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Long-Term Results from Evaluation of Advanced New Construction Packages in Test Homes: Lake Elsinore, California

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Contents

List of Figures

Unless otherwise noted, all figures and photos were created by IBACOS.

List of Tables

Unless otherwise noted, all tables were created by IBACOS.

Definitions

ACCA	Air Conditioning Contractors of America
BA	Building America program of the U.S. Department of Energy
CDD	Cooling degree day
cfm	Cubic feet per minute
DHW	Domestic hot water
HDD	Heating degree day
LAMEL	Lighting, appliances, and miscellaneous electric loads
RH	Relative humidity
TMY3	Typical Meteorological Year 3

Executive Summary

This report presents the long-term evaluation results from a hot-dry climate project that examines the room-to-room temperature conditions that exist in a high performance envelope, the performance of a simplified air distribution system, and a comparison of modeled energy performance with measured energy use. The project, a prototype house built by K. Hovnanian Homes' Ontario Group, is located in Lake Elsinore, Riverside County, California, and achieves a 50% level of whole-house source energy savings with respect to the Building America (BA) Benchmark Definition 2009 (Hendron and Engebrecht 2010).

One purpose of the long-term monitoring of this project was to show to heating, ventilation, and air-conditioning contractors and mechanical system designers the performance benefits of this type of system, with the hope that they will incorporate these practices into their system designs moving forward. One year of temperature measurements in three rooms indicates that the temperature difference between the measured locations and the thermostat were within the Air Conditioning Contractors of America (ACCA) Manual RS (Rutkowski 1997) recommendations 90.3% of the time in heating mode and 100% of the time in cooling mode. The air distribution system is operating efficiently with average delivered temperatures adequate to facilitate proper heating and cooling and only minor average temperature differences observed between the system's plenum and farthest register. The results show that the compact spider branch design provided adequate heating and cooling in addition to lower installation costs. Despite initial contractor resistance, this is a recommended design, and future research should investigate methods of outreach to mechanical installers and designers to encourage them to incorporate this design in their homes.

Monitored energy use results for the house indicate that it is using less energy than predicted by modeling. A comparison of modeled to measured energy consumption by end use determined little agreement between modeled and measured values.

1 Introduction and Background

Since 2009, IBACOS has been working with K. Hovnanian Homes' Ontario Group on constructing a BA prototype house that not only achieves the 50% level of energy savings when compared to the BA Benchmark Definition 2009 (Hendron and Engebrecht 2010) but also surpasses the California Title 24 (California Building Standards Commission 2008) level of performance by 30% and complies with southern California's ENERGY STAR® program. The builder is interested in understanding the barriers associated with building a higher performing house and whether this package of measures is something that they could incorporate fully or in part in the future. The Cambria Hills, Plan 2-A, model was chosen for the project. It is a one-story, detached, single-family, slab-on-grade house with three bedrooms and approximately 2,032 ft^2 of finished floor area. The house faces predominantly south and has a three-car attached garage on the front, as shown in Figure 1.

Figure 1. Front elevation of the prototype house

The house achieved a 52.4% level of source energy savings with respect to the BA Benchmark Definition 2009 (Hendron and Engebrecht 2010). The builder achieved this performance level by making some significant changes from their typical construction practices for the building envelope, as well as the space conditioning and domestic hot water (DHW) systems. For the exterior walls, the builder used several advanced framing techniques, such as ladder blocking where interior partition walls intersected with the exterior wall, two- and three-stud corners, and reduced framing around window and door openings. A one-coat stucco system with 1-in. expanded polystyrene insulation board was substituted in place of the traditional three-coat stucco finish. The exterior wall cavity was insulated with netted and blown fiberglass insulation that achieves R-15 for a 2 × 4 stud depth. The resulting envelope exceeded the airtightness target of 3.0 ACH @ 50 Pa with a value of 2.8 ACH @ 50 Pa. The space conditioning system was redesigned to include more efficient equipment and an air distribution system that is more centrally located in the attic (spider branch design) and is airtight. Typically, K. Hovnanian Homes installs a tank-type water heater in the garage; however, the builder modified an exterior common wall between the garage and the laundry room of this house to make space for a tankless condensing water heater that has an energy factor of 0.94 and is mounted within the conditioned space. General specifications for the prototype house are included in Table 1.

