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Comfort and HVAC Performance for a New Construction Occupied Test House in Roseville, California

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IBACOS, Inc.

October 2013

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Office of Energy Efficiency and Renewable Energy

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Definitions

ACCA	Air Conditioning Contractors of America
ACH	Air changes per hour
ACH50	Air Changes per Hour at 50 Pascals
AFUE	Annual fuel utilization efficiency
AHU	Air handler unit
BEopt	Building Energy Optimization (software)
EF	Energy factor
HVAC	Heating, ventilation, and air conditioning
PV	Photovoltaic
RESNET	Residential Energy Services Network
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient

Executive Summary

K. Hovnanian Homes constructed a 2,253-ft^2 single-story slab-on-grade ranch house for an occupied test house (new construction) in Roseville, California. IBACOS conducted one year of monitoring and analysis that focused on the effectiveness of the space conditioning system at maintaining acceptable temperature and relative humidity levels in several rooms of this home, as well as room-to-room differences and the actual measured energy consumption by the space conditioning system. More specifically, the purpose of the monitoring was to evaluate and demonstrate the energy and indoor environmental quality benefits for a centrally located heating, ventilation, and air conditioning system integrated with the bulkhead attic configuration. The IBACOS research team began the long-term monitoring and analysis after the home was occupied in February 2012 and continued through January 2013.

This home is representative of most of the housing types this builder constructs in its Northern California division and has the air handler unit and ducts relocated to inside the thermal boundary. The unit was relocated from the attic to a mechanical closet, and the ductwork was located inside an insulated and air-sealed bulkhead in the attic.

To describe the performance and comfort in the home, the research team selected representative design days and extreme days from the annual data for analysis. To ensure that temperature differences were within reasonable occupant expectations, the team followed guidance from Air Conditioning Contractors of America Manual RS by Rutkowski (1997).

At the end of the monitoring period, the occupant of the home reported there were no comfort complaints in the home. The variance between the modeled heating and cooling energy and the actual amounts used can be attributed to the variance in temperatures at the thermostat from the modeled inputs.

1 Introduction and Background

Results discussed in this report follow the performance of the short-term monitoring results for an occupied test house (new construction) in Roseville, California, as described by Stecher et al. (2013). Monitoring and analysis described in this long-term monitoring report focused on the effectiveness of the space conditioning system at maintaining acceptable temperature and relative humidity levels in several rooms of the home, as well as room-to-room differences and the actual measured energy consumption by the space conditioning system. The IBACOS research team began the long-term monitoring and analysis after the home was occupied in February 2012 and continued monitoring through January 2013. The home was occupied by one or two individuals at different times during the long-term monitoring period.

The builder, K. Hovnanian Homes, constructed a ranch-style house in Roseville, California (Figure 1). This 2,253-ft^2 single-story slab-on-grade ranch house has three bedrooms and two bathrooms and is representative of most of the housing types this builder constructs in its Northern California division. Table 1 lists the house specifications.

Figure 1. Front view of the test house

Table 1. Test House Specifications

Concrete Slab	R-7.5 Vertical Slab Edge Insulation
Exterior Walls	2 × 4 16-in. on center R-15 with R-3 sheathing
Roof	Attic floor R-49 with radiant barrier, with built-in bulkhead to accommodate ductwork below insulation and raised heel trusses
Exterior Doors	R-4
Windows	U = 0.28; SHGC = 0.26
Building Airtightness	2.45 ACH50 tested; 1.7 ACH50 target
Mechanical Ventilation	Air Cycler VS into return duct with Air Cycler Smart Exhaust switch in bathrooms
Heating	95% AFUE natural gas furnace located in the mechanical closet in the master bedroom closet
Cooling	16 SEER
Ductwork	R-6 in conditioned bulkhead, R-8 in unconditioned space buried under R-49 insulation; 2.4% total leakage compared to fan flow as measured by RESNET duct tightness procedure
Water Heater	Tankless, gas, 0.94 EF
Appliances	ENERGY STAR® refrigerator and dishwasher
Lighting	80% fluorescent
PV System	2.4 kW
% Better Than Building America House Simulation Protocols (Hendron and Engebrecht 2010)	31.9% without PV system; 57.5% with PV system

ACH50 is air changes per hour at 50 Pascals. AFUE is annual fuel utilization efficiency. EF is energy factor. PV is photovoltaic. RESNET is Residential Energy Service Network (www.resnet.us). SEER is seasonal energy efficiency ratio. SHGC is solar heat gain coefficient.

The heating, ventilation, and air conditioning (HVAC) space conditioning system efficiency ratings for the furnace and cooling equipment are 95% AFUE and 16 SEER, respectively. A high percentage of AFUE and a high SEER rating value indicate greater efficiency of the equipment. In this case, the specified 95% AFUE and 16 SEER are near the upper end of efficiency for a natural gas furnace and electric air-conditioning equipment.

The air handling unit (AHU) typically is located in the unconditioned area of the attic, where it is exposed to extreme temperatures throughout the year. In this home, the AHU was relocated from the unconditioned attic to a central location inside the conditioned space of the home, with ductwork located mostly within the thermal barrier through the construction of an insulated bulkhead inside the attic. The bulkhead and any ducts penetrating outside the bulkhead are covered with R-49 loose-fill insulation. Locating the AHU centrally within the home and the ductwork inside conditioned space will mitigate the impact of the attic temperature extremes and will allow the system to operate more efficiently.

IBACOS selected all registers for the design airflows and room sizes with face velocities in the range of 400 ft per minute and noise criteria at NC20. Registers are located in the ceiling, toward the interior of rooms, allowing for a central compact duct system.

To gather data for the study of the effectiveness of the space conditioning system at maintaining acceptable temperature and relative humidity levels, as well as room-to-room differences and the temperature distribution within a given room, the research team placed sensors throughout the home. Figure 2 shows the sensor locations, as well as the duct layout and supply register locations.

