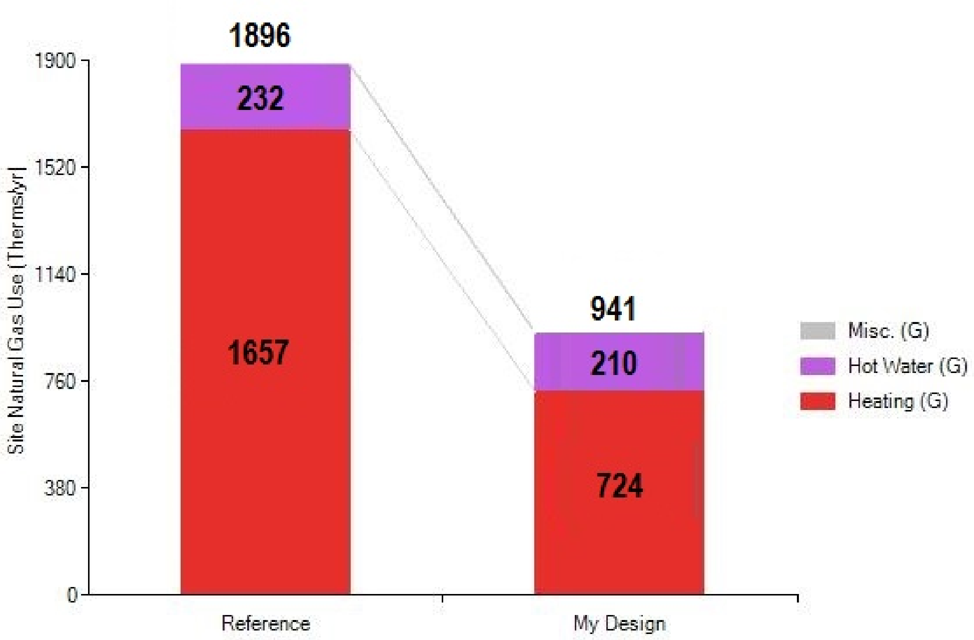


Figure 29. Test House 3: Natural gas

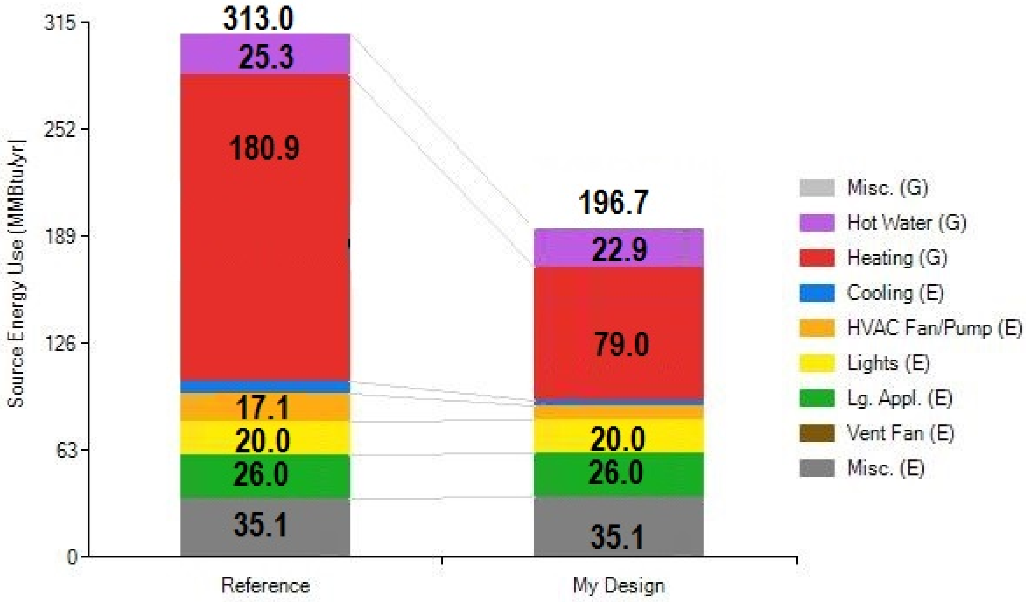