Table 1. Technical Specifications for the Lake Elsinore, California, Prototype House

Component	Specification
Concrete Slab	Slab on grade, uninsulated
Exterior Walls	R-15 netted and blown fiberglass in 2 x 4, 16 in. on center wall cavity, R-4 expanded polystyrene exterior sheathing beneath the one-coat stucco system
Roof	R-38 insulation on the attic floor with a radiant barrier on the underside of the roof deck sheathing
Exterior Doors	R-4
Windows	U-value = 0.35, solar heat gain coefficient = 0.30; vinyl framed
Building Airtightness	2.8 ACH @ 50 Pa tested (3.0 ACH @ 50 Pa target)
Mechanical Ventilation	ASHRAE Standard 62.2 (ASHRAE 62.2, 2010), exhaust only (using a continuously operating exhaust fan in the laundry room; 50 cfm continuous)
Heating	92% annual fuel utilization efficiency furnace
Cooling	14 seasonal energy efficiency ratio condensing unit
Ductwork	Spider branch design, R-8, in unconditioned vented attic, tested as 2.7 CFM @ 25 Pa duct leakage to outside per 100 ft^2 of conditioned floor area (≤3 cfm target)
Water Heater	Gas tankless, energy factor 0.94, located in conditioned space (laundry room)
DHW Distribution	Cross-linked polyethylene, no pipe insulation
Appliances	All ENERGY STAR
Fluorescent Lighting	90% fluorescent lighting
Photovoltaic System	N/A
% Better than BA Benchmark Definition 2009 (Hendron and Engebrecht 2010)	**52.4%**

2 Evaluation Research Questions

The main research goal for this project was to evaluate the performance of the space conditioning system, including the duct distribution system. Compared to the builder's standard duct layout, which includes long duct runs with diffusers located at the exterior walls, the duct distribution system for this test house was designed to be more compact and to distribute conditioned air to the house from ceiling diffusers located near interior walls in the ceiling. All registers were in the ceiling of the house and were sealed to the drywall. The air handler unit was located in the unconditioned attic space together with the ductwork. This more centralized location of the mechanical equipment and compact distribution of ductwork were expected to provide adequate comfort to homeowners while reducing material costs and installation labor.

The shortened duct runs could be installed using the builder's typical practices. Total duct length was reduced from 207 to 118 ft. This 44% reduction in duct length enabled corresponding savings in materials and labor. A cost analysis for the package of measures was reported previously by IBACOS (2010). However, much resistance was encountered in discussions with the heating, ventilation, and air-conditioning trade contractors and mechanical system designers for this project regarding the load calculation, system sizing, and design strategies proposed for this test house. Contractors are unfamiliar with centrally located systems using compact duct runs that throw air toward exterior walls. Therefore, contractors are reluctant to take on the liability of the performance of these systems because the systems deviate significantly from their standard system design approach. The purpose of the long-term monitoring of this project was to show heating, ventilation, and air-conditioning contractors and mechanical system designers the performance benefits of this type of system, with the hope that they will incorporate these practices into their system designs moving forward.

Research questions for this test house project focused on measuring the ability of the downsized space conditioning system to maintain acceptable levels of indoor temperature and relative humidity (RH) in the hot-dry climate. Data were collected, quantifying the performance of both the equipment and the distribution ductwork. Short-term testing and long-term monitoring were conducted to answer the following research questions:

- How effective is the proposed space conditioning system at maintaining acceptable temperatures in several rooms of the house, including the master bedroom and the family room and kitchen area? How does temperature uniformity vary between the heating and cooling seasons?
- To what extent does the location of the ductwork in the unconditioned attic impact its performance with respect to occupant comfort? What are the delivered supply temperatures at specific registers? How long after system startup does it take for the temperature of the supply air measured at the point of delivery (register) to reach the temperature measured at the main plenum? How does it vary between the heating and cooling seasons?
- How do temperature levels vary with system runtime?
- How does the actual measured energy consumption of four major subcategories (heating; cooling; hot water; and lighting, appliances, and miscellaneous electric loads [LAMELs])

compare to projected energy consumption using EnergyGauge USA (version 2.8.03) when actual weather and operating conditions are normalized? Is there any clear evidence that these differences are due to weather, occupant behavior, modeling errors, or system performance issues?