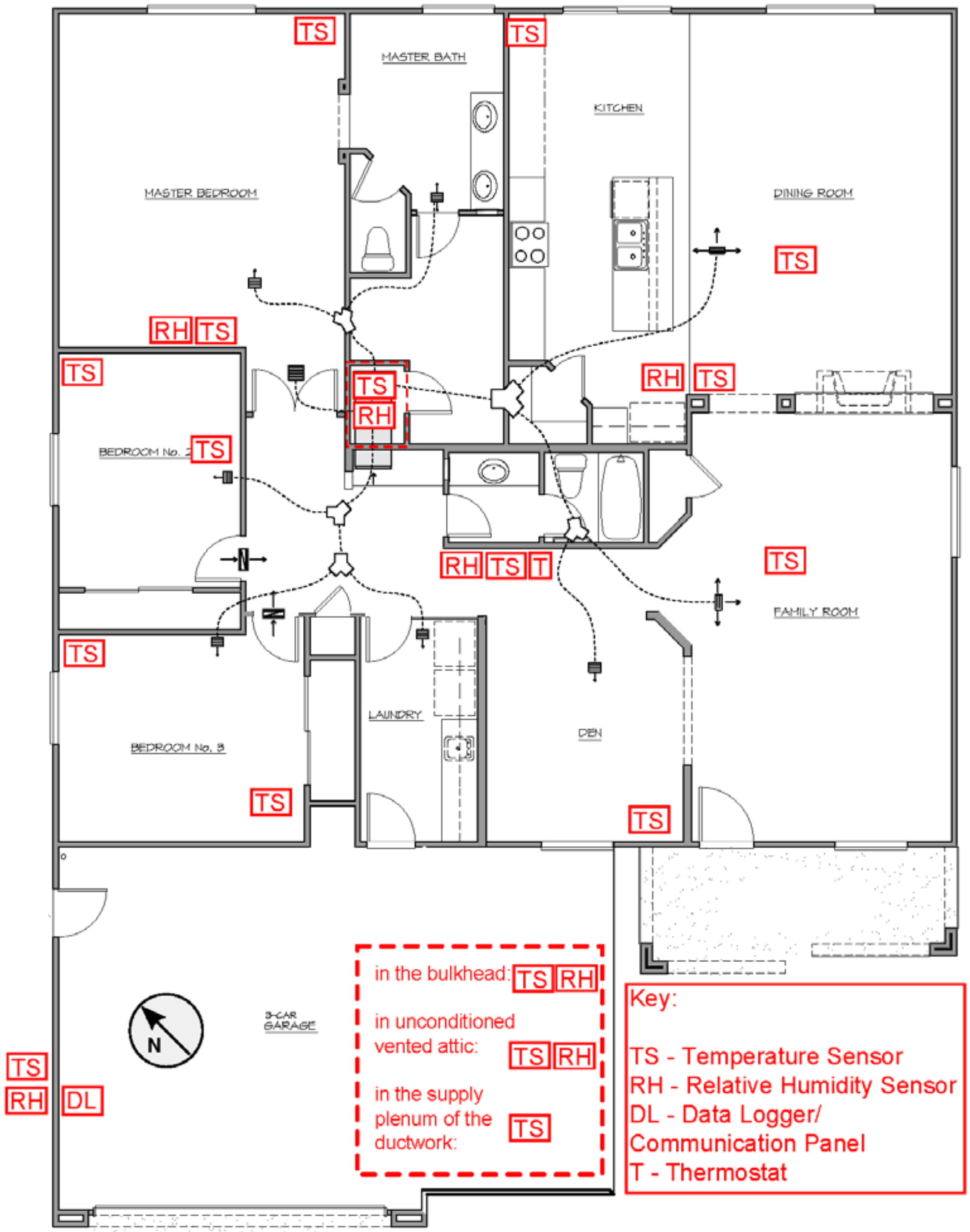

Figure 2. Floor plan showing sensor locations, duct layout, and supply register locations

To ensure that temperature differences would be within reasonable occupant expectations, the research team followed guidance from ACCA Manual RS by Rutkowski (1997). Although air temperature is only one factor in measuring overall thermal comfort (ASHRAE 2010), Rittelmann (2008) found that, in well-insulated homes with low-e windows, air temperature and mean radiant temperature track fairly closely, except when the windows are experiencing direct solar gain. Therefore, the team did not measure mean radiant temperature in this study.

2 Research Questions

Improvements to the building enclosure (e.g., increased levels of insulation, efficient windows, and air sealing) can help reduce the heating and cooling demands in a home and therefore potentially reduce the size of the HVAC equipment and the number of zones needed to condition the home. Appropriately sizing the HVAC equipment based on the reduced loads will help the system run more efficiently and will provide a more comfortable indoor environment. Locating the furnace centrally within the home will eliminate the impact of the temperature extremes and will allow the system to operate more efficiently. The use of a compact duct system—a compact air distribution system that locates the HVAC equipment centrally within the home and uses similar-length, shorter duct runs to the interior of the rooms—can maximize performance and comfort in an energy-efficient home.

This report addresses the following research questions:

1. How effective is the HVAC system at maintaining acceptable temperature and relative humidity levels in several rooms of the house?

2. How do temperature and relative humidity vary in each measured room from the temperature at the thermostat?

3. What is the temperature distribution in each measured room, using ceiling supply registers located closer to the center of the house?

4. What is the difference in temperature in the insulated bulkhead cavity compared to the uninsulated attic and living space of the house?

5. What are the delivered supply temperatures at each register? Are the ducts in the insulated bulkhead cavity performing as if they are in conditioned space?

6. What is the homeowner’s perception of the temperatures and relative humidity levels in the house?

7. How does the actual measured energy consumption for heating and cooling compare to the projected energy consumption using Building Energy Optimization (BEopt) modeling when actual weather and operating conditions are normalized? Is there any clear evidence that these differences are caused by weather, occupant behavior, modeling errors, or system performance issues?

3 Experimental Methods

The IBACOS research team conducted long-term monitoring of this occupied test house from February 2012 through January 2013, providing data during the summer cooling and winter heating seasons as well as the spring and fall shoulder seasons. For performance analysis, the research team chose specific extreme day conditions and design day conditions along with annual performance. Table 2 shows the design temperatures, and Table 3 shows the conditions for the days of extreme cold, days of extreme hot, design temperature during the heating season, and design temperature during the cooling season.

Table 2. Design Condition Temperatures

Design Condition	Temperature (°F)
Heating Design Temperatures	32
Cooling Design Temperatures	97

Table 3. Temperatures for Extreme Days and Design Days During Long-Term Monitoring

	Date	Temperature (°F)
Cold Extreme Day	January 13, 2013	22.5
Hot Extreme Day	August 13, 2012	109.3
10-Day Span Design Heating	December 30, 2012	33.4
10-Day Span Design Cooling	August 21, 2012	96.9

As Table 3 shows, January 13, 2013 was the coldest measured day (while the home was occupied), with an outdoor temperature of 22.5°F. August 13, 2012 was the hottest measured day, with an outside temperature of 109.3°F. December 30, 2012 was within design conditions during the heating season; the outside low temperature was 33.4°F. August 21, 2012 was within design conditions during the cooling season; the outside high temperature was 96.9°F.

Rutkowski (1997) indicates dry-bulb temperature variances from the thermostat setting during the cooling season as measured at the thermostat to be ± 3°F. Similarly, the temperature during the heating season in any room should be ± 2°F of the thermostat set temperature. Room-to-room temperature differences or floor-to-floor temperature differences should be no greater than 4°F in the heating season and no greater than 6°F in the cooling season. Although air temperature is only one factor in measuring overall thermal comfort (ASHRAE 2010), Rittelmann (2008) found that, in well-insulated houses with low-e windows, air temperature and mean radiant temperature track fairly closely, except when the windows are experiencing direct solar gain. Therefore, the research team did not measure mean radiant temperature in this study.

