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Commissioning of the Fresno, California, Retrofit Unoccupied Test House

D. Stecher and C. Imm
IBACOS, Inc.

June 2013

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Commissioning of the Fresno, California, Retrofit Unoccupied Test House

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On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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Definitions

ACCA	Air Conditioning Contractors of America
ACH50	Air changes per hour at 50 Pascals
AHU	Air handling unit
BEopt	Building Energy Optimization (software)
Btu	British thermal unit
Btu/h	British thermal unit per hour
CFD	Computational fluid dynamics
CFM	Cubic feet per minute
DHW	Domestic hot water
EF	Energy factor
ERV	Energy recovery ventilator
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilation, and air conditioning
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
XPS	Extruded polystyrene

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The authors thank GreenEarthEquities for its involvement in the development, design, and construction of this innovative project. The authors also thank the U.S. Department of Energy's Building America Program for funding this research.

Executive Summary

Commissioning of instrumentation and limited short-term testing have been completed on a retrofit unoccupied test house in Fresno, California. This house is intended to be used as a laboratory in which several different methods of space conditioning distribution will be evaluated. This report provides background on the project, including specifications of the house and models used in its development, along with models to be evaluated through its operation.

IBACOS anticipates that houses achieving 50% whole-house source energy savings with respect to the Building America 2010 Benchmark (Hendron and Engebrecht 2010) will be "low load." Low load is defined by IBACOS as a house with a thermal enclosure that yields a maximum space heating and cooling load of less than 10 Btu/ft^2-h of conditioned floor area (31.5 W/m^2). IBACOS hypothesizes that heating and cooling energy in low-load houses would be distributed sufficiently throughout the house via convective currents through open doors or transfer grilles, buoyancy, and conduction through interior partition walls.

To evaluate this hypothesis, IBACOS worked with a retrofitter in Fresno, California, to create a test facility and instrumentation setup to enable the testing of several experimental alternatives to traditional forced-air distribution designs. Based on the specifications implemented during the retrofit, resultant calculated design loads are 16,680 Btu/h (4,888 W) in heating and 15,934 Btu/h (4,700 W) in cooling. This corresponds to 10.3 Btu/ft^2-h (32.5 W/m^2) and 9.8 Btu/ ft^2-h (31.2 W/m^2) on a per-unit area basis, respectively. Building Energy Optimization (BEopt) modeling shows energy savings of 50.1%.

IBACOS installed a central space conditioning unit with flexible configuration options, including shutting off supply ducts to specific rooms, and passive high- and low-through-wall transfer grilles to simulate various terminal conditions that are characteristic of simplified systems such as those incorporating mini-split heat pumps, distributed fan coil units, or central ventilation systems. Through the course of one year, IBACOS will assess the ability of each system to meet Air Conditioning Contractors of America (ACCA) Manual RS standards for temperature uniformity (Rutkowski 1997) and ASHRAE Standard 55-2010 sections: 5.2.5 Temperature Variations with Time, 7.3.2 Temperature Cycles and Drifts, and 7.4 Measuring Conditions (ASHRAE 2010). This field work and corresponding analytic modeling will be used to draw larger conclusions for a variety of climatic regions and house configurations.

The initial test to be performed in the facility is to determine the ability of market-available, acoustically dampened, and light-shielding passive high and low transfer grilles located in interior partition walls to maintain sufficient room air temperatures in non-actively conditioned rooms when partition doors are closed. This testing will be performed in conjunction with a computational fluid dynamics (CFD) model. The CFD model includes the air volume of the hallway, hall bathroom, and northeast bedroom of the house.

To assess the performance of the distribution strategies, monitoring equipment was installed in the house to assess the temperature of air in each room and relevant external conditions acting on the enclosure (e.g., outdoor temperature and incident solar radiation). This equipment was calibrated during the initial setup and short-term testing of the house. Work performed included ice bath testing of the thermocouples, determination of the air handling unit (AHU) and outdoor

unit electricity consumption values to trigger runtime “on” status, airflow testing of the distribution ductwork, whole-house air leakage testing, and operation of the door actuator mechanisms.

Commissioning of long-term installed instrumentation showed all devices, except the bottom-of-door transfer grille flaps, to be functioning properly within the discussed limits of their measurement capabilities. Results of these tests also revealed an issue with the ice bath test method: accidental electrical grounding of the thermocouple junction when the wire shielding also is in contact with the ice bath.

The next steps are to perform testing to validate the CFD model for room-to-room air transfer via over-door and bottom-of-door transfer grilles, with the eventual goal of using that model to determine the expected airflow volume through the transfer grilles under various conditions. Those results will be discussed in a future report.

1 Introduction and Background

There are alternatives to today's standard ducted forced-air systems, such as distributed fan coils with minimized ducts, terminal fan coil units, and point source units with buoyant force or ventilation driven distribution. These systems, which can have lower total installed costs than traditional ducted forced-air systems (Stecher 2011), allow the thermal enclosure characteristics of low-load houses to provide first-cost savings in addition to operational cost savings. More research is needed to evaluate the conditions where simplified space conditioning systems will work in new and retrofitted houses. Guidance is needed on the design and installation of these systems to support a wider adoption throughout the new construction and retrofit markets.

1.1 Background

IBACOS anticipates that houses achieving 50% whole-house source energy savings with respect to the Building America 2010 Benchmark (Hendron and Engebrecht 2010) will be "low load." Low load is defined by IBACOS as a house with a thermal enclosure that yields a maximum space heating and cooling load of less than 10 Btu/ft^2-h of conditioned floor area (31.5 W/m^2). IBACOS hypothesizes that heating and cooling energy in low-load houses will be distributed sufficiently throughout the house via convective currents through open doors or transfer grilles, buoyancy, and conduction through interior partition walls.

This hypothesis is based, in part, on research performed by Brown and Solavson (1962), who first characterized heat flow through a rectangular opening using the Nusselt, Grashof, and Prandtl numbers as shown in Equation 1:

$$Nu = C \times {Gr_D}^{0.5} \times Pr \, , \tag{1}$$

where

C is an experimentally determined coefficient in the range of 0.2 to 0.33

Nu is the Nusselt number, the ratio of convective to conductive heat transfer through the opening

Gr_D is the dimensionless Grashof number, which approximates the ratio of buoyancy to viscous forces acting on the air

Pr is the Prandtl number, the ratio of the momentum diffusivity to thermal diffusivity of the air

Characterizing the flow mathematically enables approximation of convective airflow through an open doorway based on the dimensions of the doorway and the temperature difference between the two rooms.

Additional research by Barakat (1985) helped validate Brown and Solavson's work and indicated that the steady-state heat transfer through an open doorway at a 2.7°F (1.5°C) temperature difference was 1050 Btu/h (308 W) via natural convection with 48 Btu/h (14 W) via radiation. Building on this work, multizone airflow calculations and CFD simulations performed by Feist et al. (2005) of dwellings meeting the Passivhaus energy standard indicate that, at a temperature difference of 1.8°F (1°C) between spaces, expected heat transfer rates are 300–600 Btu/h (100–

200 W) through open doors and 0.3–0.6 Btu/ft^2-h (10–20 W/m^2) of internal partition wall area. In a low-load home, these values may provide a substantial contribution to satisfying an individual room load before providing active conditioning. Field test data obtained by IBACOS (2008, 2010a, 2010b) from a Passivhaus in Climate Zone 5 also support this hypothesis.