3 Experimental Methods

To observe the performance of the test house in every season, long-term monitoring was conducted for the one-year period of October 2010 through September 2011. Temperature and RH levels were measured in the master bedroom, in the family room and kitchen area, at the thermostat location, and outdoors. Supply air temperatures at the air handler plenum and supply register for the family room and kitchen area were measured using thermocouples.

Electrical power for the whole house, the outdoor condensing unit, the furnace fan, a group of large electrical appliances (refrigerator, dishwasher, and clothes washer), and the aggregate of LAMELs was measured using pulse output Watt-hour meters (4-Hz full-scale frequency). Natural gas consumption for the furnace and water heater was measured using a gas meter.

All sensors were connected to a central data logger with a 10-s scan rate and data storage every minute and hour. Two adults occupied the house during the monitoring period. Figure 2 through Figure 4 are representative images of the outdoor and indoor sensors installed in the test house. All temperature and RH sensors used to measure indoor, in-room conditions were mounted at 48 in. Sensor locations throughout the house are shown on the floor plan in Figure 5.

Figure 2. Outdoor temperature and RH sensor mounted on a privacy wall in the side yard

Figure 3. Indoor temperature and RH sensor in the kitchen and family room area

Figure 4. Temperature and RH sensor at the thermostat location

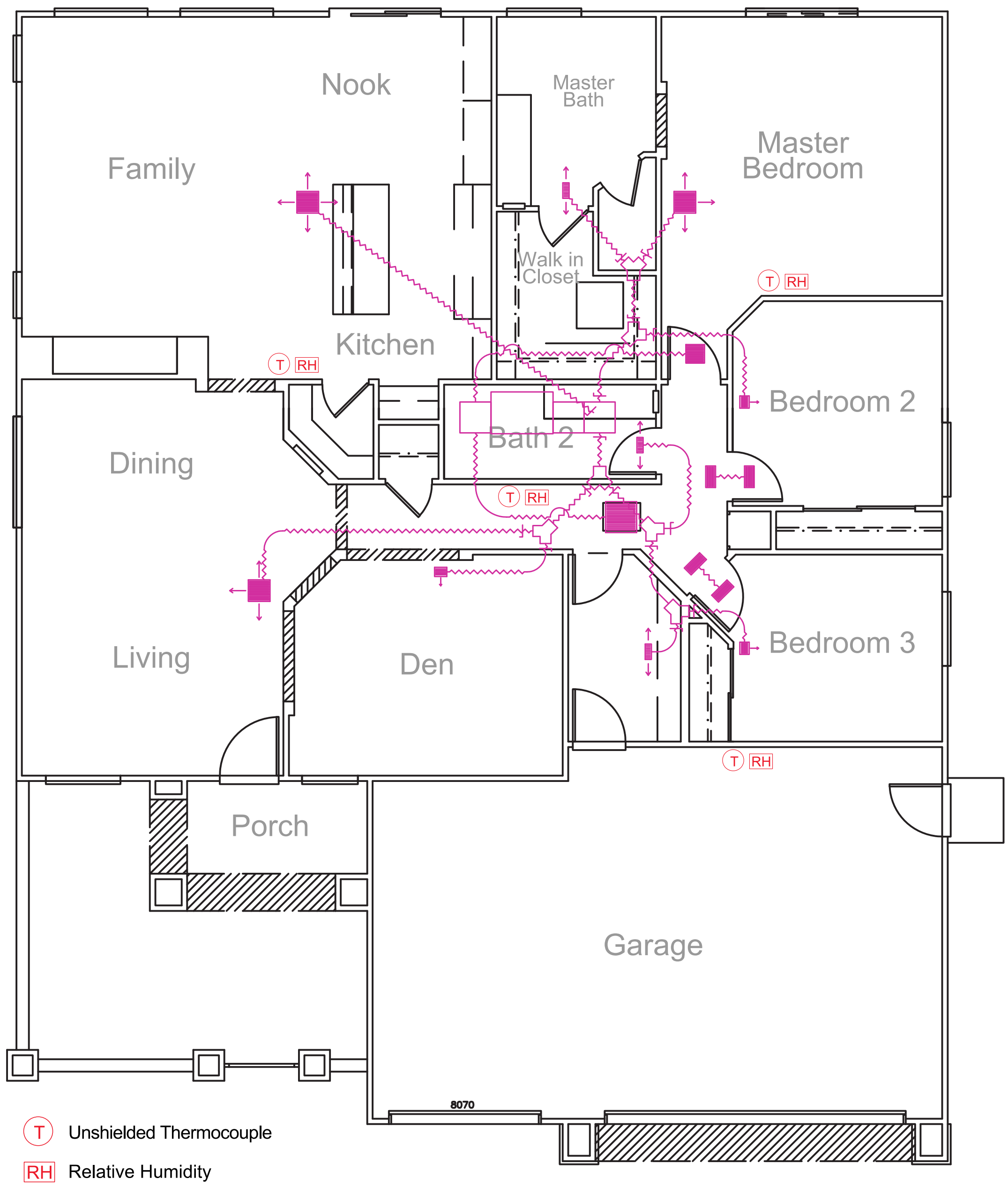

Figure 5. First-floor plan with data logger locations

4 Results

4.1 Performance of the Simplified Duct Distribution System

Hourly and minute temperature data were analyzed to compare the temperature at the thermostat location to the temperature in the master bedroom and the family room and kitchen area. For the study period, temperatures in the study rooms were sorted into hourly bins in 1°F increments above or below the thermostat temperature. The heating season is six months long and includes the period of November 1, 2010, to April 30, 2011. The cooling season is six months long and includes the month of October 2010 and the period from May 1, 2011, to September 30, 2011. Results during heating system and cooling system operation are shown in Figure 6 and Figure 7, respectively. Results when the conditioning system is not operating are shown in Figure 8.

