U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Comfort in High-Performance Homes in a Hot-Humid Climate

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IBACOS, Inc.

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Office of Energy Efficiency and Renewable Energy

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

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

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

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Unless otherwise noted, all tables were created by IBACOS.

Definitions

ACCA	Air Conditioning Contractors of America
CLO	Clothing (insulation)
HVAC	Heating, Ventilating, and Air Conditioning
MET	Metabolic (rate)
IRB	Institutional Review Board

Acknowledgments

The authors acknowledge Armin Rudd of ABT Systems, LLC for his technical guidance in planning and executing the study.

Executive Summary

Although space-conditioning systems are required to meet standards such as those in the Air Conditioning Contractors of America (ACCA) Manual RS (Rutkowski 1997) and the ASHRAE Standard 55 (ASHRAE 2013) comfort criteria, little is known about how space-conditioning systems are actually operating in the field and if these systems are meeting those standards. Unconventional space-conditioning systems may be necessary for low-load homes in the future. It is important to know how current systems are functioning in existing homes and to what temperatures occupants typically set the thermostats in their homes.

The U.S. Department of Energy's Building America research team IBACOS set out to find some answers. By using low-cost data loggers and occupant surveys to monitor 37 single-family homes that have standard heating, ventilating, and air-conditioning (HVAC) equipment, the team gained insight into how sensitive occupants are to comfort in their homes relative to the ACCA and ASHRAE standards. This study focused on one climate zone (hot-humid); however, future studies may find differences among occupants' ideas of thermal comfort in other climate zones. Data were collected from installed sensors during a 2-month period from late August 2014 through late October 2014. The final aspect of this project was to review the business metrics associated with builders involved in a comfort and performance guarantee program.

The results of this study—taken as an aggregate—show that the homes provided room-to-room temperature differences less than 6°F 95% of the time. Temperature differences were less than 4°F 80% of the time. Some homes showed better or worse performance. On average, two-story homes had a 3.3°F temperature difference between rooms; single-story homes had an average of a 2.2°F temperature difference between rooms. Occupants who did not use programmable thermostats had an average set point of 75°F. Homes in which the thermostats were programmed with a setback schedule showed a median baseline temperature value of 74°F and had a median afternoon setback of 75°F.

System runtime was analyzed and showed that the room-to-room temperature uniformity in some homes worsened during an on cycle, whereas the uniformity improved in other homes. That is, when the system was running, some rooms were receiving too much or too little air relative to the rest of the house, and the temperatures in those rooms were moving away from the temperatures of the other rooms in the house.

Finally, analysis of the thermostat data shows a wide degree of variability among homes in the study. Interpretation of the measured data suggests that 21 occupants made no regular adjustments to the thermostats in their homes, seven had regular setbacks, seven showed varying setbacks, and 10 appeared to follow no pattern (with random adjustments).

Ultimately, the data show that current systems are maintaining expected levels of comfort. As expected, it is more challenging to maintain a uniform temperature in all rooms of two-story homes, and future systems should address this issue. Furthermore, the data show that the majority of homes maintained relative humidity levels below 60% without any supplemental dehumidification.

1 Introduction and Background

Questionnaires conducted over the last few years by the Best Practices Research Alliance[1] reveal that providing satisfactory comfort in new homes is one of the top priorities of production homebuilders. Providing comfort in low-load homes is a challenge that is well documented by U.S. Department of Energy Building America research teams such as IBACOS. Previous research has identified three main systematic challenges that production builders must overcome to provide consistent comfort: (1) floor-to-floor stratification, (2) isolated hot or cold rooms, and (3) humidity control.

The issues around floor-to-floor stratification have been documented in numerous reports. Ueno and Loomis (2014) found that in new-construction high-performance test houses (in International Energy Conservation Code climate zone 5) that are heated and cooled with mini-split heat pumps, at least one ductless head unit was needed per floor to provide adequate comfort. In research conducted by Herk et al. (2015), new-construction two-story homes in Denver, Colorado, showed some degree of floor-to-floor stratification. These homes had high-performance enclosures but used traditional heating and cooling air-delivery systems, which suggests a need for alternative space-conditioning systems. Rittelmann (2008) conducted a study of head-to-toe and floor-to-floor stratification. He found that floor-to-floor stratification could be kept within 4°F under most external conditions in a high-performance test house with a well-designed air-delivery system.