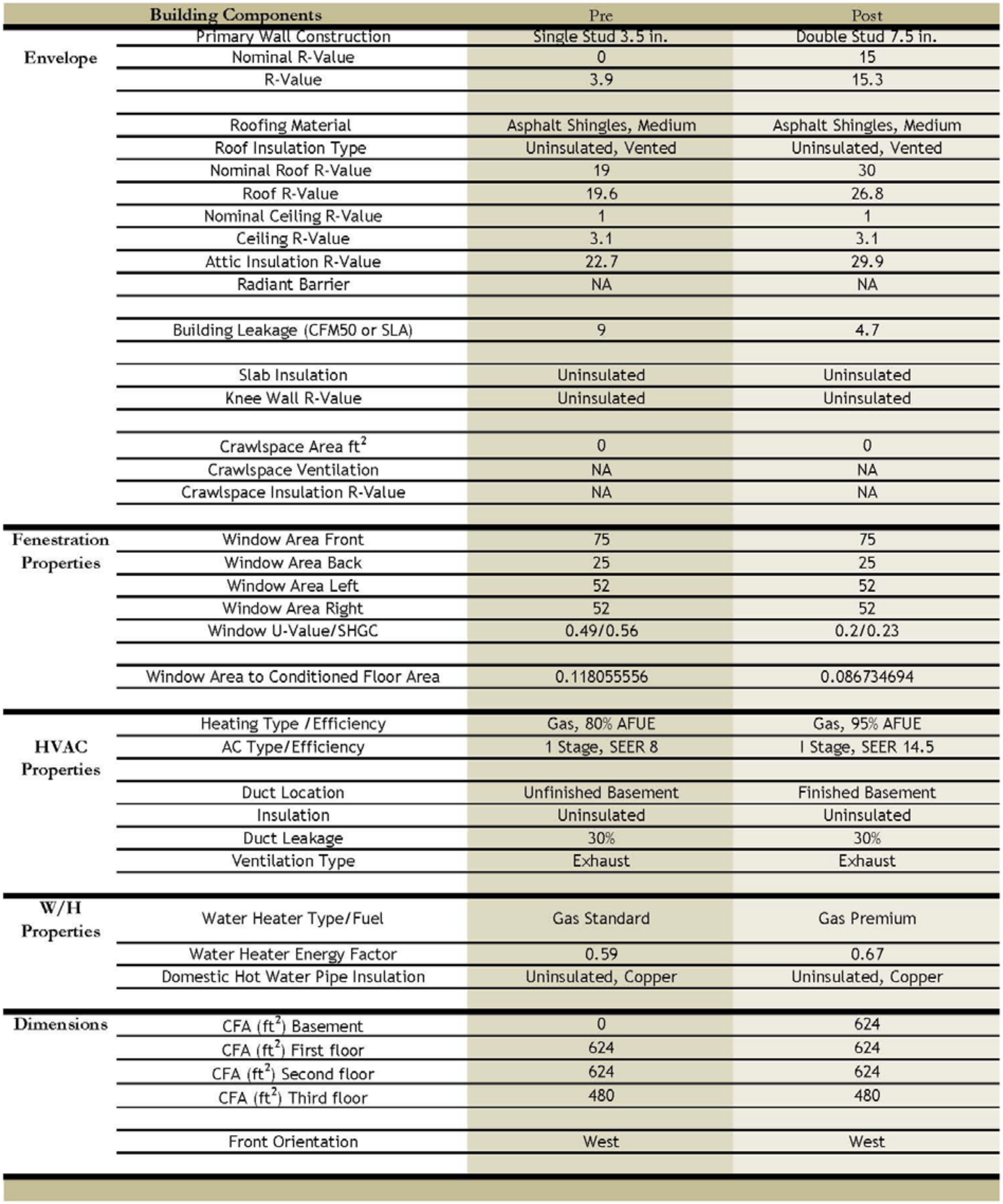
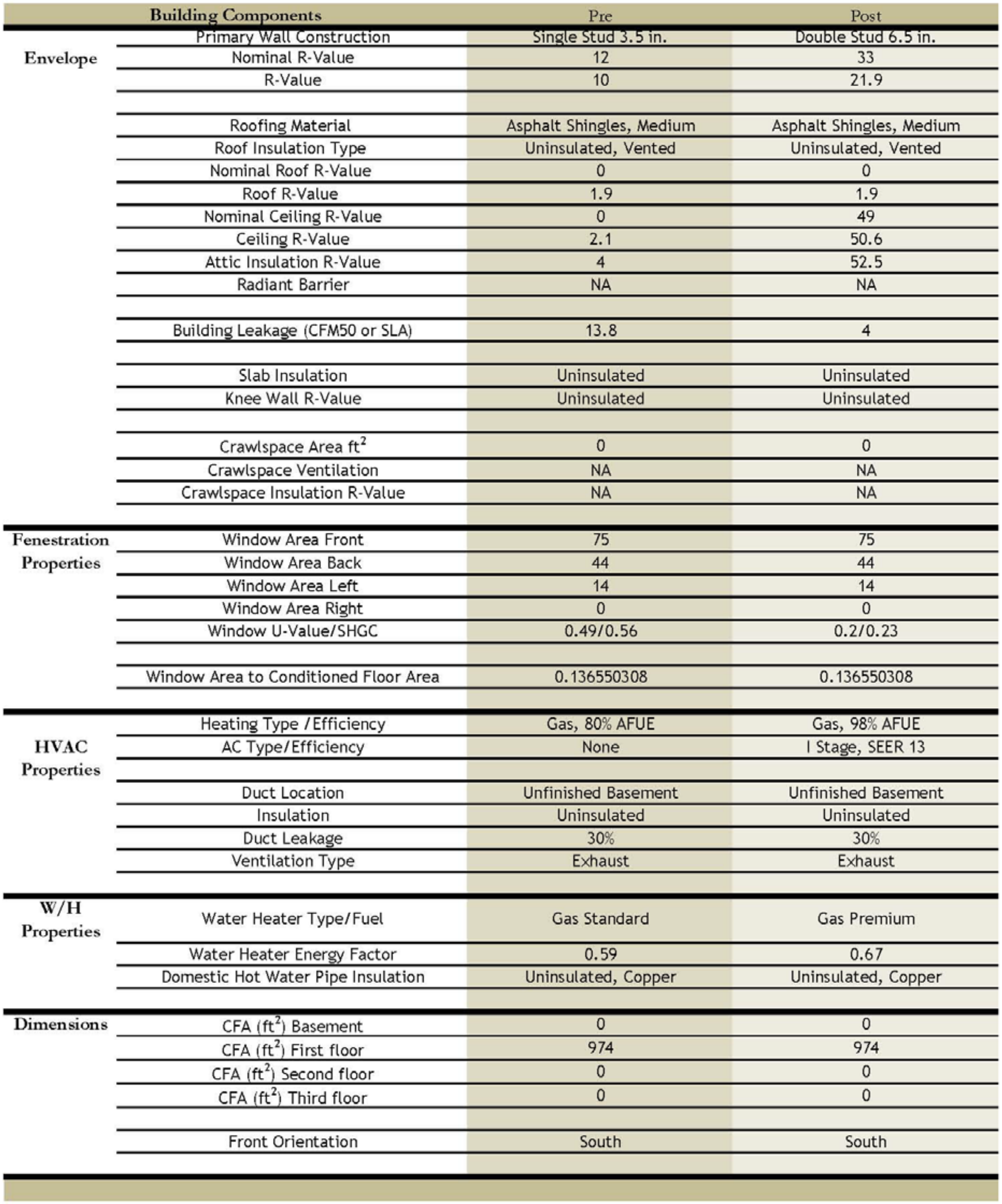