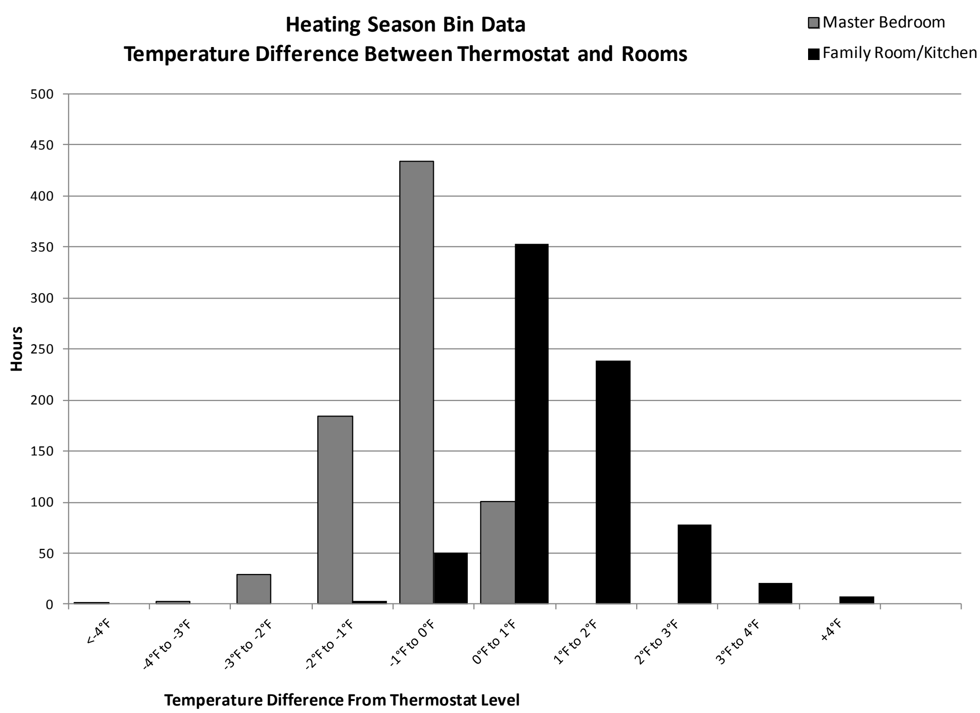

Figure 6. Heating season temperature differences

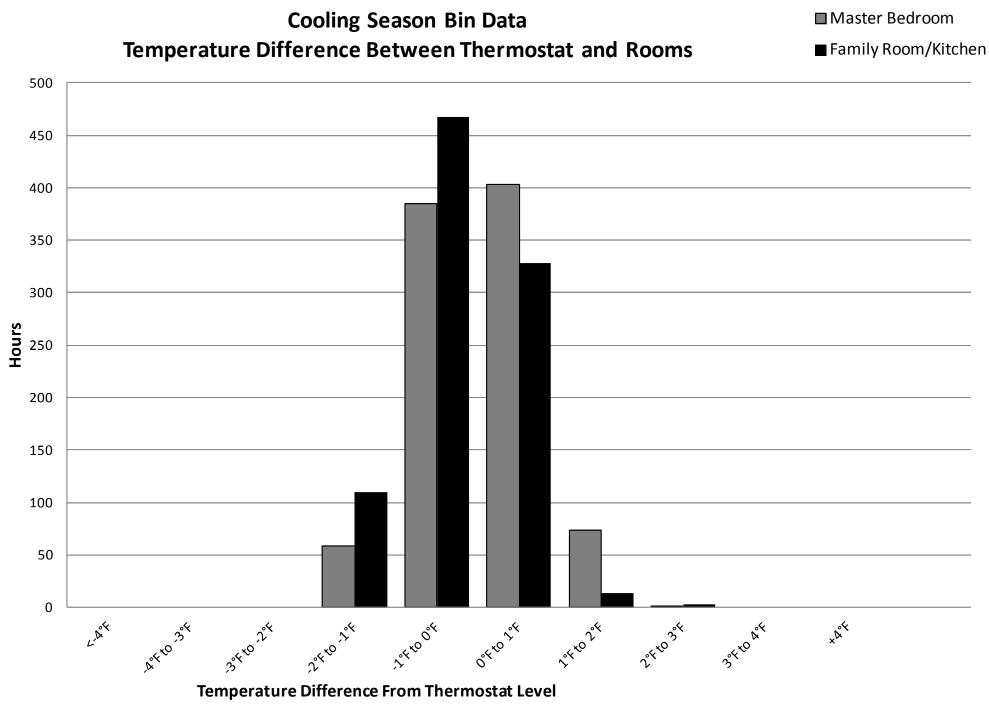

Figure 7. Cooling season temperature differences

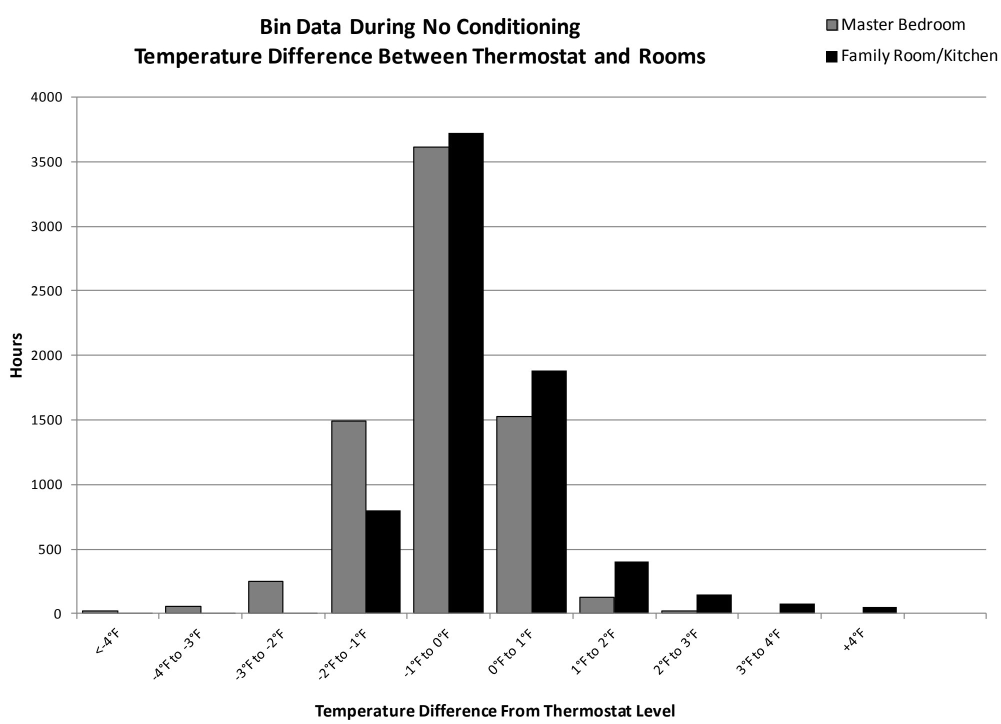

Figure 8. Temperature differences when the conditioning system is not operating

ACCA Manual RS (Rutkowski 1997) recommends that during heating, the temperatures in rooms other than those where the thermostat is located should be no more than ± 2°F of the temperature at the thermostat. Although no time factor is given in the ACCA Manual RS recommendations, a time-based hourly bin analysis was performed on the data collected. During the heating system operation, the master bedroom and the family room and kitchen area were within this temperature range 95.3% and 85.2% of the time, respectively. The house experienced 696 hours of conditioning during the five-month heating season, equal to 18.7% of the time.

During the cooling system operation, ACCA Manual RS (Rutkowski 1997) recommends that the temperatures in rooms other than those where the thermostat is located should be no more than ±3°F of the temperature at the thermostat. The master bedroom and the family room and kitchen area were within this range 100% of the time. The house experienced 602 hours of conditioning during the seven-month cooling season, equal to 16.6% of the year-long monitoring period.