Temperature excursions beyond the recommended guidelines of Air Conditioning Contractors of America (ACCA) Manual RS (Rutkowski 1997) in specific rooms can be caused by a number of factors. These factors include: system problems from insufficient airflow resulting from poor duct design or balancing, enclosure, and other design issues; significant solar heat gains relative to the rest of the house; greater surface area associated with rooms that are isolated from the remainder of the house or adjacent to semiconditioned spaces such as garages; and occupant issues such as significant internal gains caused by occupant-installed equipment.

Humidity control is a growing concern in hot-humid climates as improved building enclosures reduce the sensible cooling demand and duration. This problem was well documented by Rudd (2014). As the duration of central system runtime is reduced, interior humidity can exceed 60% relative humidity, which leads to concerns about comfort, health, and building durability. Alternative strategies for latent load control are needed—such as stand-alone or central dehumidification systems. However, these systems can add to costs and can increase energy consumption. Rightsizing central cooling equipment can reduce humidity levels, does not add to system cost, and reduces energy consumption; however, systems with low thermal capacity may not be available from manufacturers. Furthermore, heating, ventilating, and air-conditioning (HVAC) contractors often are reluctant to rightsize equipment because of industry stigma and the perception that peak loads will not be met.

[1] Best Practices Research Alliance. www.theresearchalliance.org/.

1.1 Large-Scale Thermal Comfort Research

Most research about thermal comfort focuses on commercial buildings and controlled laboratory experiments. Some large-scale studies of residential dwellings have been conducted; however, many such studies were conducted in multifamily dwellings or among a sample with inconsistent building stock (Arena et al. 2010). Few studies have looked at the indoor environment of new high-performance single-family residences in a specific climate zone. This study will help to fill the knowledge gap by providing data about how these new single-family residences are performing.

1.2 Comfort Metrics

Research about the concept of thermal comfort has been conducted for many generations. Several important milestones have been discussed by de Dear et al. (2013). Perhaps the most significant models to gain wide acceptance are the Predicted Mean Vote Index[2] and the Predicted Percentage Dissatisfied Index[3] as defined by Fanger (1970). Adaptive thermal comfort concepts best characterize Predicted Mean Vote and Predicted Percentage Dissatisfied. ASHRAE Standard 55 (ASHRAE 2013) has adopted these factors and today is one of the *de facto* standards for thermal comfort.

ASHRAE Standard 55 (ASHRAE 2013) specifies six primary factors that impact the thermal comfort of an occupant:

1. Metabolic (MET) rate
2. Clothing (CLO) insulation
3. Air temperature
4. Radiant temperature
5. Air speed
6. Humidity.

To fully define comfort, the values of all these factors must be known. Although all these factors can be controlled in a laboratory setting, measuring and controlling each factor for a long-term study in occupied homes is not feasible. Therefore, some assumptions had to be made.

The two simplest factors to measure are air temperature and humidity. The other environment-specific factors include radiant temperature and air speed. Air speed measurements must be specific and localized to be accurate and are difficult to gather in an occupied test house. Radiant temperature asymmetry can have a significant impact on an occupant's perceived comfort. Accurately measuring the mean radiant temperature requires a specialized device that mimics the direction human surfaces face. This device must be positioned exactly where the occupant is located. For this study, such an installation was impossible. Furthermore, asymmetric radiant effects due to wall temperature in a highly insulated house are less significant in the cooling season.

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[2] The Predicted Mean Vote Index predicts the mean response of a larger group of people according to an ASHRAE thermal sensation scale.
[3] The Predicted Percentage Dissatisfied Index is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment.

The nature of the project involved human subjects who were under scrutiny; therefore, approval from the Institutional Review Board (IRB) first was necessary before the project could begin. IBACOS submitted pertinent information about the project to the IRB, and ultimately an IRB committee decided that the project was not classified as Human Subject Research.