Referencing Figure 2, the temperature distribution using ceiling supply registers located closer to the center of the home was measured by placing sensors 52 in. above the finished floor on an interior wall and an exterior wall to track the uniformity across the space. The thermostat set point is correlated by the temperature sensor placed next to the thermostat.

To study the similarity of conditions in the bulkhead to the conditioned space and ventilated attic space, the research team placed temperature and relative humidity sensors in the unconditioned attic space and at the floor of the bulkhead. They also located temperature sensors within the supply plenum and at both a register in the family room and a register in the dining room to determine the magnitude of loss or gain in the ducts located inside the insulated bulkhead.

The team monitored electricity consumption by the AHU and outdoor unit, along with the generated electricity from the PV system, the amount of electricity fed into the grid, and the amount of electricity drawn from the grid. The team also monitored natural gas consumption from the furnace and hot water usage.

4 Results and Discussion

The IBACOS research team evaluated data from design condition days and extreme condition days to determine the effectiveness of the HVAC system at maintaining acceptable temperature and relative humidity levels during both the heating and cooling seasons. In this section, temperature distributions within rooms using ceiling supply registers located closer to the center of the home are plotted on an annual basis. The occupants' perceptions of the comfort conditions in the home are described, and the actual measured energy consumption for heating and cooling is compared to the projected energy consumption using BEopt when actual weather and operating conditions are normalized.

4.1 Thermostat Set Points

The research team based the BEopt modeling and the HVAC design on the interior temperatures of 70°F for the heating season and 75°F for the cooling season. By examining the data from the sensor located next to the thermostat, the research team drew some conclusions about how the HVAC system was being controlled. The histograms in Figure 3 show that, during the winter heating season, the temperatures were mostly at or lower than the design temperature, reducing the impact on the HVAC system energy use; for the summer cooling season, the lower set points increased the impact on the system.

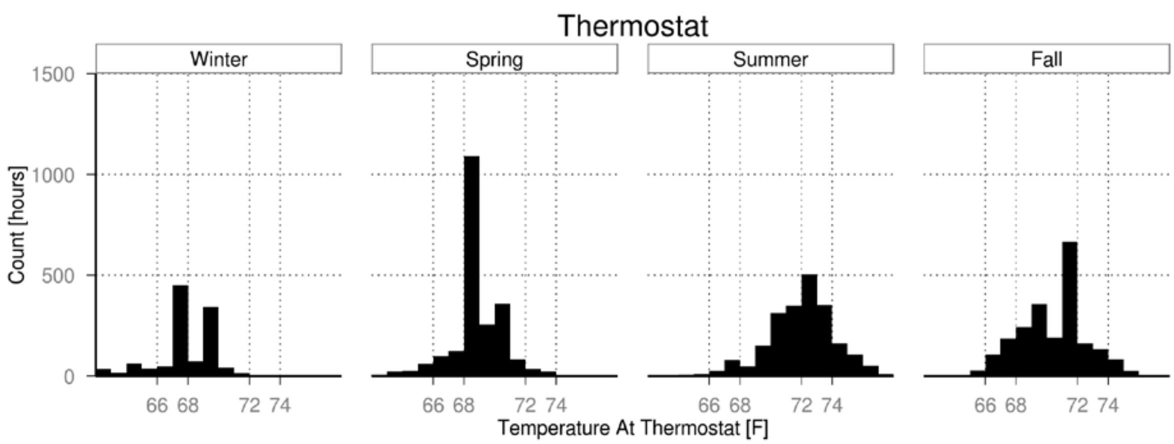

Figure 3. Histograms of temperatures at the thermostat

4.2 Heating Season Design Day System Effectiveness

Figure 4 shows the outdoor and room temperatures for a 10-day span around the day chosen by the research team as a representative heating design temperature day—December 30, 2012. On that day, the outdoor low temperature reached 33.4°F. The thermostat was steady, with a daily average of 67.5°F.

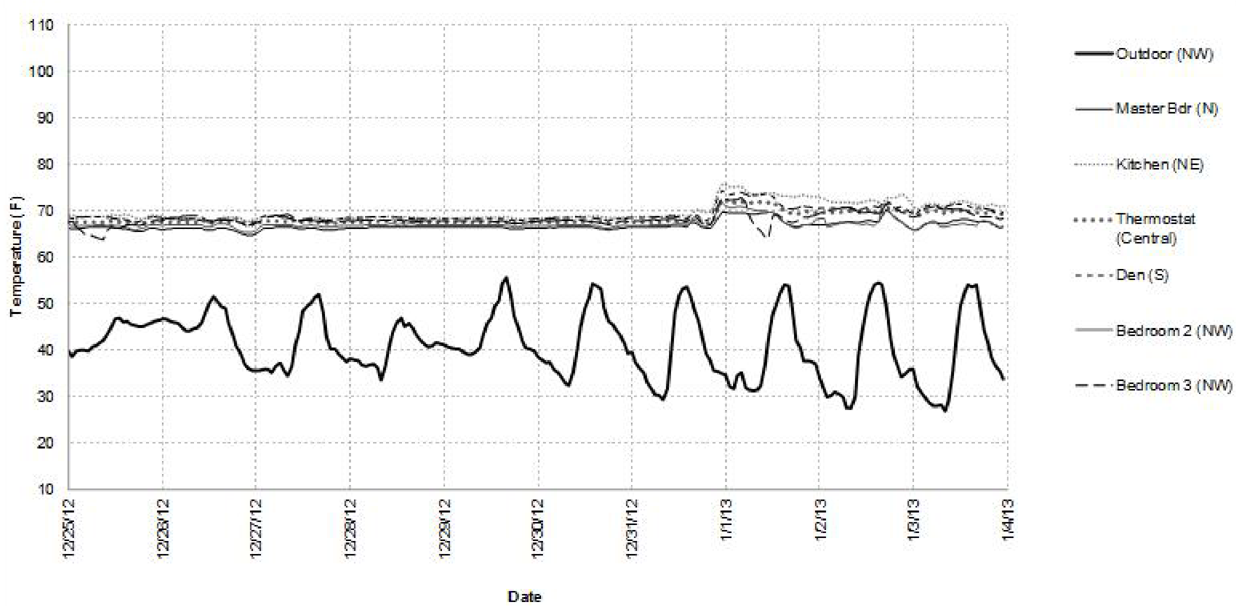

Figure 4. Room-to-room and outdoor temperatures for a 10-day span around the heating design temperature day of December 30, 2012

Room-to-room relative humidity values for the 10-day span around the heating design day conditions on December 30, 2012 (Figure 5) are closely aligned and well within the comfort criteria, even when the outdoor conditions are high humidity.