Although there are no ACCA Manual RS recommendations (Rutkowski 1997) for when the space conditioning system is not operating, the monitoring period contained long periods of time with no operation. The longest period when the conditioning system was not operating was 578 hours and occurred between April 23 and May 17. During periods when no conditioning occurred, the master bedroom and the family room and kitchen area were within ±2°F of the temperature at the thermostat 95.2% and 96.0% of the time, respectively.

The extreme temperatures at each measurement location occurred when the conditioning system was not operating and are summarized in Table 2. The master bedroom experienced the lowest temperature of all studied rooms, with a value of 60.3°F at the end of November after the conditioning system was not operated for 55 hours and the outdoor temperature reached 46.5°F (suggesting that the occupants were away from the house for a number of days). In the family room and kitchen area, the lowest temperature recorded was 62.8°F on December 27. At the thermostat, the lowest temperature recorded was 64.0°F on January 31 after the conditioning system was not operated for 15 days. The highest recorded temperatures occurred during a 2-h period on August 27 when the thermostat reached 86.4°F, the master bedroom reached 86.7°F, and the family room and kitchen area reached 86.0°F. These peaks occurred 3 h after the outdoor temperature reached 105.2°F and 22 h after the cooling system ran last. It appears likely that the occupants did not activate the thermostat during this particular period of extremely warm indoor temperatures.

Table 2. Extreme Temperatures at Each Measurement Location

Temperature Case	Temperature at Master Bedroom	Temperature at Family Room and Kitchen Area	Temperature at Thermostat