For this project, occupants in their own houses were assumed to have greater control over MET rate and CLO insulation than they would in a typical office environment. Generally speaking, occupants wear a comfortable ensemble in their own houses. An occupant can balance comfort and energy efficiency by modifying clothing choice and indoor set point. For the analysis in this report, the team assumed the occupants had a CLO value of 0.5, which is typical for someone in casual attire. Although the MET rate of an occupant may increase for periods (e.g., exercising in a home gym or carrying a heavy load of groceries), these periods are usually brief and should not have a major impact on the analysis.

Investigation of comfort can go from the smallest granularity (i.e., finite element models that simulate every component of the human experience) to the simplest question: Does a builder or contractor receive a comfort complaint from the homeowner? The results of this study land somewhere in the middle of those two extremes.

An ideal study to identify the situations in which a homebuilder is at risk for comfort complaints would involve installing sensors in hundreds of homes—unknown to the occupants—and then carefully tracking the instances of comfort callbacks. A model then could be created that would estimate the probability of a comfort callback based on measured thermal metrics. Figure 1 illustrates the concept of this type of model in hypothetical numbers. The greater the average room-to-thermostat deviation, the greater the likelihood a homeowner will request a comfort callback. At some temperature difference, nearly every homeowner will feel uncomfortable and will make a comfort callback. An HVAC designer and homebuilder then could decide on the acceptable callback level and could design a system to meet such thermal requirements.

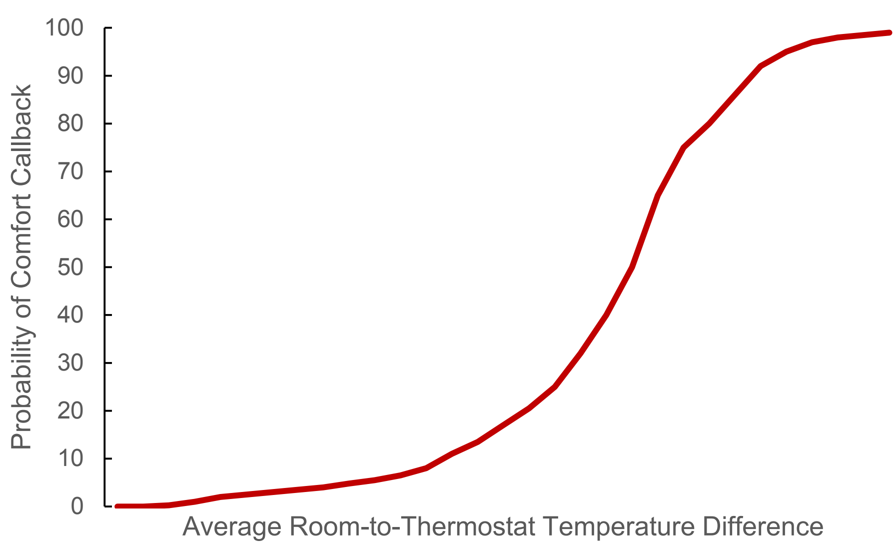

Figure 1. Hypothetical probability of callback function

Unfortunately, a complete ideal data set that is necessary to create a callback probability model is not available. However, for this report the room-to-room and room-to-thermostat variabilities were measured in 37 homes. Thus, assuming that the homeowners are comfortable in their homes and that they live in homes with a comfort guarantee (i.e., if they are uncomfortable they will make a callback), then some idea of acceptable comfort limits can be discussed. The comfort guarantee is critical in making the assumption that occupants are comfortable.

U.S. Department of Energy Building America teams have identified the thermostat set point as the most sensitive factor in residential energy modeling (Metzger and Norton 2014). An additional benefit of the current study is that the data that were collected can be used in future studies by combining them with data from many climate zones to analyze the indoor temperature set point across the United States. This report will discuss system runtime as a variable that strongly influences total energy consumption; however, the report will not provide a detailed analysis of HVAC energy consumption.