However, if interior partition doors are not always open, the potential for heat transfer to occur via natural convection can be reduced. Fortunately, Emery (1969) found that when a small rectangular opening of height h is placed in a wall at the ceiling plane and one is placed at the floor plane on the order of $h/H \geq 0.05$, where h is measured up from the floor for the lower opening and down from the ceiling for the upper opening and H is the floor-to-ceiling height, no loss in flow occurs compared to the baseline case of a single, clear opening of height H in the wall spanning from the floor to the ceiling. This assumes the width of all openings is the same in both cases. Based on this work, there is potential for an approach of strategically locating holes in interior partition walls to enable airflow via natural convection from one space to another in a house, even when interior partition doors are closed.

The purpose of this multi-report study is to determine the viability of strategically placed holes (also known as passive high- and low-through-wall transfer grilles) in interior partition walls to maintain sufficient room air temperatures in non-actively conditioned rooms when partition doors are closed by evaluating the modeled and field-measured performance of a system using market-available, acoustically dampened, and light-shielding through-wall transfer grilles. The general approach for the study is to measure the temperature differentials between the bedrooms when not directly served by the heating, ventilation, and air-conditioning (HVAC) system and the main living space of the house, in addition to the temperature of air moving through the transfer grilles. This information will be used to calibrate a CFD model, which then will be used to determine the expected flow rate through the transfer grilles at various temperature differentials between the spaces on either side of the transfer grilles. Using a model to determine the flow rate is necessary because direct measurement of airflow is impractical due to the expected low velocity through the transfer grilles.

The following research questions will be answered:

- Over the course of one year, to what extent is the experimental space conditioning distribution strategy able to meet ACCA and ASHRAE guidelines for room-to-room temperature uniformity and stability, respectively? What are the frequency, duration, and amplitude of non-uniformity of the temperature between bedrooms/bathrooms and the thermostatically controlled space? Under what weather conditions does the non-uniformity occur?
- In what ways and by how much does the measured performance of the distribution system differ from the computer-modeled performance?
- How substantially does the experimental strategy differ from the control strategy in its ability to meet the ACCA guidelines?

To ensure that temperature differences are within reasonable occupant expectations, the research team will use guidance by Rutkowski (1997). Rutkowski requires dry-bulb temperature variances from the thermostat setting during the cooling season as measured at the thermostat to be ± 3°F

(± 1.67°C). Similarly, the temperature variances during the heating season in any room should be ± 2°F (± 1.11°C) of the thermostat set temperature. Room-to-room temperature differences or floor-to-floor temperature differences should be no greater than 4°F (2.22°C) in the heating season and no greater than 6°F (3.33°C) in the cooling season. Although air temperature is only one factor in measuring overall thermal comfort (ASHRAE 2010), Rittelmann (2006) 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.

The research team will compare the measured performance of the experimental transfer grille system to the measured performance of a typical distribution system with conditioned air actively supplied to all living spaces, bedrooms, and bathrooms via a ducted forced-air system. This will serve as the experimental "control." In all cases, supply registers will be mounted high on interior partition walls in a retrofit unoccupied test house in Fresno, California. This test facility and the instrumentation setup discussed herein are intended to enable the testing of the heretofore discussed experimental air-based alternatives to traditional forced-air distribution and other experimental options as they come to light.

2 Mathematical and Modeling Methods

Modeling was performed for whole-house load and distribution system development using the appropriate ACCA manuals as cited below. Energy modeling was performed using the Building Energy Optimization with Hour-by-Hour Simulations, Version 1.2 (BEopt) software to provide a context with respect to annual energy for the pre-retrofit and post-retrofit cases. CFD models were developed to be validated using data obtained from the field test results.

2.1 BEopt

Although the focus of this research is not to validate whole-building energy consumption models, to put the results in context with other Building America projects, modeling was completed using BEopt Version 1.2 with the specifications shown in Table 1. Note that many of these specifications, such as lighting and appliances, are not relevant to the testing to be performed in the house and will not be installed in the house at the time of testing. Therefore, their values were not modified between the pre- and post-retrofit models.

Table 1. Retrofit Specifications

Assembly	Pre-Retrofit Specification	Post-Retrofit Specification
Exterior Walls	2 × 4 studs at 16 in. on center with R-13 fiberglass batts	2 × 4 studs at 16 in. on center with fiberglass batts removed and replaced by R-13 blown-in cellulose
Ceiling	R-7 blown cellulose	R-60 blown cellulose
Foundation	Uninsulated slab on grade	Uninsulated slab on grade
Windows	Double-pane aluminum frame with ¼ in. air space	Double-pane low-E vinyl frame, U-0.30, SHGC-0.30
Infiltration	1660 CFM50 (7.66 ACH50)	345 CFM50 (1.59 ACH50)
Ventilation	Exhaust only—intermittent, user actuated	Single-point ERV, continuous runtime at 40 CFM
Appliances	Standard, not ENERGY STAR®	Standard, not ENERGY STAR
Lighting	14% compact fluorescent	14% compact fluorescent
HVAC	Air source heat pump—13 SEER, 8.1 HSPF	Air source heat pump—20.5 SEER, 13 HSPF*, installed capacity at 500 CFM, 16,890 in heating, 16,710 in cooling
DHW	40-gal tank—gas fired, atmospheric vented, 0.67 EF	40-gal tank—gas fired, atmospheric vented, 0.67 EF

*Note: The manufacturer's ratings are 20.5 SEER (seasonal energy efficiency ratio) and 13 HSPF (heating seasonal performance factor); however, these values were unavailable in BEopt, and insufficient information was available from the manufacturer at the time of modeling to manually create a user option. Therefore, the values modeled were the highest available.
ACH50 is air changes per hour at 50 Pascals. CFM is cubic feet per minute. DHW is domestic hot water. EF is energy factor. ERV is energy recovery ventilator. SHGC is solar heat gain coefficient.

2.1.1 Specification Development

Discussions occurred with the builder on the cost of measures for the thermal enclosure of the test house to achieve a minimum of 50% energy savings from pre-retrofit conditions. A rigorous cost analysis for the thermal enclosure was outside the scope of this project, and IBACOS assumed that other U.S. Department of Energy research projects are more aggressively investigating that issue. Trade-off options that the research team considered during discussions with the retrofit contractor include the following: occupant comfort, health and safety; building and equipment durability; system reliability; building code compliance; and building and equipment maintainability. Some measures were acknowledged to be cost effective in the future, and for some measures, future advancements in technology are expected to result in greater energy savings.