Master Bedroom Low (November 28)	60.3°F	67.5°F	65.0°F
Family Room and Kitchen Area Low (December 27)	67.4°F	62.8°F	68.2°F
Thermostat Low (January 31)	63.5°F	63.7°F	64.0°F
High (August 27)	86.7°F	86.0°F	86.4°F

4.2 Performance of the Longest Duct Run

To determine the magnitude and duration of time that heat loss or gain from the ductwork located in unconditioned space might be influencing occupant comfort, minute-averaged temperature data were analyzed to compare the temperature difference, during conditioning periods, between the supply plenum temperature sensor and the supply register temperature sensor of the longest duct run (the duct serving the family room and kitchen area). The maximum temperature difference between the two sensors in the heating season always occurred as the furnace began a new cycle; however, the difference was inconsistent, with the air temperature at the register ranging from 14°F warmer to 10°F cooler than the air temperature at the plenum, with no clear trends. These extremes were brief, lasting less than 1 min. Within 2 min into each furnace operation cycle, the supply plenum temperature became approximately equal to the register temperature (within 0.5°F). In the final 2–3 min of each cycle, after the furnace stopped firing but the air handler continued to operate, the temperature at the plenum was slightly lower than the temperature at the register. On average during heating system operation, the measured temperature of the air in the supply plenum was at 98.3°F, which was 0.5°F warmer than the temperature at the supply register.