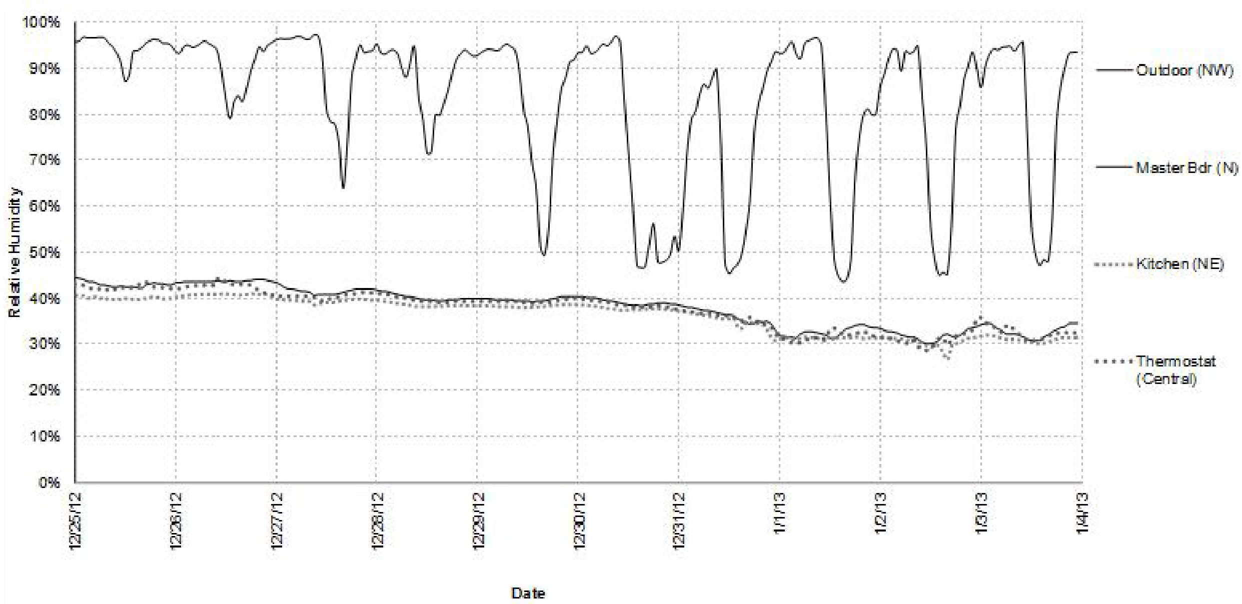

Figure 5. Room-to-room and outdoor relative humidity for a 10-day span around the heating design day of December 30, 2012

On the day the research team identified as an extreme cold day—January 13, 2013 (Figure 6)—the outdoor low temperature dropped to 22.5°F. The thermostat was steady, with a daily average of 70.2°F and a system runtime of 60%. When the research team examined room-to-room variation for the extreme cold day, January 13, 2013, two rooms fell outside the ± 2°F criteria set recommended by Rutkowski (1997), being on the warm side. The kitchen ran above the comfort criteria band most of the daytime hours, with the greatest spread of 2.7°F occurring at 5:00 p.m.

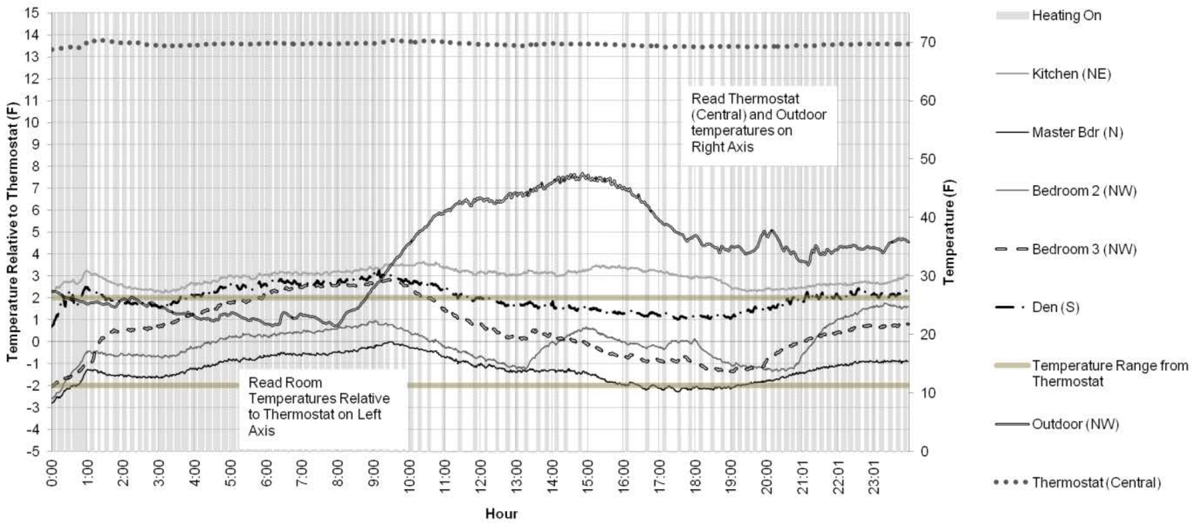

Figure 6. January 13, 2013 extreme cold day temperature variation from the thermostat

4.3 Cooling Season Distribution Effectiveness

Figure 7 shows the outdoor and room temperatures for a 10-day span around the day chosen by the research team as a representative cooling design temperature day—August 21, 2012. On that day, the outdoor high temperature reached 96.9°F. The thermostat was steady, with a daily average of 74.8°F and a system runtime of 35%. When the team examined the room-to-room temperature variation for the cooling design day conditions, the temperatures of all rooms fell within the ± 3°F criteria set by Rutkowski (1997), with the exception of the master bedroom for a brief time during the morning setback time.