The enclosure retrofit specifications determined by the design team for the west-facing, slab-on-grade, 1,621-ft^2 Fresno, California, retrofit unoccupied test house include the following: 2 × 4 wall construction with R-13 cellulose, vented attic with R-60 blown-in cellulose, windows with a 0.30 U-value and 0.30 SHGC, and rigorous air-sealing measures. For the most part, these specifications—shown in Table 1—are the standard practice for the retrofitter on their projects. However, the addition of 1-in. extruded polystyrene (XPS) (R-5) insulated sheathing for the wall assembly was initially discussed as an option to meet the energy consumption and peak load requirements. This option also was modeled in BEopt. Although the option ultimately was not selected, it is discussed in the modeling results.

2.1.2 BEopt Results

BEopt results indicated a whole-house energy savings of 50.1% based on the specified thermal enclosure strategy. These results are shown graphically in Figure 1. No changes to other major energy consumption areas were modeled for this study because the house will remain unfinished without final lighting, appliances, or DHW system throughout the course of the research. However, substantial savings could be realized by making upgrades in these areas to bring a completed house incorporating the specified thermal enclosure upgrades beyond the 50% savings level.

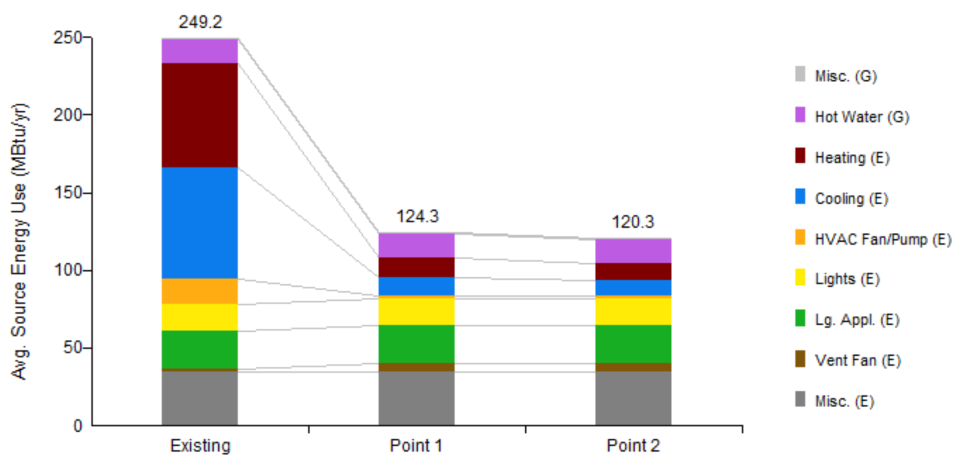

Figure 1. BEopt results

The modeling results in Figure 1 show that the above inputs without exterior foam would provide a savings of 50.1% (Point 1) and with 1 in. of XPS (R-5) exterior foam a savings of 51.7% (Point 2). Insufficient retrofit construction cost data are available in BEopt. Therefore, discussions with the builder indicated that, because the existing stucco needed only minor repairs, it was not economically viable on a first-cost basis to add exterior foam.

An infiltration level of 2 ACH50 was used in initial models, with the following actions performed by the builder in an attempt to achieve this goal:

- Applying spray foam to all top plates and penetrations through the ceiling, including exterior walls (performed by removing perimeter roof sheathing)
- Patching all cracks in the exterior stucco finish and sealing around all penetrations
- Caulking the bottom plate of the exterior walls to the concrete slab
- Installing new windows and doors with functional weather stripping (the old windows were removed with existing stucco immediately adjacent to the windows, and new construction windows with flanges were installed and the stucco patched).

Whole-house air leakage testing discussed later in this report revealed the actual leakage rate of the house to be 1.59 ACH50. This value was used in the BEopt models in Figure 1.

2.2 Load Calculation and Distribution System Development—ACCA Manuals J, S, and D

To establish the low-load nature of the house, ACCA Manual J (Rutkowski 2006) calculations for peak total and room-by-room design loads were performed based on the post-retrofit specification packages outlined in Table 1. The calculations were performed using the Wrightsoft software Right-Suite Universal 8.0.11 (Wrightsoft). The input assumptions include the following:

- One occupant in each bedroom and one occupant in the family room (four total occupants)
- Peak internal gains of 2,400 Btu/h (703 W) according to ACCA Manual J Section 9 Appliance, Equipment and Lighting Load Scenario 1, which assumes the house contains "a refrigerator, range with vented hood, dish washer, clothes washer and vented clothes dryer, and contains electronic equipment and lighting allowances." The peak internal gains are distributed as follows: "1000 Btu/h (293 W) for the kitchen, 500 Btu/h (147 W) for the utility room, and 900 Btu/h (264 W) for a TV or computer and a few lighting fixtures" (Rutkowski 2006).

The resultant whole-house design loads were 16,680 Btu/h (4,888 W) in heating and 15,934 Btu/h (4,700 W) in cooling. This corresponds to 10.3 Btu/ft^2-h (32.5 W/m^2) and 9.8 Btu/ft^2-h (31.2 W/m^2) on a per-unit area basis, respectively. Although the cooling value is below the low-load threshold of 10 Btu/ft^2-h (31.5 W/m^2), the heating value is slightly greater. However, the exact threshold value is somewhat arbitrary, and the heating value for this house is appreciably small and close enough to the threshold value to facilitate the testing of the alternative distribution system.

Table 2 shows the individual room loads. Using these loads and ACCA Manual S protocol (Rutkowski 1995), the research team selected the equipment to be installed in the house based on the manufacturer's equipment data. Because the calculated airflow value needed for the house was smaller than the smallest size of AHU available, it was necessary, upon system installation and commissioning, to set the volumetric airflow of the electronically controlled AHU to the appropriate value using the manufacturer-provided interface. The variable capacity outdoor unit was able to reduce its output to match this reduced airflow value. Due to the climate and unoccupied status of the house, sensible loads account for 95% of the design load.

Table 2. Individual Room Loads

Room	Area (ft^2)	Heating Load (Btu/h)	Cooling Load (Btu/h)
Family	311	3,179	4,268
Dining	374	2,383	1,992
Kitchen	105	1,616	1,114
Laundry	38	964	442
Hall	133	652	480
Master Bedroom	213	1,377	1,828
Master Bath	42	626	309
Master Walk-in Closet	35	875	336
Bedroom 2	154	2,123	1,965
Bedroom 3	142	1,404	1,488
Bath 2	75	462	347

Three distribution system possibilities were evaluated in the ACCA Manual D (Rutkowski 2009a) design process:

1. A ducted distribution system to the bedrooms and bathroom and a single point of distribution into the main living space
2. A ducted distribution system to the bedrooms, a single point of distribution into the main living space, and no conditioned air to the bathrooms
3. A system with a single point of delivery into the main living space, with no additional active circulation to the remainder of the house but including over-door and bottom-of-door transfer grilles to facilitate free movement of air with the bedroom doors closed.

Using ACCA Manual D protocol (Rutkowski 2009a), the duct systems were sized based on the individual room loads calculated by Wrightsoft Right-Suite Universal 8.0.11 (Wrightsoft). Trunks were sized to enable 700–900 fpm (3.56–4.57 m/s) and branches at 400–500 fpm (2.03–2.54 m/s). The design pressure drop between each branch was maintained to within ±0.01 in. of water column (±2.5 Pa).