During the cooling season, the highest recorded temperature of air in the supply plenum immediately prior to operation was 103°F on August 26. During the first minute of operation, the average temperature within the supply plenum was 85°F; within 3 min, it was 65°F and falling. On average during cooling system operation, the supply plenum was at 60.1°F, which was 4.5°F cooler than the temperature at the supply register.

4.3 Comparison of Modeled Energy Use to Monitored Energy Use

The actual measured energy consumption of the four major subcategories (heating, cooling, hot water, and LAMELs) was compared to projected energy consumption using EnergyGauge (version 2.8.03). The results are shown in Table 3. The natural gas consumption of the dryer and range were not submetered, but their contribution to the total source energy consumption of the house was estimated by rerunning the energy models based on the actual number of occupants (two) in the house during the monitoring period instead of the assumed number (four) used when performing the initial modeling according to the BA Benchmark Definition 2009 (Hendron and Engebrecht 2010). The natural gas consumption of the dryer and range based on the actual number of occupants is estimated to be 17.9 Mbtu/yr source energy.

Table 3. Modeled Source Energy Use Compared to Monitored Source Energy Use

<table>
<tr><th rowspan="2">Description</th><th colspan="4">Modeled Annual Source Energy</th><th colspan="2"></th></tr>
<tr><th>BA Benchmark Definition 2009*</th><th>Regional Standard Practice</th><th>Builder's Standard Practice</th><th>Prototype House</th><th>Prototype Home Monitored Source Energy (Oct. 2010–Sept. 2011)</th><th>Normalized Prototype Home Monitored Source Energy (Oct. 2010–Sept. 2011)</th></tr>
<tr><th>End Use</th><th>(MBtu/yr)</th><th>(MBtu/yr)</th><th>(MBtu/yr)</th><th>(MBtu/yr)</th><th>(MBtu/yr)</th><th>(MBtu/yr)</th></tr>
<tr><td>Space Heating</td><td>50</td><td>33</td><td>24</td><td>21</td><td>15</td><td>14</td></tr>
<tr><td>Space Cooling</td><td>51</td><td>12</td><td>12</td><td>7</td><td>14</td><td>13</td></tr>
<tr><td>DHW</td><td>19</td><td>19</td><td>14</td><td>9</td><td>12</td><td>12</td></tr>
<tr><td>Lighting</td><td>23</td><td>18</td><td>22</td><td>8</td><td rowspan="3">30</td><td rowspan="3">30</td></tr>
<tr><td>Appliances and MELs</td><td>56</td><td>56</td><td>55</td><td>55</td></tr>
<tr><td>Outdoor Air Ventilation</td><td>3</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Subtotal</td><td>209</td><td>139</td><td>126</td><td>99</td><td>71</td><td>69</td></tr>
<tr><td>Photovoltaic Panel Generation</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Total</td><td>209</td><td>139</td><td>126</td><td>99</td><td>71</td><td>69</td></tr>
</table>

* From Hendron and Engebrecht (2010).

Using the Inverse Modeling Toolkit (ASHRAE 2002), a change point regression was performed on measured energy consumption to estimate the balance point temperature of the test house. The measured natural gas usage of the furnace was regressed against the actual outdoor temperatures (National Weather Service 2011) to find the temperature at which no heating was required (i.e., the heating balance point temperature). This balance point temperature was calculated to be 71°F. Using this balance point temperature, the total actual heating degree days (HDDs) were calculated for the measured outdoor dry bulb temperatures and the Typical Meteorological Year 3 (TMY3) outdoor dry bulb temperature used for the model. An adjustment factor was calculated by dividing the TMY3 HDDs (base 71) by the actual HDDs (base 71) and was used to normalize the measured heating use to compare with the model (which was calculated using TMY3). In cooling, the adjustment happened similarly, using a three-parameter cooling model to estimate the balance point temperature or the temperature below which no cooling is required. In this case, the balance point temperature was calculated to be 67°F. Then, by comparing the cooling degree days (CDDs) (base 67) of the measured dry bulb temperatures from the analysis period to the CDDs (base 67) of the TMY3 dry bulb temperature data, an adjustment factor was derived. This adjustment factor was used to normalize the measured cooling use to the TMY3 weather data of the model.

Table 3 shows the heating and cooling energy consumption normalized to the modeled weather conditions.