Figure 30. Test House 3: Source energy



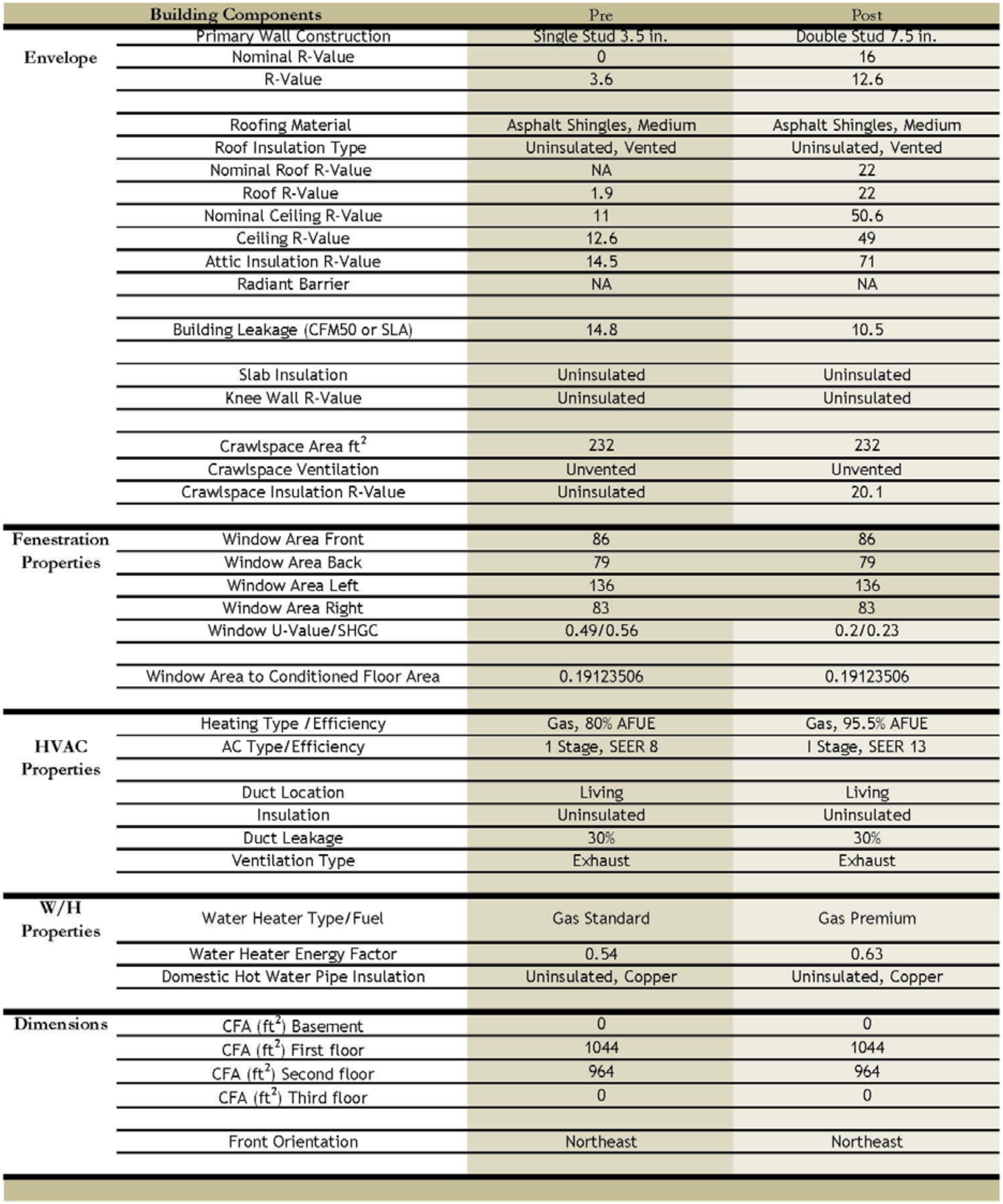
Building Components		Pre	Post
Envelope	Primary Wall Construction	Single Stud 3.5 in.	Double Stud 7.5 in.
	Nominal R-Value	0	15
	R-Value	3.9	15.3
	Roofing Material	Asphalt Shingles, Medium	Asphalt Shingles, Medium
	Roof Insulation Type	Uninsulated, Vented	Uninsulated, Vented
	Nominal Roof R-Value	19	30
	Roof R-Value	19.6	26.8
	Nominal Ceiling R-Value	1	1
	Ceiling R-Value	3.1	3.1
	Attic Insulation R-Value	22.7	29.9
	Radiant Barrier	NA	NA
	Building Leakage (CFM50 or SLA)	9	4.7
	Slab Insulation	Uninsulated	Uninsulated
	Knee Wall R-Value	Uninsulated	Uninsulated
	Crawlspace Area ft^2	0	0
	Crawlspace Ventilation	NA	NA
	Crawlspace Insulation R-Value	NA	NA
Fenestration Properties	Window Area Front	75	75
	Window Area Back	25	25
	Window Area Left	52	52
	Window Area Right	52	52
	Window U-Value/SHGC	0.49/0.56	0.2/0.23
	Window Area to Conditioned Floor Area	0.118055556	0.086734694
HVAC Properties	Heating Type / Efficiency	Gas, 80% AFUE	Gas, 95% AFUE
	AC Type/Efficiency	1 Stage, SEER 8	I Stage, SEER 14.5
	Duct Location	Unfinished Basement	Finished Basement
	Insulation	Uninsulated	Uninsulated
	Duct Leakage	30%	30%
	Ventilation Type	Exhaust	Exhaust
W/H Properties	Water Heater Type/Fuel	Gas Standard	Gas Premium
	Water Heater Energy Factor	0.59	0.67
	Domestic Hot Water Pipe Insulation	Uninsulated, Copper	Uninsulated, Copper
Dimensions	CFA (ft^2) Basement	0	624
	CFA (ft^2) First floor	624	624
	CFA (ft^2) Second floor	624	624
	CFA (ft^2) Third floor	480	480
	Front Orientation	West	West