The team sized the supply registers in the bedrooms and bathrooms using ACCA Manual T protocol (Rutkowski 2009b), which states that at terminal velocity, the registers should have a throw distance of 1.0–1.2 times the distance from the register to the opposite wall. To accomplish this, the team measured the distance from the register face to the exterior wall and added 2 ft to ensure the register has sufficient throw to reach the exterior wall and turn down to create air circulation within the space. The team used these throw distances and ACCA Manual T noise criteria requirements to select the registers.

2.3 Computational Fluid Dynamics

To assess the viability of the natural convection air transfer strategy (System 3), the research team created a finite element CFD model using ANSYS CFX (ANSYS). The CFD model consists of a single fluid material (air) encompassing the volume of the hallway, hall bathroom, and northeast bedroom (see Figure 2 and Figure 3). The purpose of the model is to determine the expected flow rates through the over-door and bottom-of-door transfer grilles under various exterior temperatures and temperature differences between the hallway and bedroom. The heat transfer via conduction is expected to occur through the interior partition walls in the as-built house; however, because of the limited wall area in direct contact with the actively conditioned hallway, the interior partition walls were assumed to be adiabatic. This assumption will be considered when comparing the modeled values to field measured data. The exterior wall, ceiling, and window boundaries are treated with convection boundary conditions, based on specified R-values and outside bulk temperature. The floor assembly also was assumed to be adiabatic. A curved-face free-flowing air boundary layer is established at the end of the hallway where it meets the main living space. This type of boundary layer enables convective heat transfer across it while ensuring that the amount of air in the model remains constant.

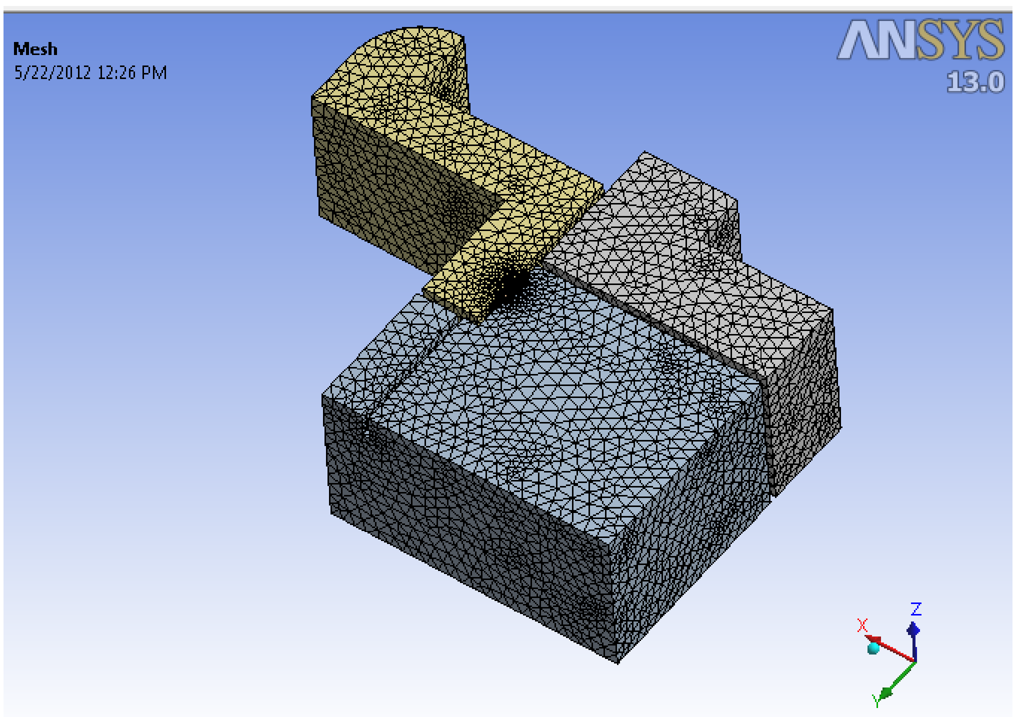

Figure 2. CFD model mesh of the bedroom (light blue), bathroom (gray), and hallway (tan)

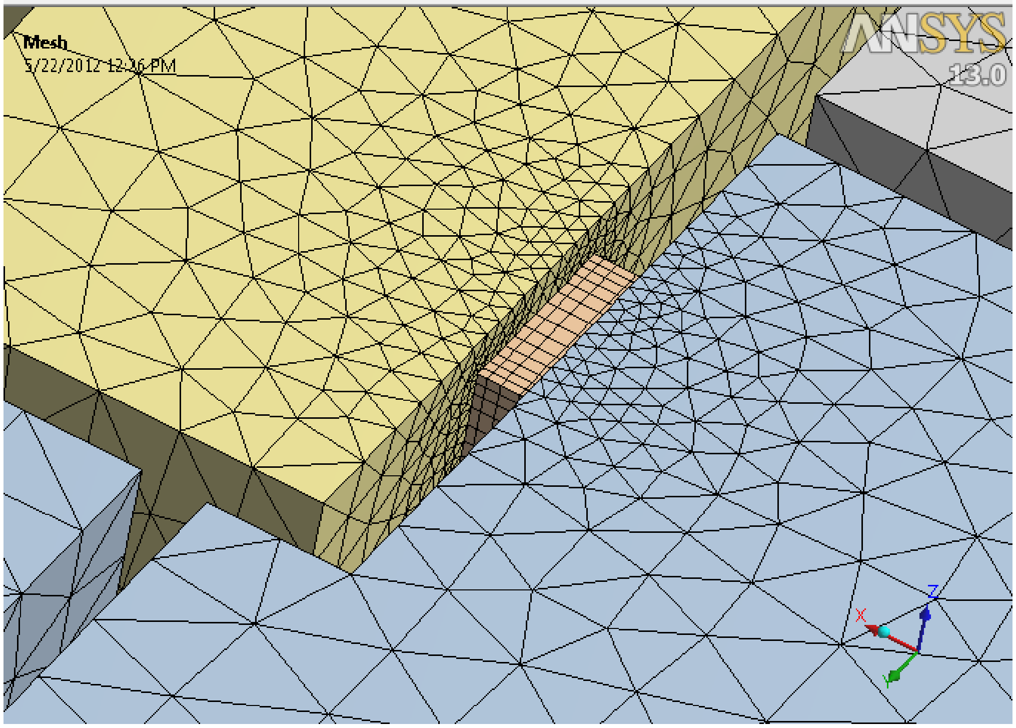

Figure 3. Close-up of CFD model mesh showing the upper transfer grille (pink) connecting the bedroom (light blue) and hallway (tan)

The mesh is primarily tetrahedral, but hexahedrals, prisms, and pyramids also were used when appropriate. It contains 41,016 nodes and 137,512 elements. The residuals value of the mesh is less than 2×10^{-5}. Results of this model and comparison to performance in the as-built house will be the subject of a future report.

3 Long-Term Test Equipment

3.1 HVAC Distribution Systems

The retrofitter's standard practice is to relocate the AHU and ductwork inside conditioned space via the use of a dropped ceiling in the hallway and the use of a ducted mini-split AHU. For this experiment, the conventionally sized AHU was located in the living room, as shown in Figure 4. The ductwork was routed through the hallway, as shown in Figure 5, but the dropped ceiling was not installed.