5 Discussion

Temperature data were analyzed and sorted into bins to compare the temperature at the thermostat location to the temperature in the master bedroom and the family room and kitchen area. During the hours outside the acceptable limits defined in ACCA Manual RS (Rutkowski 1997), the family room and kitchen area tended to be warmer, and the master bedroom was cooler than the thermostat location. During the cooling season, temperatures in the rooms studied never exceeded 3°F from the temperature at the thermostat, with most of their time within 1°F. They also remained within 1°F when no conditioning was occurring.

Data that were analyzed comparing the temperature difference, during conditioning periods, between the supply plenum temperature sensor and the supply register temperature sensor of the longest duct run (the duct serving the family room and kitchen area) determined that the air distribution system performed efficiently. During heating, the average temperature at the supply register was measured as 97.8°F, a level high enough to ensure adequate heating. Furthermore, on average, there was an insignificant temperature difference (0.5°F) between the two sensors, and typically within 4 or 5 min, any temperature difference that had existed at system startup had been eliminated, indicating quick response to occupant temperature requirements. During cooling, the air distribution system was shown to be more susceptible to environmental influences because the average change in temperature between the two sensors was 4.5°F (with the supply register warmer on average). But the average temperature delivered at the register was 64.6°F, a value low enough to facilitate cooling.

Monitored energy use results for the house indicate that it is using less whole-house source energy than predicted from modeling. Most of the decrease occurs because substantially less energy is used cumulatively for LAMELs, which composed almost two-thirds of the total modeled energy consumption. One possible reason for the difference between modeled and measured is that the occupants of this house may not have all the devices that are assumed in the miscellaneous electric load calculations. The reduction in the number of occupants from four to two between modeled and measured results did not improve the measured hot water energy consumption, which increased by 33% over the modeled value.

Weather-normalized measured energy use for cooling exceeded the modeled value by 6 MBtu/yr, while heating was lower than the modeled value by 7 MBtu/yr. The source of the large discrepancy remains unclear. Measured average thermostat set point was 70°F during heating and 79°F during cooling. However, during cooling, hourly data indicate periods of time with long system runtime and long periods of time with no system runtime, indicating that the homeowners were setting back the thermostat. Unfortunately, there is no clear pattern that might relate to high energy consumption (such as operating the cooling only in the late afternoon and early evening when outdoor temperatures peaked).

6 Conclusions

Temperature measurements in three rooms in a high performance house in Lake Elsinore, California, indicate that the temperature difference between the measured locations and the thermostat were within recommendations 90.3% of the time in heating mode and 99.3% of the time in cooling mode. Temperature uniformity between rooms was better (and extremely high) during cooling system operation than during heating system operation. Ceiling registers, as used in this house, generally are accepted to distribute cooled air more effectively than heated air, and this is reflected in the room temperature measurements. Because the temperatures in the rooms studied were within 1°F of each other for most of the time that the space conditioning system was not operating, the high performance enclosure of the house appears to doing a good job of maintaining temperature uniformity within the house and in keeping external weather influences at bay.

Temperature measurements at the supply plenum and the supply register (for the longest duct run) locations suggest that the air distribution system is delivering air efficiently and at temperatures necessary to provide heating and cooling as required. When operating in cooling mode, the system experiences a greater average temperature difference between the two locations than when operating in heating mode (4.5°F versus 0.5°F), although this variation in cooling is not a concern. This finding may suggest that the system is impacted more by its location in an unconditioned attic when cooling occurs, but the room temperatures relative to the set point during cooling are so uniform that this situation poses no comfort performance issues. In general, the results show that high performance homes can have short ductwork with registers located toward the interior and can provide installation cost savings while maintaining occupant comfort.

Monitored energy use results for the house indicate that it is using less energy than predicted from modeling. A breakdown of energy use according to end use determined little agreement between the comparable values. After normalizing for weather conditions, measured combined heating and cooling system source energy use was determined to be less than predicted by 4 MBtu/yr, with heating half of what had been predicted and cooling double of what had been predicted. The results appear to indicate that the modeling overestimated the heating energy use and underestimated the cooling energy use requirements. Measured hot water energy use was determined to be greater than that predicted by modeling, while LAMEL energy use was found to be significantly less than modeled. LAMEL energy use is likely affected by the fact that the house has fewer occupants than were considered in the modeling.

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