Figure 31. Test House 1 parameters



	Building Components	Pre	Post
Envelope	Primary Wall Construction	Single Stud 3.5 in.	Double Stud 6.5 in.
	Nominal R-Value	12	33
	R-Value	10	21.9
	Roofing Material	Asphalt Shingles, Medium	Asphalt Shingles, Medium
	Roof Insulation Type	Uninsulated, Vented	Uninsulated, Vented
	Nominal Roof R-Value	0	0
	Roof R-Value	1.9	1.9
	Nominal Ceiling R-Value	0	49
	Ceiling R-Value	2.1	50.6
	Attic Insulation R-Value	4	52.5
	Radiant Barrier	NA	NA
	Building Leakage (CFM50 or SLA)	13.8	4
	Slab Insulation	Uninsulated	Uninsulated
	Knee Wall R-Value	Uninsulated	Uninsulated
	Crawlspace Area ft^2	0	0
	Crawlspace Ventilation	NA	NA
	Crawlspace Insulation R-Value	NA	NA
Fenestration Properties	Window Area Front	75	75
	Window Area Back	44	44
	Window Area Left	14	14
	Window Area Right	0	0
	Window U-Value/SHGC	0.49/0.56	0.2/0.23
	Window Area to Conditioned Floor Area	0.136550308	0.136550308
HVAC Properties	Heating Type / Efficiency	Gas, 80% AFUE	Gas, 98% AFUE
	AC Type/Efficiency	None	I Stage, SEER 13
	Duct Location	Unfinished Basement	Unfinished Basement
	Insulation	Uninsulated	Uninsulated
	Duct Leakage	30%	30%
	Ventilation Type	Exhaust	Exhaust
W/H Properties	Water Heater Type/Fuel	Gas Standard	Gas Premium
	Water Heater Energy Factor	0.59	0.67
	Domestic Hot Water Pipe Insulation	Uninsulated, Copper	Uninsulated, Copper
Dimensions	CFA (ft^2) Basement	0	0
	CFA (ft^2) First floor	974	974
	CFA (ft^2) Second floor	0	0
	CFA (ft^2) Third floor	0	0
	Front Orientation	South	South