1.3 Research Questions

This work attempts to understand the current state of comfort in modern high-performance production homes that are located in hot-humid climates. Specifically, the variability of comfort was analyzed; the goal was to understand general trends across many homes. Another goal of this research was to further identify what conditions might be causing comfort-related risks for builders. By monitoring homes that have a comfort guarantee, researchers can assume occupants are comfortable in their houses if those occupants have not made callbacks—thus removing a critical amount of uncertainty. A byproduct of this report will be an analysis of system runtime, which can be used to understand the sizing of each system relative to the actual load on each home.

This project addresses the following research questions:

1. How much do temperatures and relative humidity vary from room to room in houses constructed in the last 7 years to meet comfort guarantee program requirements—assuming the occupants consider their homes to be comfortable?
2. How do occupants use their space-conditioning equipment controls for scheduled setbacks and nonscheduled adjustments?
3. How do builders feel that participating in a comfort and performance guarantee program has impacted their business? What business metrics are associated with their involvement in terms of cost, marketing, and performance?

2 Mathematical and Modeling Methods

2.1 Data Analysis Methods

Upon the completion of measurement, data from each Onset HOBO logger[4] were downloaded and were stored as a comma-separated file for each logger, using the logger serial number as the file name. Two key files then were created: one that contained the house and room associated with each serial number, and another containing the house survey results from each home. Given this input data structure, the team used the scripting language Python[5] for easy data analysis and plot and table output. This framework allowed the team to continuously update input parameters as needed and to rapidly modify the nature of each phase of analysis. The team also used the data package pandas[6] to store and manipulate values and then used matplotlib[7] to create high-quality raster graphics.

Because of inconsistencies with the exact timestamp for the HOBO data, all room air temperature measurements were resampled from their 10-min intervals to 1-min intervals. All calculations presented in this report use the resampled 1-min data.

2.2 System Runtime Determination

To minimize the time and expense associated with each monitoring installation, the team decided to measure the supply air temperature as a surrogate for system runtime. Installing electric sensors on an HVAC system is time consuming, and electric sensors are more expensive than simple temperature and humidity data loggers. Onset HOBO UX-100-M sensors were installed on a supply register near the central air handling unit of each home in the study, such that airflow was directed across the sensor element.

The research team then used Python to analyze the data collected from each supply register. Through the trial of several algorithms, the team decided on the following method to determine HVAC system runtime.

The average temperature change over the next 5 min was calculated for each time step, such that single-minute fluctuations would not affect the analysis. Local maxima and minima were identified, which correspond to the largest changes in the signal slope. Each local maxima was then considered an on cycle if the average temperature change over the next 5 min also was greater than a threshold. Because of variations in sensor signal, the threshold was determined for each house using the standard deviation. Calculating runtime in this fashion filtered high-frequency noise but kept the start and end points of each cycle as close to the actual values as possible.

This method is illustrated in Figure 2; the sensor signal is plotted in blue and the forward rolling average of the signal's slope is shown in green. (This number has been offset by +50 to show on the graph.) The local maximum and minimum of the rolling average then are identified, and if these values are higher or lower than the shown thresholds, an on or off cycle is flagged. Each

[4] Onset HOBO UX100 loggers. Onset Computer Corporation, Bourne, MA. www.onsetcomp.com/.
[5] Python scripting language. Python Software Foundation. www.python.org/.
[6] pandas data package. http://pandas.pydata.org/.
[7] matplotlib. http://matplotlib.org/.