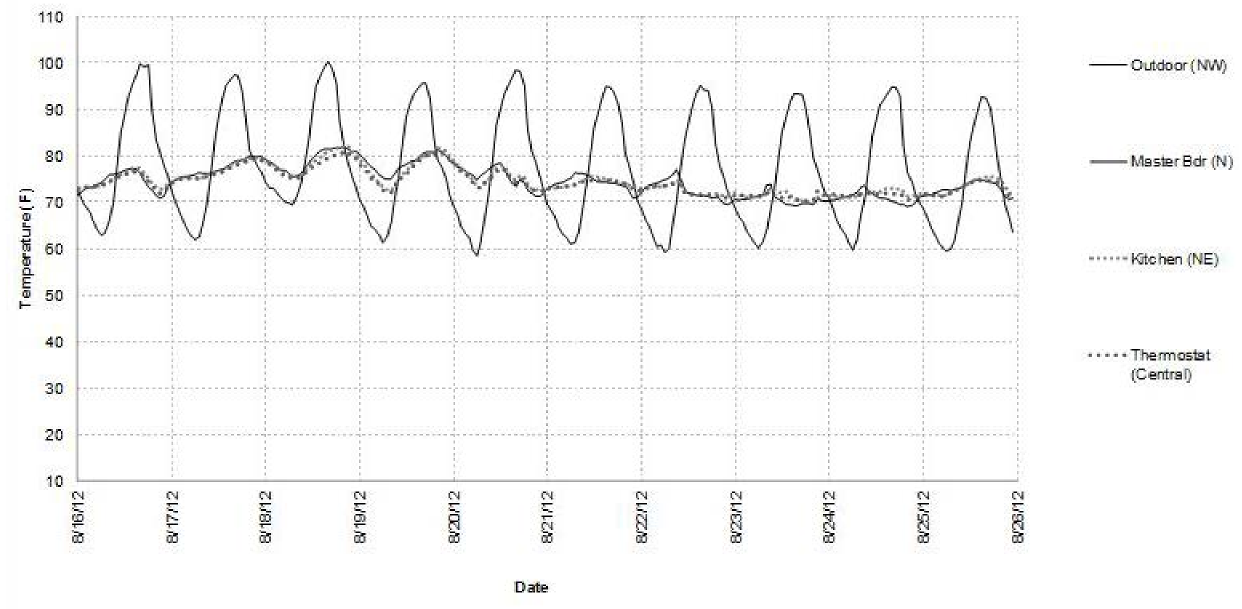

Figure 7. Room-to-room and outdoor temperatures for a 10-day span around the cooling design temperature day of August 21, 2012

Room-to-room relative humidity values for the cooling design day conditions on August 21, 2012 (Figure 8) are closely aligned, below the outdoor relative humidity and well within the 50% comfort criteria.

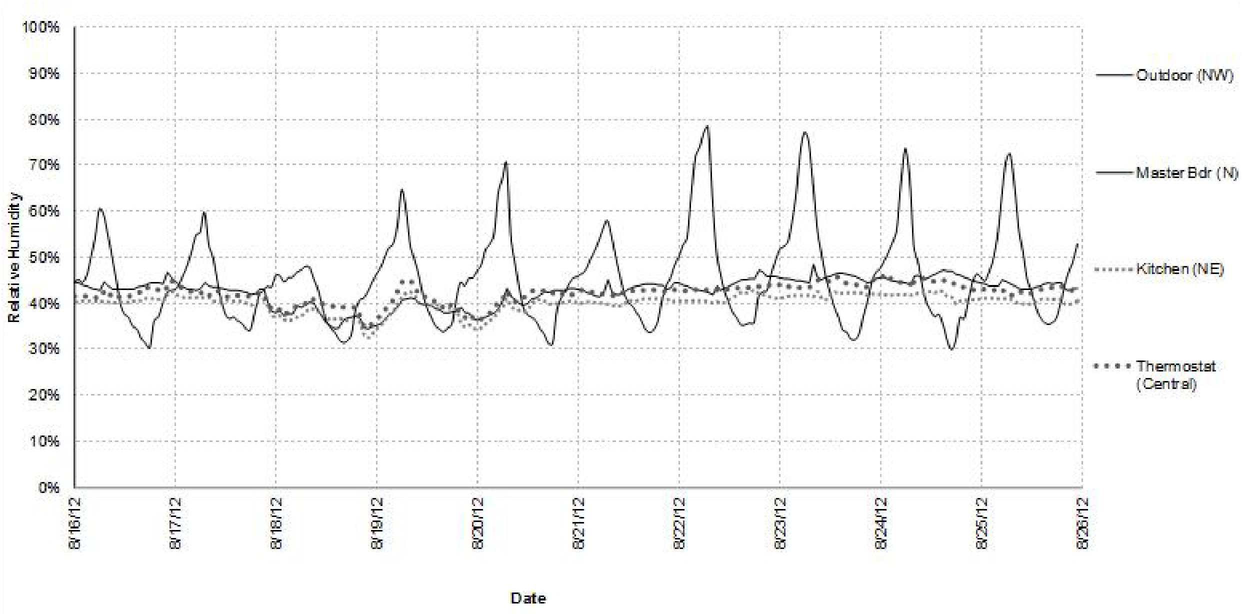

Figure 8. Room-to-room and outdoor relative humidity for a 10-day span around the cooling design day of August 21, 2012

On the day identified by the research team as an extreme hot day, August 13, 2012 (Figure 9), the outdoor high temperature reached 109.3°F, with the thermostat steady at a daily average of

72.1°F and a system runtime of 37%. Even with a long setback time of 4:00 a.m. to 4:00 p.m., the temperature at the thermostat rose by only 6°F. When the research team examined the room-to-room temperature variation for the extreme hot day conditions, the temperatures of all rooms fell within the ± 3°F criteria set by Rutkowski (1997), after the equipment caught up from the long setback time of 4:00 a.m. to 4:00 p.m.

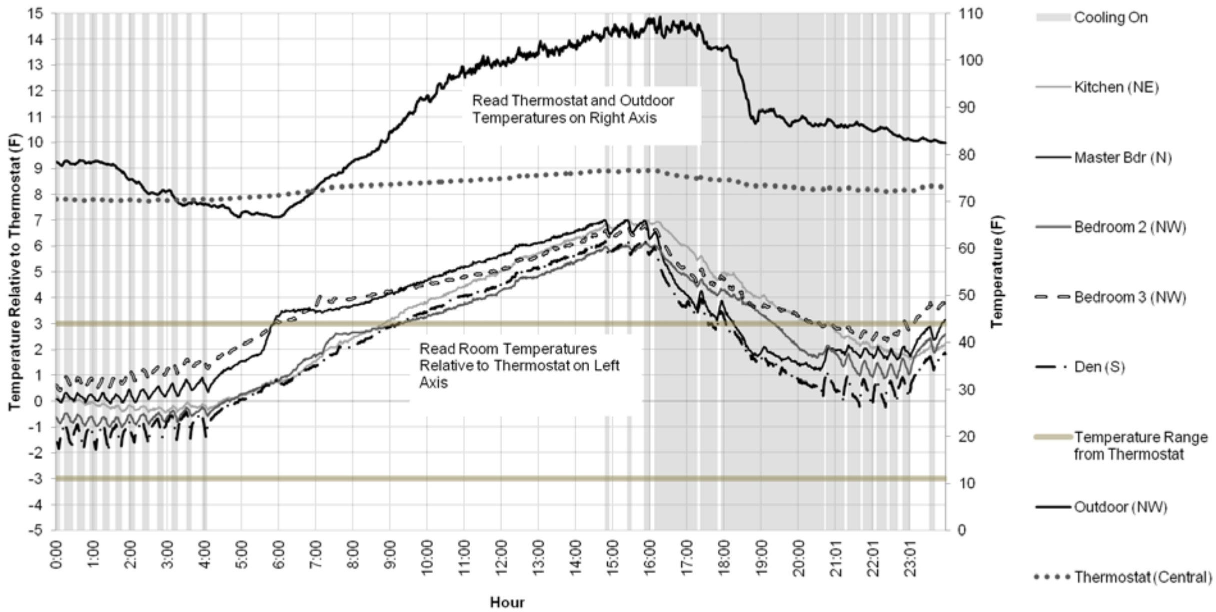

Figure 9. August 13, 2012 extreme hot day temperature variation from the thermostat

4.4 Register Location Effectiveness

The temperature distributions within the four rooms with dual sensors (one interior and one exterior) are plotted in Figure 10 through Figure 13, showing that ceiling supply registers located closer to the center of the room are properly supplying and mixing the conditioned air. Stecher et al. (2013) reported the short-term monitoring results for this home and discussed how stratification is avoided by the mixing properties of the registers.