Figure 4. Test HVAC equipment installed in the living room, showing dampers to enable a single point of delivery

Figure 5. Test ductwork routed through the hallway and located inside conditioned space

To answer the research questions for this project, three distribution systems will be evaluated:

1. A ducted distribution system to the bedrooms and bathrooms and a single point of distribution into the main living space (see Figure 6)
2. A ducted distribution system to the bedrooms, a single point of distribution into the main living space, and no conditioned air to the bathrooms (see Figure 7)
3. A system with a single point of delivery into the main living space, with no additional active circulation to the remainder of the house but including over-door and bottom-of-door transfer grilles to facilitate free movement of air with the bedroom doors closed (see Figure 8 and Figure 9).

The three distribution systems were implemented in the test house by using zone dampers controlled by a central data logger. By opening and closing specific dampers, as detailed in Table 3, each system could be operated for a specific duration of time (e.g., one week). The zone damper numbers in Table 3 correspond with the labels shown in Figure 6 through Figure 8. The bottom-of-door transfer grilles for System 3 were capable of being shut via a data logger-controlled flap (Figure 9) so that they would be active only during the operation of System 3. In addition to their functionality in System 3, the upper transfer grilles serve as a return air pathway for System 1 and System 2; the bedroom doors are connected to data logger-controlled actuators (Figure 10) that enable them to be opened or closed remotely. The AHU is located in the living room (Figure 11).