Figure 32. Test House 2 parameters

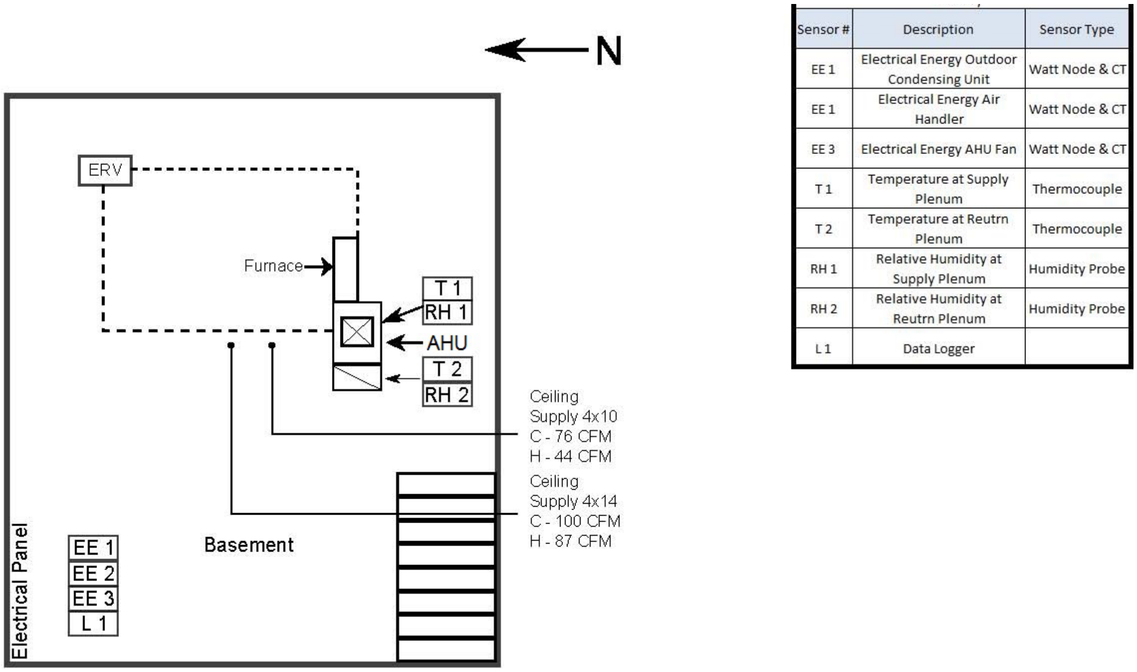


	Building Components	Pre	Post
Envelope	Primary Wall Construction	Single Stud 3.5 in.	Double Stud 7.5 in.
	Nominal R-Value	0	16
	R-Value	3.6	12.6
	Roofing Material	Asphalt Shingles, Medium	Asphalt Shingles, Medium
	Roof Insulation Type	Uninsulated, Vented	Uninsulated, Vented
	Nominal Roof R-Value	NA	22
	Roof R-Value	1.9	22
	Nominal Ceiling R-Value	11	50.6
	Ceiling R-Value	12.6	49
	Attic Insulation R-Value	14.5	71
	Radiant Barrier	NA	NA
	Building Leakage (CFM50 or SLA)	14.8	10.5
	Slab Insulation	Uninsulated	Uninsulated
	Knee Wall R-Value	Uninsulated	Uninsulated
	Crawlspace Area ft^2	232	232
	Crawlspace Ventilation	Unvented	Unvented
	Crawlspace Insulation R-Value	Uninsulated	20.1
Fenestration Properties	Window Area Front	86	86
	Window Area Back	79	79
	Window Area Left	136	136
	Window Area Right	83	83
	Window U-Value/SHGC	0.49/0.56	0.2/0.23
	Window Area to Conditioned Floor Area	0.19123506	0.19123506
HVAC Properties	Heating Type / Efficiency	Gas, 80% AFUE	Gas, 95.5% AFUE
	AC Type/Efficiency	1 Stage, SEER 8	I Stage, SEER 13
	Duct Location	Living	Living
	Insulation	Uninsulated	Uninsulated
	Duct Leakage	30%	30%
	Ventilation Type	Exhaust	Exhaust
W/H Properties	Water Heater Type/Fuel	Gas Standard	Gas Premium
	Water Heater Energy Factor	0.54	0.63
	Domestic Hot Water Pipe Insulation	Uninsulated, Copper	Uninsulated, Copper
Dimensions	CFA (ft^2) Basement	0	0
	CFA (ft^2) First floor	1044	1044
	CFA (ft^2) Second floor	964	964
	CFA (ft^2) Third floor	0	0
	Front Orientation	Northeast	Northeast

Figure 33. Test House 3 parameters

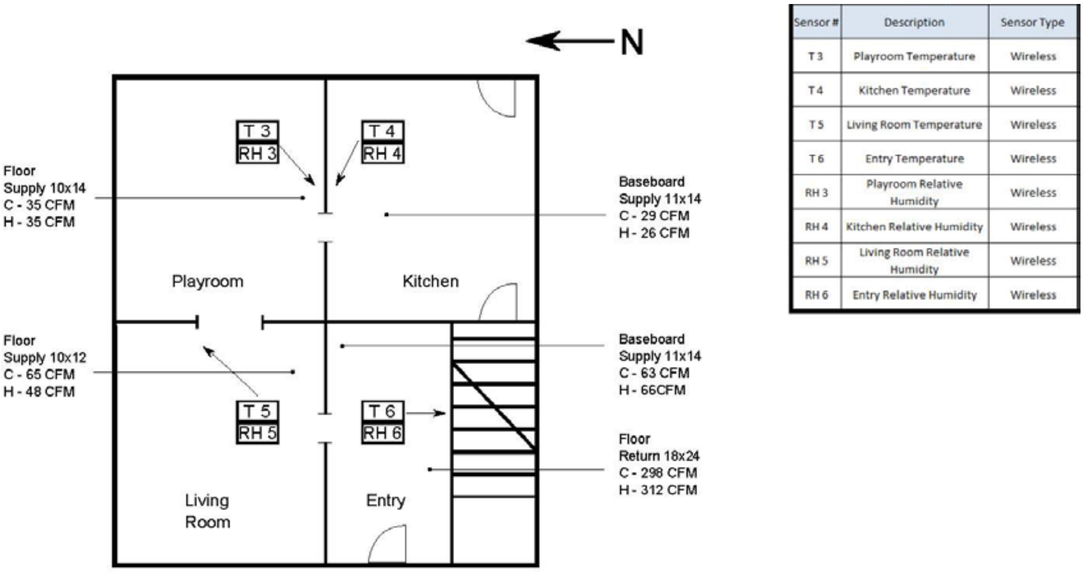
Appendix B: Monitoring System Design Diagrams

Figure 34 through Figure 42 show the locations of the long-term monitoring systems (installed temperature and RH sensors), the duct layout, and the supply and return register locations for all three test houses.