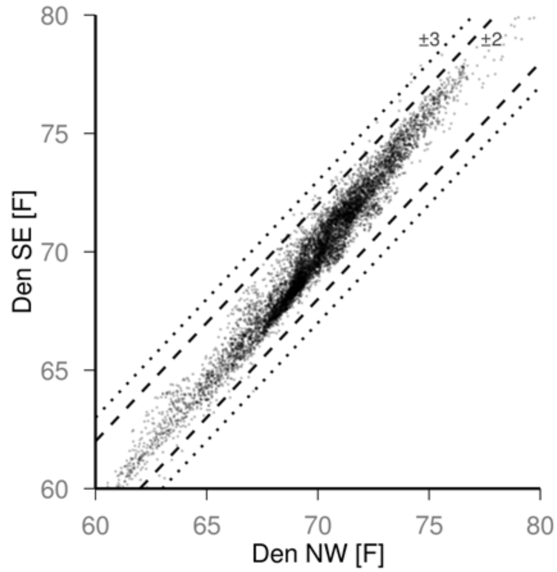

Figure 10. Temperature distribution from the den southeast wall to the northwest wall

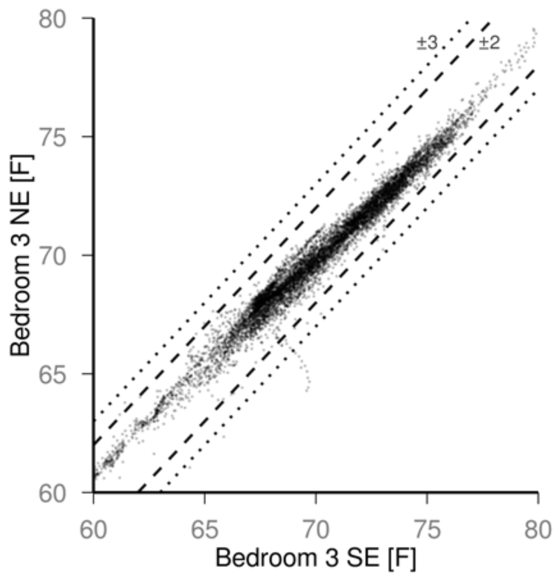

Figure 11. Temperature distribution from the Bedroom 3 northeast wall to the southeast wall

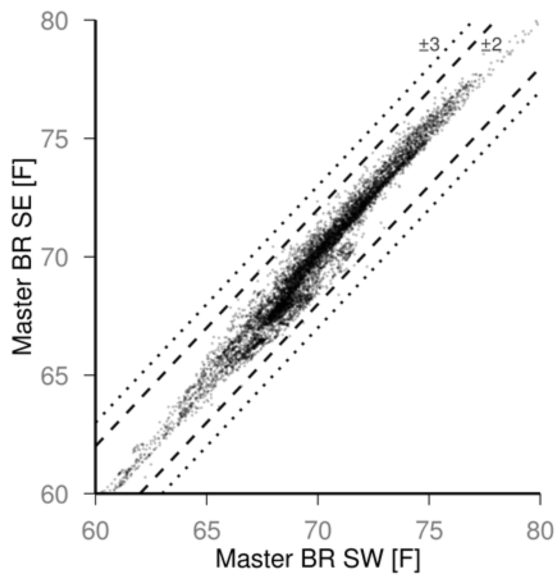

Figure 12. Temperature distribution from the master bedroom southeast wall to the southwest wall

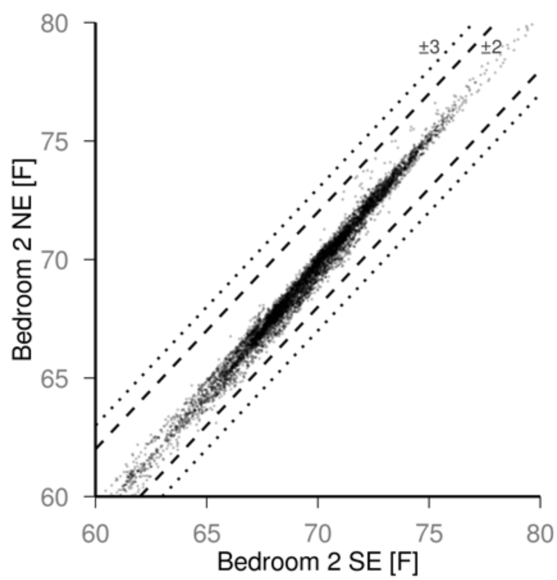

Figure 13. Temperature distribution from the Bedroom 2 northeast wall to the southeast wall

4.5 Inverted Insulated Bulkhead Performance

The research team measured the performance of the insulated inverted attic bulkhead by the temperature differences between the bulkhead, the attic, and the living space of the home, along with the temperature difference of the air being delivered through the ducts in the bulkhead. Figure 14 shows the variation between the temperatures in the bulkhead, in the attic, and at the thermostat for the extreme cold day of January 13, 2013. The bulkhead temperatures were running much closer to the living space temperatures, showing the ductwork was being isolated from the attic temperature extremes.

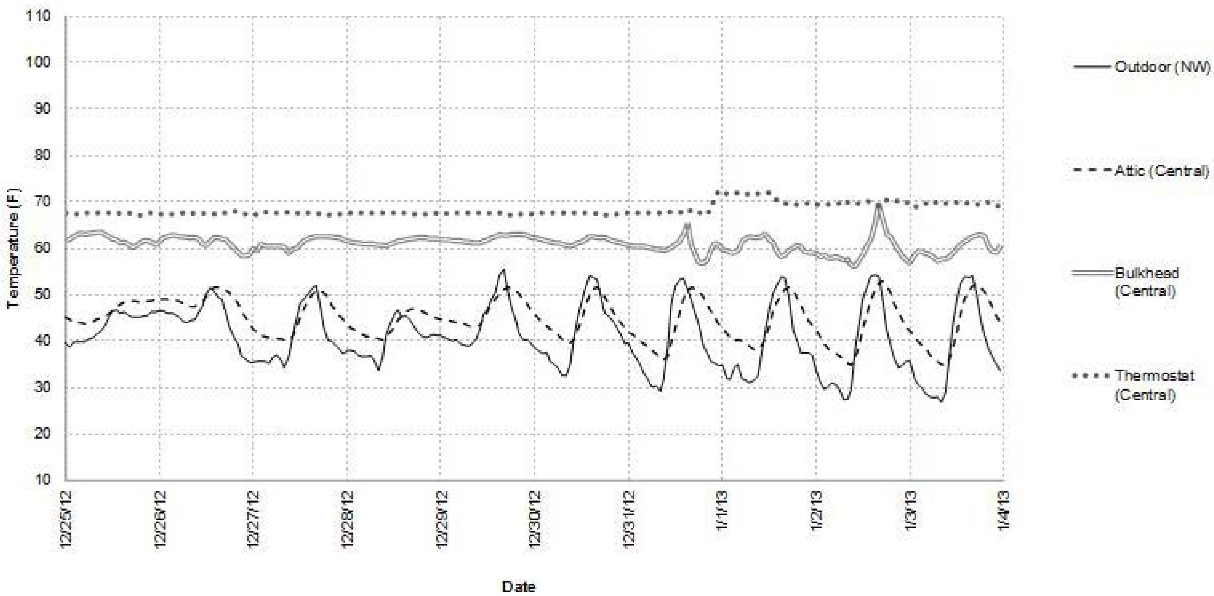

Figure 14. Attic bulkhead and thermostat temperature variation around the January 13, 2013 extreme cold day