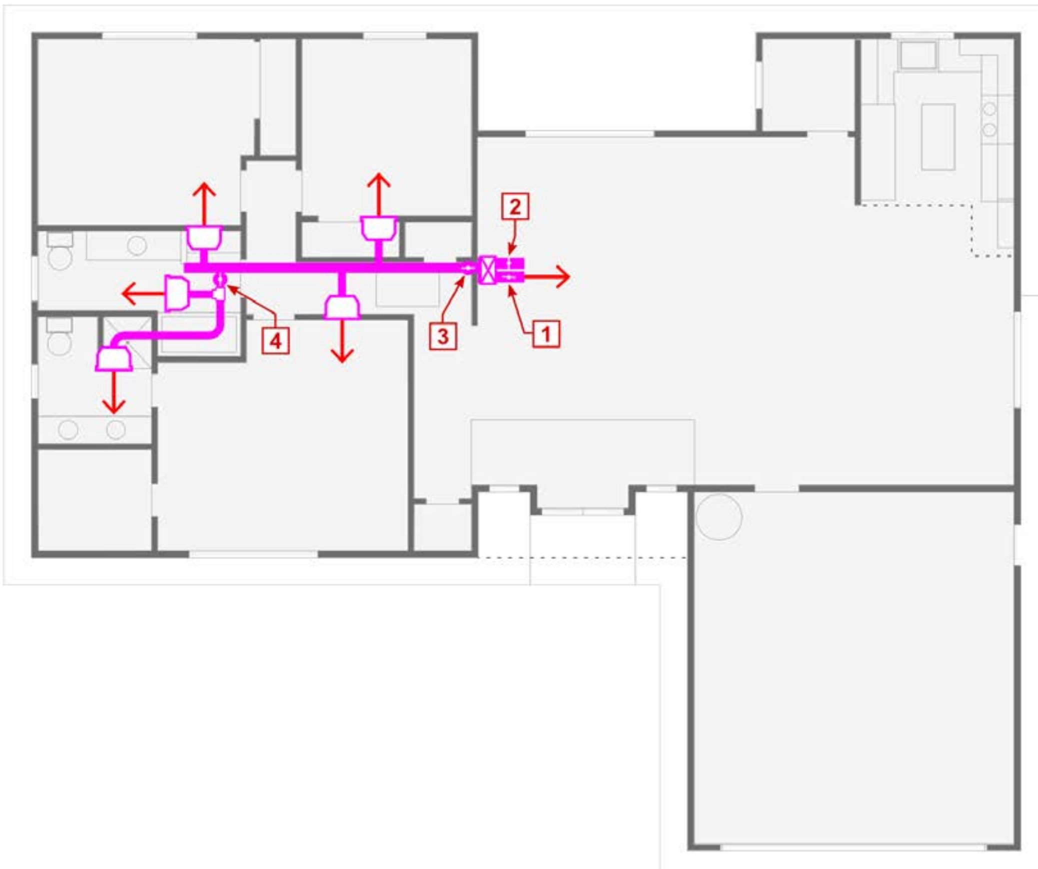

Figure 6. Distribution strategy 1

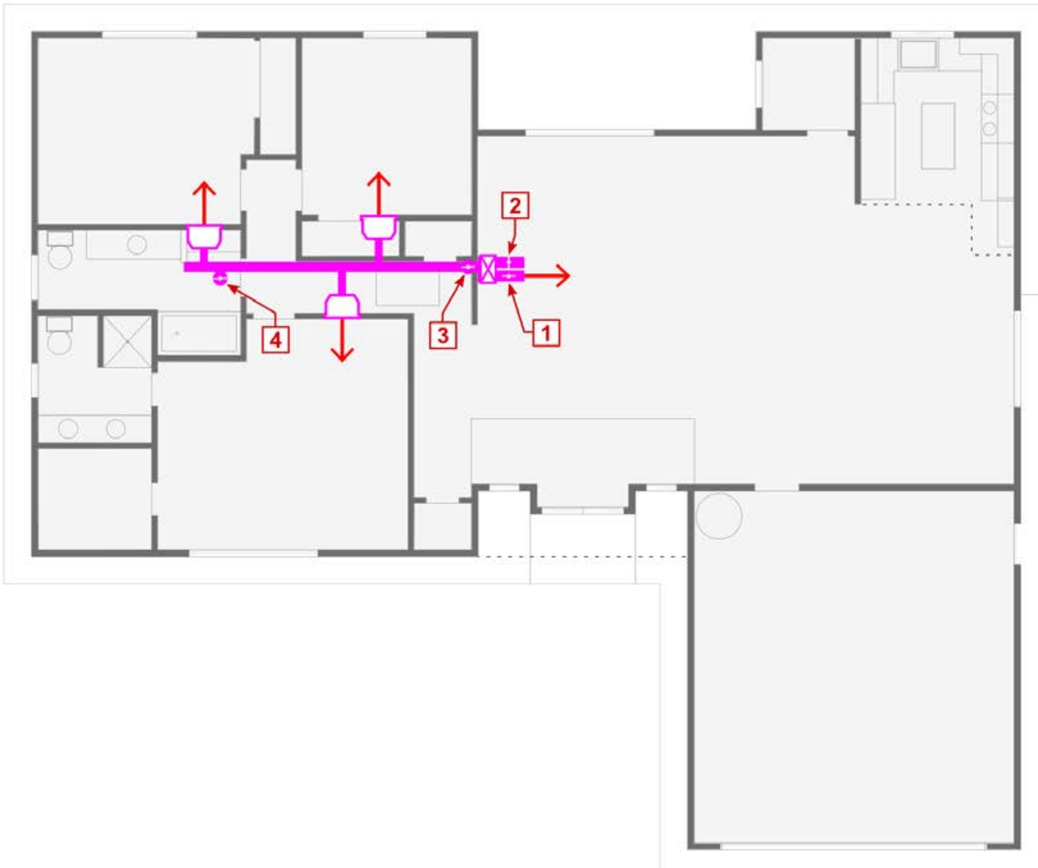

Figure 7. Distribution strategy 2

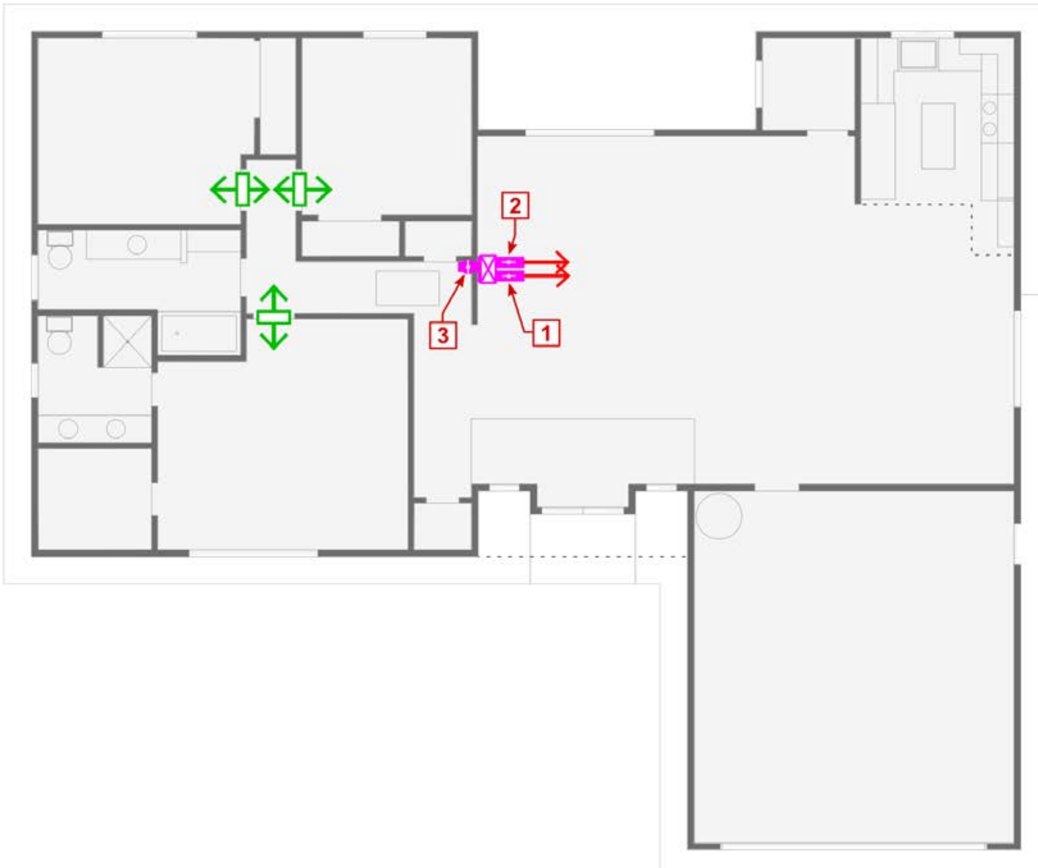

Figure 8. Distribution strategy 3

Figure 9. Typical bedroom with active forced-air register (upper left), above-door transfer grille (upper right), and bottom-of-door transfer grille (middle right)

Table 3. Distribution System Control Dampers

Zone Dampers	1	2	3	4
System 1	Open	Closed	Open	Open
System 2	Open	Closed	Open	Closed
System 3	Open	Open	Closed	Closed

Figure 10. Bedroom door actuator

Figure 11. Test AHU location (upper right) in the main living space; a typical shielded aspirated thermocouple is shown in the foreground

3.2 Long-Term Measurements

Although the subject of another report, long-term testing will be performed at this house. Each system must operate in the weather conditions experienced throughout an entire year because the exact time and combination of conditions that may cause failure in each passively conditioned room currently are unknown. Although failures may occur during peak conditions, if successes occur during midseason conditions, the heat flux occurring through the enclosure during those times (either directly measured or calculated) can be determined and used as a boundary condition for the effectiveness of the system.

Long-term measurements and data logger-controlled devices are listed in Table 4 and Table 5, respectively, and their approximate locations in the house are shown in Figure 12.

Table 4. Long-Term Measurements

Measurement	Equipment Needed
Air temperature in each of the bedrooms, bathrooms, kitchen, living room, dining room, and hallway	Shielded aspirated Type-T thermocouples mounted 43 in. from floor
Air relative humidity measured in the living room	Campbell Scientific CS210 mounted 43 in. from floor
AHU runtime averaged temperature via unshielded thermocouple at each supply location at point of maximum velocity	Unshielded Type-T thermocouples with maximum velocity location determined by hot wire anemometer trace
AHU runtime averaged temperature at central return via unshielded thermocouple	Unshielded Type-T thermocouples
Air temperature at each above-door and bottom-of-door transfer grille location	Unshielded Type-T thermocouples
Heat flux through floor slab to ground	Hukseflux heat flux transducer
Runtime of HVAC system: AHU and heat pump outdoor unit	Continental Control System Wattnode
Runtime of ERV	Continental Control System Wattnode
Surface temperature measurements at a representative window (or sliding glass door) on each wall orientation. For each location, four surface temperature measurements will be made: center of glass, edge of glass, frame, and opaque wall assembly.	Unshielded Type-T thermocouples
Temperature in unconditioned attic	Shielded aspirated Type-T thermocouple mounted 43 in. from floor
Temperature in unconditioned garage	Shielded aspirated Type-T thermocouple mounted 43 in. from floor
Global incident solar radiation on site with specific amount of light incident through windows determined using three-dimensional (SketchUp) solar model of the house	LI-COR 200 silicon pyranometer
Outdoor temperature and relative humidity	Vaisala HMP60 in shielded enclosure

Table 5. Data Logger-Controlled Devices

Action	Equipment Needed
Generate the anticipated peak sensible internal gains, according to ACCA Manual J (Rutkowski 2006), in each bedroom, bathroom, and the main living area	Relay-controlled unit heaters in each space with Continental Control System Wattnode to measure energy consumption
Switch between various distribution systems	Electronically controlled damper in HVAC ductwork
Close off each bottom-of-door transfer grille opening	Flap and relay-controlled actuator mechanism
Operate bathroom exhaust fans	Relay