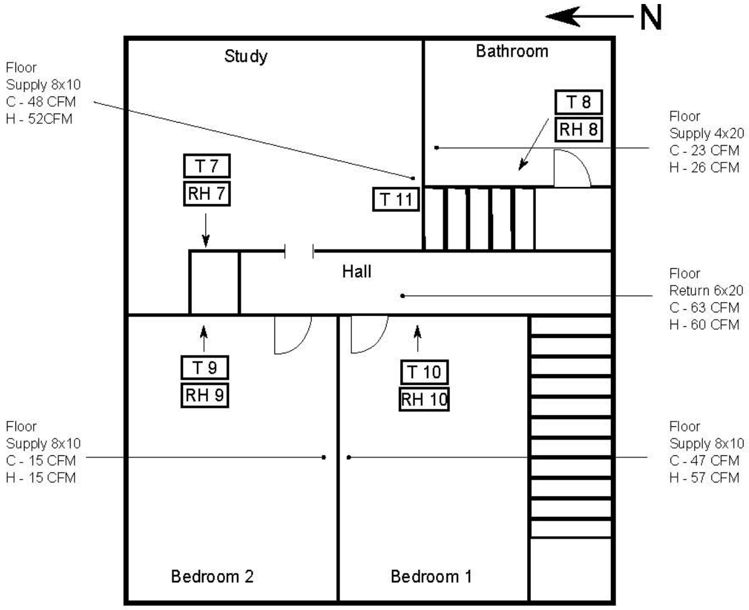
Sensor #	Description	Sensor Type
EE 1	Electrical Energy Outdoor Condensing Unit	Watt Node & CT
EE 1	Electrical Energy Air Handler	Watt Node & CT
EE 3	Electrical Energy AHU Fan	Watt Node & CT
T 1	Temperature at Supply Plenum	Thermocouple
T 2	Temperature at Reutrn Plenum	Thermocouple
RH 1	Relative Humidity at Supply Plenum	Humidity Probe
RH 2	Relative Humidity at Reutrn Plenum	Humidity Probe
L 1	Data Logger	

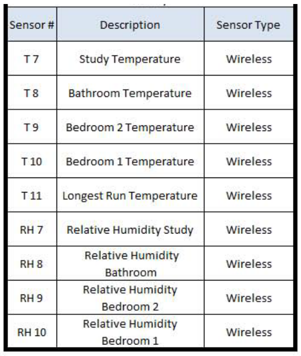
Figure 34. Test House 1, basement



Sensor #	Description	Sensor Type
T 3	Playroom Temperature	Wireless
T 4	Kitchen Temperature	Wireless
T 5	Living Room Temperature	Wireless
T 6	Entry Temperature	Wireless
RH 3	Playroom Relative Humidity	Wireless
RH 4	Kitchen Relative Humidity	Wireless
RH 5	Living Room Relative Humidity	Wireless
RH 6	Entry Relative Humidity	Wireless

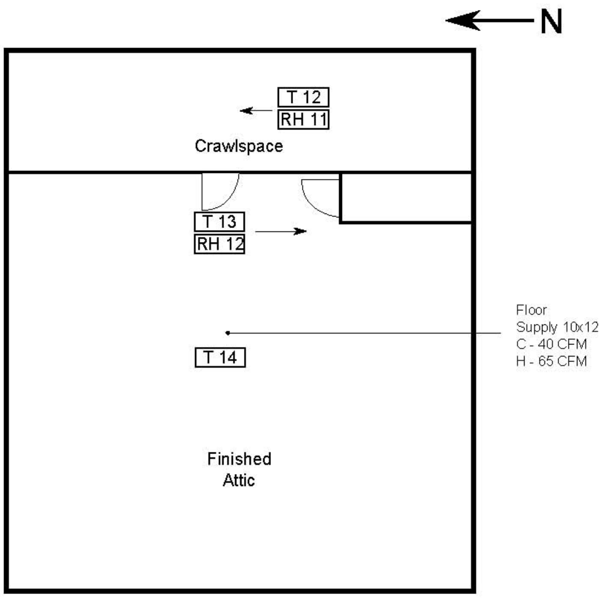
Figure 35. Test House 1, first floor

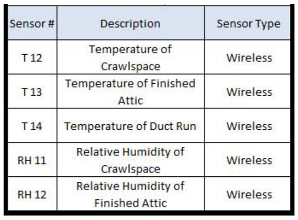




Sensor #	Description	Sensor Type
T 7	Study Temperature	Wireless
T 8	Bathroom Temperature	Wireless
T 9	Bedroom 2 Temperature	Wireless
T 10	Bedroom 1 Temperature	Wireless
T 11	Longest Run Temperature	Wireless
RH 7	Relative Humidity Study	Wireless
RH 8	Relative Humidity Bathroom	Wireless
RH 9	Relative Humidity Bedroom 2	Wireless
RH 10	Relative Humidity Bedroom 1	Wireless