Figure 15 shows the temperature difference of the heated supply air being delivered through the ducts from the supply plenum to the family room and dining room registers in the bulkhead. The largest difference between the plenum and register is 1.5°F in the family room register, with more of the duct outside the bulkhead and exposed to the attic extremes.

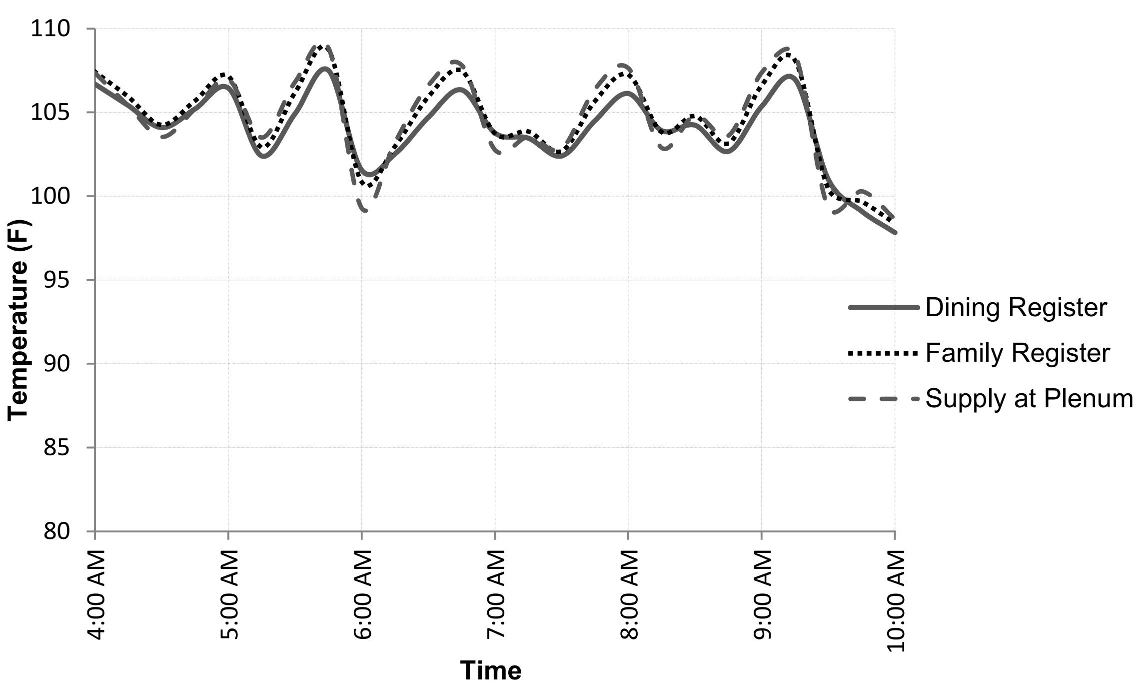

Figure 15. Supply air temperature during the morning hours of the extreme cold day of January 13, 2013

Figure 16 shows the variations between the temperatures in the bulkhead, in the attic, and at the thermostat for the extreme hot day of August 13, 2012. The bulkhead temperatures were running much closer to the living space temperatures, showing the ductwork was being isolated from the attic temperature extremes.

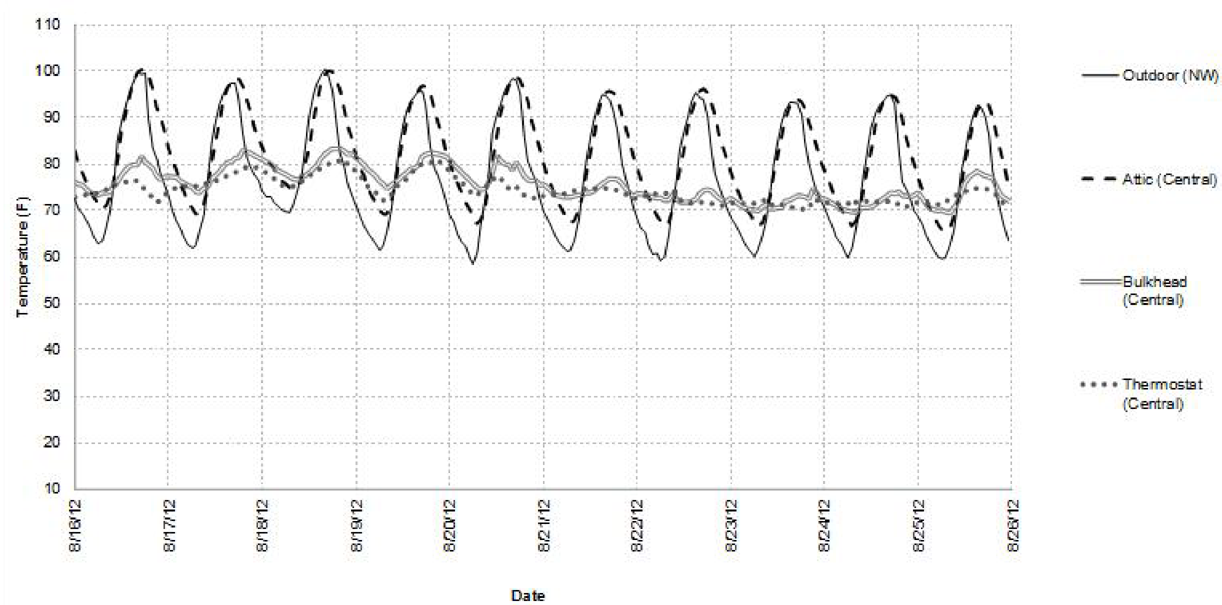

Figure 16. Attic bulkhead and thermostat temperature variation around the August 13, 2012 extreme hot day

Figure 17 shows the temperature difference of the cooled supply air being delivered through the ducts from the supply plenum to the family room and dining room registers in the bulkhead. The largest difference between the plenum and register is 1.5°F in both registers.