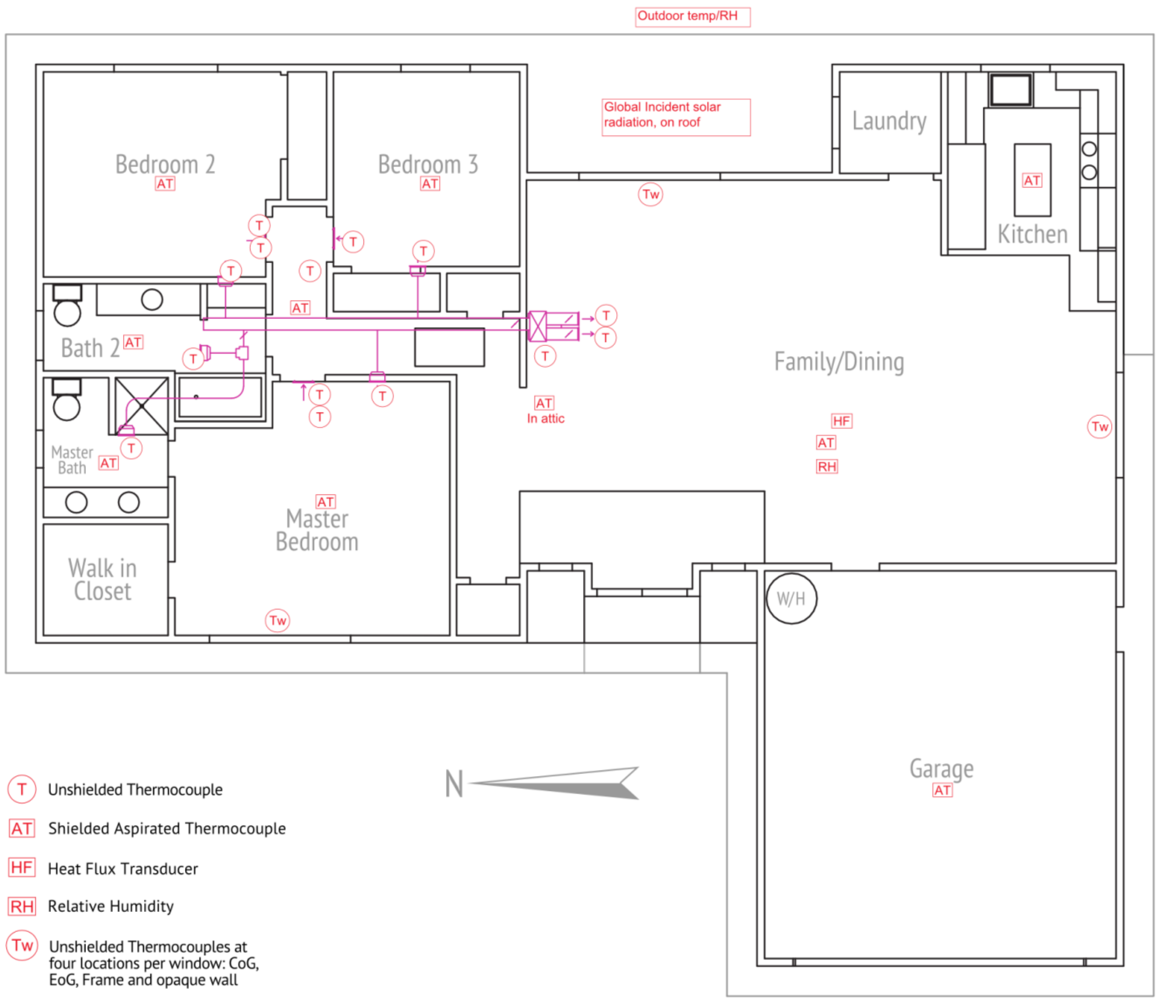

Figure 12. Sensor locations

4 Short-Term Testing and Calibration—Experimental Methods

The long-term testing equipment described in Section 3 was calibrated during the initial setup and short-term testing of the house. Calibration included the following:

- Ice bath testing of the thermocouples
- Determination of the AHU and outdoor unit electricity consumption values to trigger runtime “on” status.

Additional testing that was performed included the following:

- Airflow testing of the distribution ductwork
- Whole-house air leakage testing
- Operation of data logger-controlled output devices.

4.1 Ice Bath Testing of Thermocouples

4.1.1 Methods

Thermocouple measurements were tested for consistency by inserting them into a slurry made of crushed distilled ice and distilled water carried in a stainless steel thermos. This slurry was used because the freezing point of distilled water is a known constant of 32°F (0°C), and creating a mixture of solid ice and water ensures that the water that contacts the thermocouple is at the freezing point but is still in a liquid state. The thermocouple was inserted into this mixture until the observed temperature on the data logger output display screen stabilized (typically two scans or 40 seconds).

4.1.2 Results

Initial results from the ice bath test indicated a range of values from approximately –2°F to 2°F (~ –1°C to 1°C), with inconsistent results from thermocouple to thermocouple. All values should have been within ±0.18°F (±0.1°C) of 32°F (0°C). If all measurements had been consistently off, it would have indicated an issue with the reference thermistor. This somewhat inconsistent range of error suggested a problem with the wire. Prior to wholesale replacement, individual sections were tested. It was determined that the stainless steel construction of the vessel holding the slurry was enabling the shield wire to make electrical contact with the thermocouple junction, affecting the results of the test. The shielding was stripped back, and the wires were retested. Upon retesting, all thermocouples were shown to be within the required range.

4.1.3 Discussion

The experience from this ice bath testing of thermocouples should be noted in future guidelines, particularly the importance of ensuring that any shielding does not come in contact with the slurry or the vessel holding the slurry. Some recommendations discussed during this testing included dipping the thermocouple junction in clear nail polish to electrically insulate it or ensuring that the shielding is stripped back sufficiently (~3 in.) so that it does not make contact with the slurry.

4.2 Determination of Air Handling Unit and Outdoor Unit "On" Electricity Threshold

4.2.1 Methods

The threshold of electricity consumption at which the AHU and outdoor unit could be considered to be "on" was determined by operating each respective piece of equipment and observing the electricity consumption when operating as measured by attaching a Wattnode to the wires providing electricity to each piece of equipment. This Wattnode was sampled by a Campbell Scientific CR1000 data logger every 20 seconds. Standby electricity also was observed when the system was off and the runtime "on" threshold was set above that amount.

4.2.2 Results

Standby electrical power draw of the AHU was observed to be ~4 W, whereas the heat pump outdoor unit was ~15 W. Steady-state power draw for each was ~24 W and ~750 W, respectively. Based on these measurements, the threshold of electrical power consumption at which the AHU and heat pump outdoor unit could be considered to be "on" was determined to be any time the measured electrical power draw was greater than 7 W and 150 W, respectively. Observations of electrical power consumption after the initial tests revealed that the electric resistance backup heat, which is on the same measured circuit as the AHU, has a distinct signature and is considered to be on when the measured electrical power of the AHU circuit is greater than 200 W. These values were entered into the data logger program so that runtime could be calculated.

4.2.3 Discussion

Although the threshold "on" electricity consumption value was determined for both the AHU and the outdoor unit, this will be useful for knowing when the AHU is running to determine when to start or stop certain calculations within the data logger program. Although in this case it is not expected to be an issue due to the focus on the research of measuring the energy delivered at the supply register, as opposed to energy consumed by the system, note that simply knowing when a variable capacity outdoor unit is "on" or "off" can be insufficient for certain tests. The reason for this is that the system may be "on" but could be running in a range of capacities necessary to meet the load in the house. Analysis of these types of systems—variable capacity—will require data logger programming that enables binning of runtime into ranges of operational capacity.