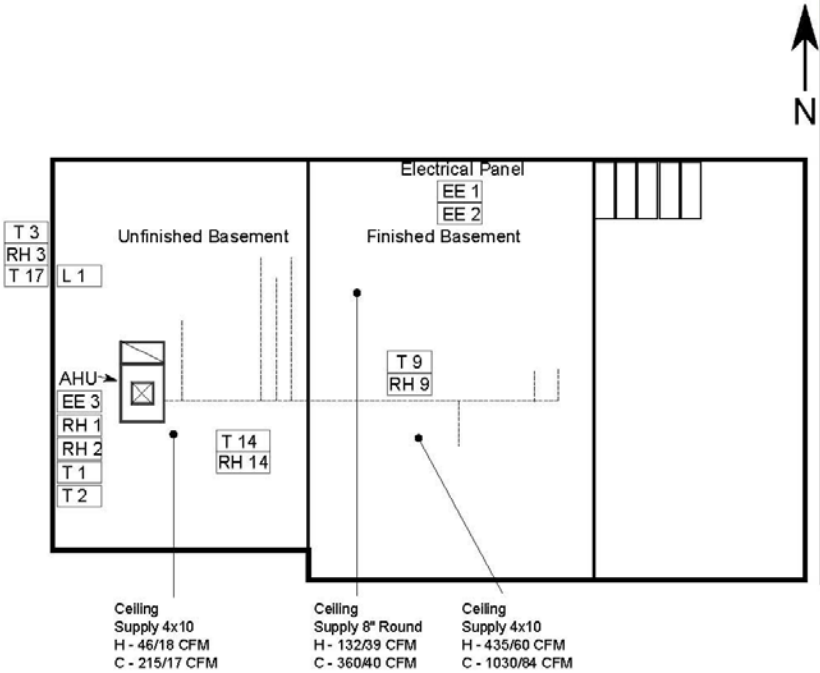
Figure 36. Test House 1, second floor





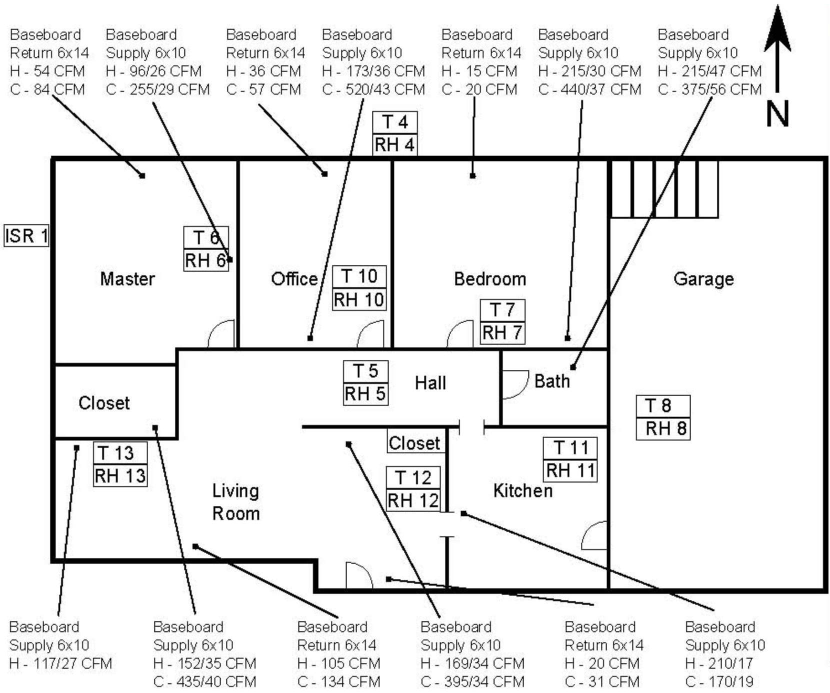
Sensor #	Description	Sensor Type
T 12	Temperature of Crawlspace	Wireless
T 13	Temperature of Finished Attic	Wireless
T 14	Temperature of Duct Run	Wireless
RH 11	Relative Humidity of Crawlspace	Wireless
RH 12	Relative Humidity of Finished Attic	Wireless

Figure 37. Test House 1, attic



Sensor #	Description	Sensor Type
EE 1	Outdoor Condensing Unit	Watt Node & CT
EE 2	Air Handler	Watt Node & CT
EE 3	AHU Fan	Watt Node & CT
RH 1	Relative Humidity Supply Plenum	Humidity Sensor
RH 2	Relative Humidity Return Plenum	Humidity Sensor
RH 3	Relative Humidity Outdoor	Humidity Sensor
RH 9	Relative Humidity Basement 1	Humidity Sensor
RH 14	Relative Humidity Basement 2	Humidity Sensor
T 1	Temperature Supply Plenum	Humidity Sensor
T 2	Temperature Return Plenum	Humidity Sensor
T 3	Temperature Outdoors	Wireless
T 9	Temperature Basement 1	Thermocouple
T 14	Temperature Basement 2	Thermocouple
T 17	Temperature Outdoors	Thermocouple
L 1	Data Logger	