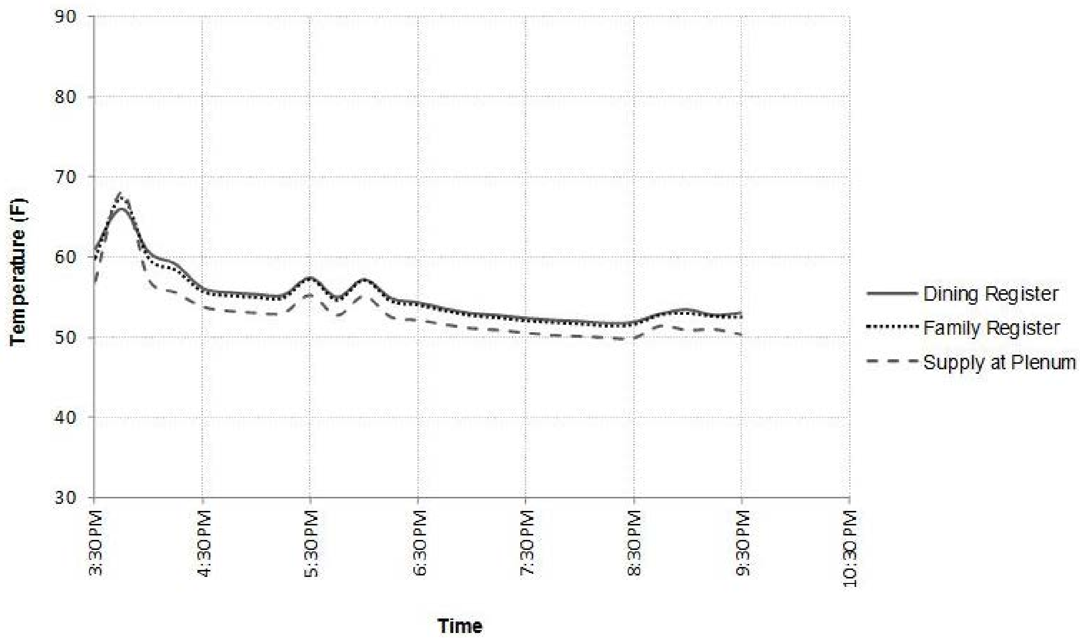

Figure 17. Supply air temperature during the morning hours of the extreme hot day of August 13, 2012

4.6 Occupant Feedback

At the end of the monitoring period, the occupant reported there were no comfort complaints in the home. The programmable thermostat was used with weekend days set cooler than weekdays. Early design concerns regarding any noise associated with the AHU being relocated from the attic to a closet in the conditioned space were not an issue; the occupant reported hearing only the outside equipment running. The occupant also reported that the utility bills during the cooling season were slightly higher than anticipated but not to the level to raise a complaint.

4.7 Energy Use

The research team used BEopt Version 1.3 to model the yearly source energy usage for the home, using the characteristics of the home and the Building America House Simulation Protocols (Hendron and Engebrecht 2010). The model assumed one occupant in the bedroom and one occupant in the living area. The team converted the measured energy of four major subcategories—heating; cooling; hot water; and lighting, appliances, and miscellaneous electrical loads—to source energy and compared that to the model output, as shown in Figure 18. No monitoring was in place to separate the lighting, large appliances, or vent fan from the miscellaneous loads; however, the combined values closely match the model.

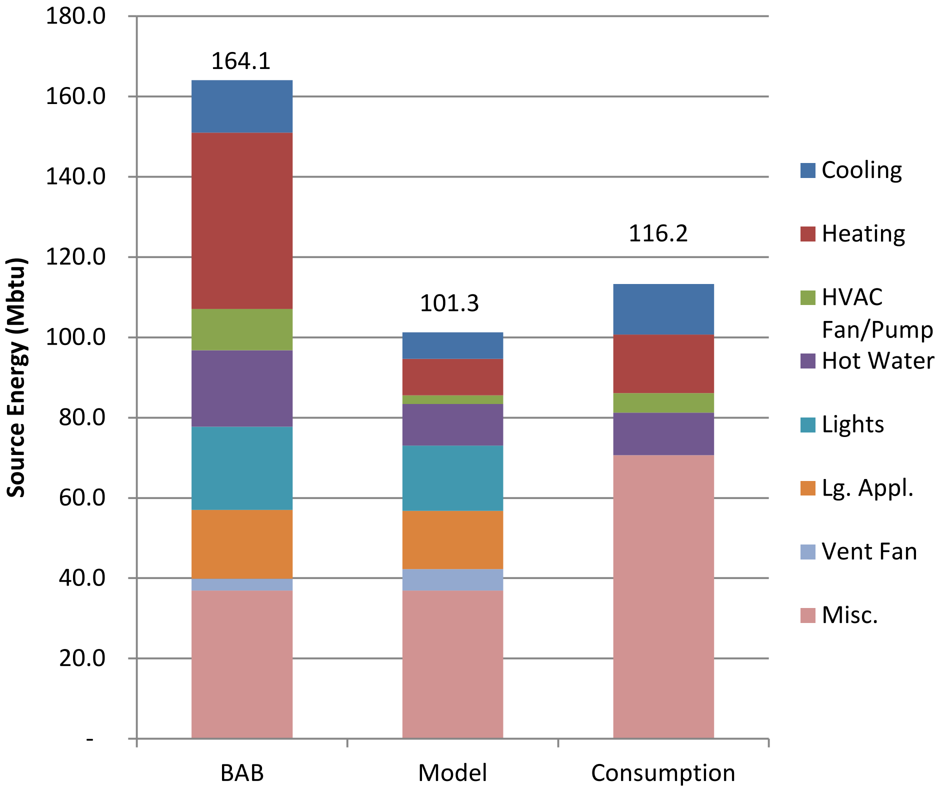

Figure 18. Predicted and actual energy consumption for one year (MBtu)

The differences between the modeled energy use for heating and cooling can largely be attributed to the varying occupant load and the thermostat set points varying from the modeled inputs, as previously shown in Figure 3. The categories of lights, large appliances, and vent fan from the model were not monitored as part of this project and are included in the miscellaneous category.

5 Conclusions

In this study, the room-to-room temperatures of the test house during the design and extreme heating and cooling days were largely within the comfort band set forth in ACCA Manual RS by Rutkowski (1997). The relative humidity conditions were below 50% year round, which is an acceptable level for the climate zone.

The inverted attic bulkhead, air sealed and insulated, isolated the ductwork from the attic extremes. According to the occupants' feedback, relocating the AHU from the attic to a closet in conditioned space had no adverse noise effects. The occupants reported being generally comfortable and pleased with the performance of the home.

The actual energy use for heating and cooling was higher than the results modeled by BEopt and can be attributed to the variance in the measured temperatures shown in Figure 3 from the 75°F heating and 70°F cooling values used in modeling. The combined water heating, lighting, vent fan, and miscellaneous electric loads closely matched the model.

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