4.3 Airflow Testing of the Distribution Ductwork

4.3.1 Methods

The measured flow volume from each supply register was determined using a low-flow balometer flow hood with an accuracy of ± 3% + 5 CFM (TSI 2012). Due to the lack of sufficient flat wall area surrounding some registers, the opening of the flow hood was made smaller using duct mask such that only the register face would fit through the opening.

Total system flow was measured using both the flow hood and a TrueFlow Air Handler Flow Meter with a digital manometer (DG700) (a.k.a. the flow plate) (Energy Conservatory 2012b).

4.3.2 Results

Results from airflow testing of the distribution ductwork with supply outlets in every space (System 1) are shown in Table 6. Measured flow rates in heating generally were lower than the specified flow rates in heating, with the exception of Bathroom 2. In cooling mode, measured flow rates were within 12% of design values, again with the exception of Bathroom 2. Total system flow was 421 CFM in cooling at a normal system operating pressure of 17.9. The design airflow was 500 CFM.

Airflow testing also was performed for System 2, where distribution ductwork supplies conditioned air to only the bedrooms and the main living space. Those results are shown in Table 7. Measured flow rates in heating generally were lower than the specified flow rates, with the percent difference ranging from –25% to –45%. In cooling mode, measured flow rates were within –13% to 20% of design values.

Table 6. System 1—Design and Measured Room Airflows

Room	Heating		Cooling	
	Specified CFM	Measured CFM	Specified CFM	Measured CFM
Family, Dining, Kitchen, Laundry Area	265	195	265	295
Master Bedroom and Walk-In Closet	79	51	79	74
Master Bath	16	16	16	24
Bedroom 2	74	51	74	74
Bedroom 3	54	34	54	48
Bath 2	13	23	13	35

Table 7. System 2—Design and Measured Room Airflows

Room	Heating		Cooling	
	Specified CFM	Measured CFM	Specified CFM	Measured CFM
Family, Dining, Kitchen, Laundry Area	265	216	265	320
Master Bedroom and Walk-In Closet	95	54	95	82
Master Bath	–	–	–	–
Bedroom 2	80	61	80	89
Bedroom 3	60	39	60	61
Bath 2	–	–	–	–

Total system airflow was measured using the flow plate. The total system flow was 421 CFM in cooling at a normal system operating pressure of 17.9. The design airflow in cooling was 500 CFM.

4.3.3 Discussion

Exact correlation between the design and measured supply airflow rates was not expected; however, the significant differences encountered were somewhat surprising. The differences are a result, in part, of the AHU operating at a lower airflow rate during heating mode than in cooling mode. They also were due to the lack of use of manual balancing dampers in the ductwork. Using balancing dampers, instead of relying on duct sizing to accomplish proper airflow, may have prevented the difference between the calculated and measured flow rates. The differences between design and measured airflows will be accounted for in future analysis of this test house.

4.4 Whole-House Air Leakage

4.4.1 Methods

The air leakage rate of the house was measured using a Minneapolis Blower Door Model 3 (Energy Conservatory 2012a).

4.4.2 Results

Results of the whole-house air leakage testing prior to retrofit were 7.66 ACH50 (1660 CFM50); after retrofit, the results were 1.59 ACH50 (345 CFM50). Leakage points were noted at the location where the refrigerant lines passed through the ceiling plane on their way to the AHU located in the living room.

4.4.3 Discussion

It is notable that, via fairly simple retrofit measures, the house was able to attain a dramatic decrease in air leakage. The construction of this house—slab on grade with stucco finish—is inherently conducive to low air leakage rates because the stucco provides a continuous air barrier on the exterior of the house that ties in readily with the slab foundation, which has few air leakage points. The remainder of the enclosure can be air sealed from above through the attic. The key to this approach is that the air sealing measures are performed when another maintenance issue is being addressed, such as when the roof is being replaced, removing the lower portion of the roof sheathing to seal the top plate of the exterior wall, which is typically a hard-to-reach area from within the attic. Another example is installing new windows at the same time the exterior stucco is being repaired due to age.

4.5 Testing of Operation of Data Logger-Controlled Output Devices

4.5.1 Methods

The research team also tested the operation of the output devices controlled by the data logger. The devices were simulated occupancy heaters, ductwork dampers, door actuators (Figure 10), and door flaps.

Testing included the following:

- Manual operation by direct connection to a power source
- Manual actuation of relay
- Actuation of relay by toggling a manual switch on the Campbell Scientific SDM-CD16 output control device (Campbell Scientific 2012)
- User-controlled remote actuation via computer (by manual entry of “1” or “0” in a text-view window in LoggerNet software) (LoggerNet 2012).

4.5.2 Results

The research team also tested the operation of the output devices controlled by the data logger. Testing included the following:

- Manual operation by direct connection to a power source showed the simulated occupancy heaters, ductwork dampers, and door actuators operated correctly. Door flaps (for covering the bottom-of-door transfer grilles) did not function correctly because the 12-V power supply provided insufficient current to operate the actuators together as planned. Upon further testing, the research team determined that these flaps would be abandoned until a lower power actuator could be specified. One has since been sourced and was installed; the details will be included in a future report.

- Manual actuation of relay facilitated the operation of the simulated occupancy heaters, ductwork dampers, and door actuators with no issue.
- Actuation of relay by toggling a manual switch on the SDM-CD16 output control device (Campbell Scientific 2012) facilitated the operation of the simulated occupancy heaters, ductwork dampers, and door actuators with no issue.
- Actuation by manual entry of “1” or “0” in a text-view window in LoggerNet software (LoggerNet 2012) initially did not enable the operation of any devices because the value would be reset with every program scan. Creating a manual mode in the program enabled this manual entry to operate the simulated occupancy heaters, ductwork dampers, and door actuators with no issue.

4.5.3 Discussion

The results of testing the data logger-controlled output devices reveal the need to perform bench testing prior to implementation in the field. Had this been performed for the door flaps, a significant amount of field time could have been saved. Bench testing is now being implemented whenever outputs are required from the data logger to increase the chance of successful operation in the field.

5 Conclusions

Historical research has shown that substantial amounts of energy can be transferred through open doors in houses. To determine if high and low transfer grilles could provide sufficient heat transfer to maintain temperatures in the bedrooms of a house, a CFD model was created. In conjunction with this model, an unoccupied test house was designed and retrofitted as a low-load house with peak heating and cooling loads of less than 2 tons and energy savings of 50% according to BEopt modeling. Three distribution strategies were installed in the house and successfully controlled using the data logger. Limited short-term testing was completed, verifying a very low air infiltration rate of 1.59 ACH50 (345 CFM50) and a minimal to significant difference between the modeled and measured airflow rates of the ducted distribution system. Instrumentation commissioned for long-term testing showed that all temperature measurements were operating within tolerances and revealed an issue with the ice bath test method with respect to accidental electrical grounding of the thermocouple junction when the wire shielding also was in contact with the ice bath.

The next steps are to perform testing to validate the CFD model for room-to-room air transfer via high and low transfer grilles, with the eventual goal of using that model to determine the expected airflow volume through the transfer grilles under various conditions.

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