Figure 38. Test House 2, basement



Sensor #	Description	Sensor Type
T 4	Outdoor Temperature	Wireless
T 5	Hall Temperature	Wireless
T 6	Master Bedroom Temperature	Wireless
T 7	Bedroom Temperature	Wireless
T 8	Garage Temperature	Wireless
T 11	Kitchen Temperature	Wireless
T 12	Living Room Temperature 1	Wireless
T 13	Living Room Temperature 2	Wireless
RH 4	Outdoor Relative Humidity	Wireless
RH 5	Hall Relative Humidity	Wireless
RH 6	Master Bedroom Relative Humidity	Wireless
RH 7	Bedroom Relative Humidity	Wireless
RH 8	Garage Relative Humidity	Wireless
RH 11	Kitchen Relative Humidity	Wireless
RH 12	Living Room Relative Humidity 1	Wireless
RH 13	Living Room Relative Humidity 2	Wireless
ISR 1	Incident Solar Radiation	Wireless

Figure 39. Test House 2, first floor

Sensor #	Description	Sensor Type
EE 1	Electric Energy Outdoor Condensing Unit	Watt Node & CT
EE 2	Electric Energy Air Handler	Watt Node & CT
L 1	Data Logger	

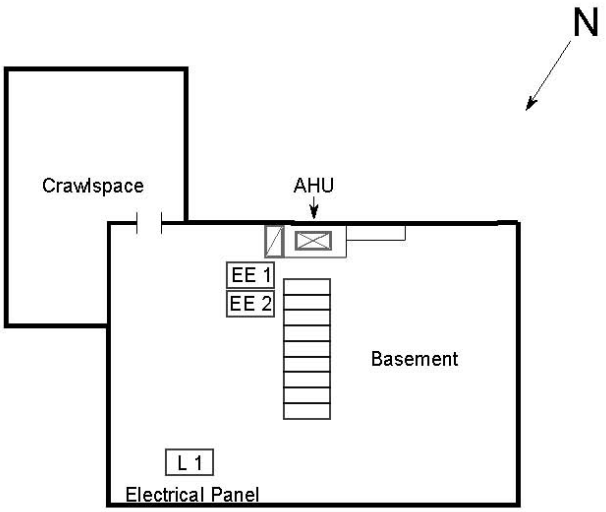


Figure 40. Test House 3, basement

Sensor #	Description	Sensor Type
T 1	Office Temperature	Wireless
T 2	Living Room Temperature	Wireless
T 3	Kitchen Temperature	Wireless
T 4	Dining Room Temperature	Wireless
RH 1	Office Relative Humidity	Wireless
RH 2	Living Room Relative Humidity	Wireless
RH 3	Kitchen Relative Humidity	Wireless
RH 4	Dining Room Relative Humidity	Wireless

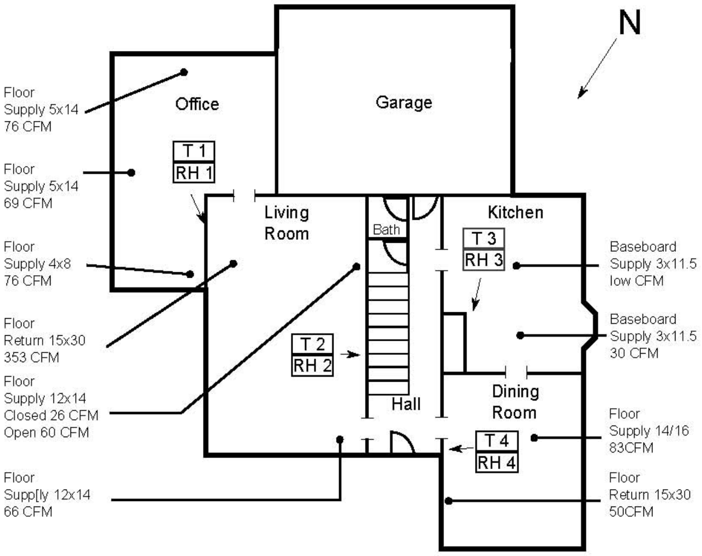


Figure 41. Test House 3, first floor

Sensor #	Description	Sensor Type
T 5	Bedroom 1 Temperature	Wireless
T 6	Bedroom 2 Temperature	Wireless
T 7	Master Bedroom Temperature	Wireless
T 8	Bathroom Temperature	Wireless
T 9	Longest Duct Run 1	Wireless
T 10	Longest Duct Run 2	Wireless
RH 5	Bedroom 1 Relative Humidity	Wireless
RH 6	Bedroom 2 Relative Humidity	Wireless
RH 7	Master Bedroom Relative Humidity	Wireless
RH 8	Bathroom Relative Humidity	Wireless

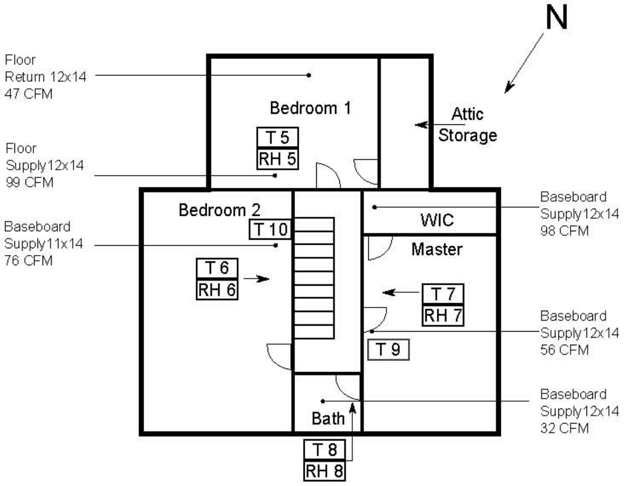


Figure 42. Test House 3, second floor

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