identified on cycle is shown in gray. The calculation of the rolling average can be expressed by the following function:

$$f(x) = \frac{1}{n}\sum_{t=0}^{n} x_t - x_{t-1}$$

where

n = time periods to average over (a 5-min interval was used)

x_t = sensor reading at time t

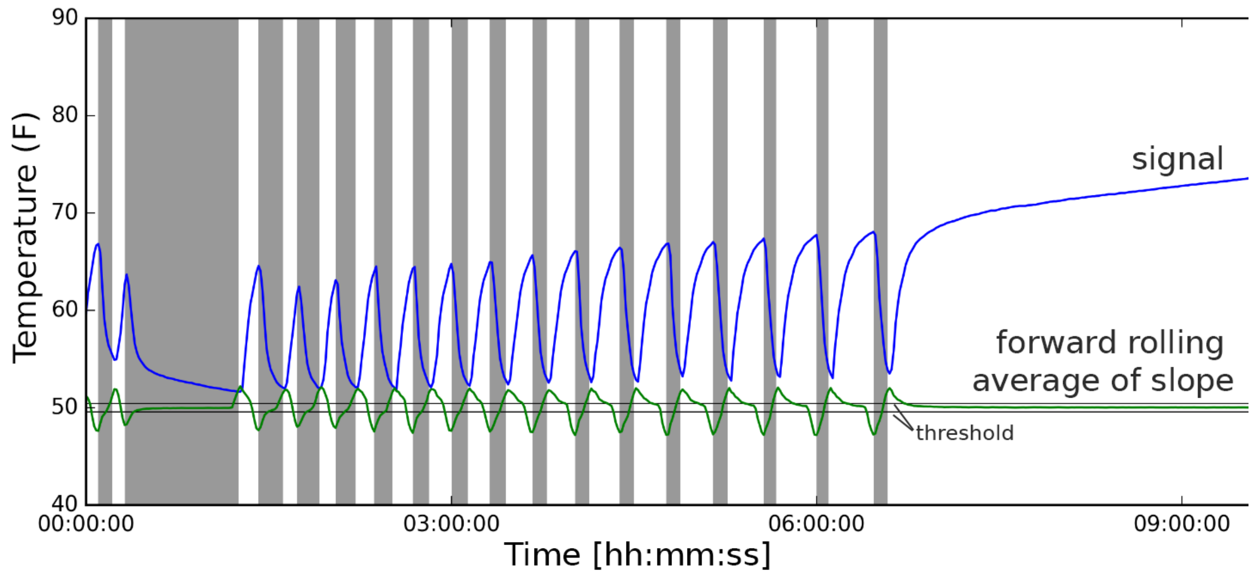

Figure 2. Illustration of the system runtime calculation method

2.3 Uncertainty Analysis

According to ACCA Manual RS, the room-to-thermostat temperature variation in occupied space may not exceed 2°F during the heating season and 3°F during the cooling season (Rutkowski 1997). Additionally, the room-to-room temperature difference should be less than 4°F (2°F average) in the heating season and less than 6°F (4°F average) in the cooling season.

The team performed a propagation of error analysis to determine the likelihood of drawing an incorrect conclusion about whether a room passed the ACCA standard because of sensor error. This analysis was highly dependent on the room-to-thermostat temperature difference distribution, in that the closer and more frequent a measurement was to the ±2°F threshold, the greater the likelihood of drawing an incorrect conclusion. To perform the error analysis, the team employed a Monte Carlo method for determining the likelihood of drawing an incorrect conclusion. For this method, IBACOS made the following assumptions:

- Sensor error is random and normally distributed, with listed inaccuracies indicating the 95% interval (two standard deviations).
- Measurement uncertainty is independent between sensors.
- Room air temperature to thermostat temperature is normally distributed, with the room air temperature centered at the thermostat temperature.

An analysis of previously measured data from a new-construction unoccupied test house in Pittsburgh, Pennsylvania, has indicated that the typical room-to-thermostat temperature difference followed a normal distribution, with standard deviations ranging from 1.7 to 2.4°F.

Using R software,[8] the team took 100,000 normally distributed samples of possible sensor measurements and errors and then calculated the average failure rate in correctly determining the pass rate of a room according to the ACCA Manual RS standard (Rutkowski 1997). Figure 3 indicates these probabilities for the HOBO sensor chosen with an error of 0.38°F. Based on Figure 3, the team concluded that there is close to a 95% confidence in correctly determining failure rates with the HOBO data logger. To create this figure, the team ran the simulation for a number of discrete values for room-to-thermostat standard deviation and created a curve based on these results.

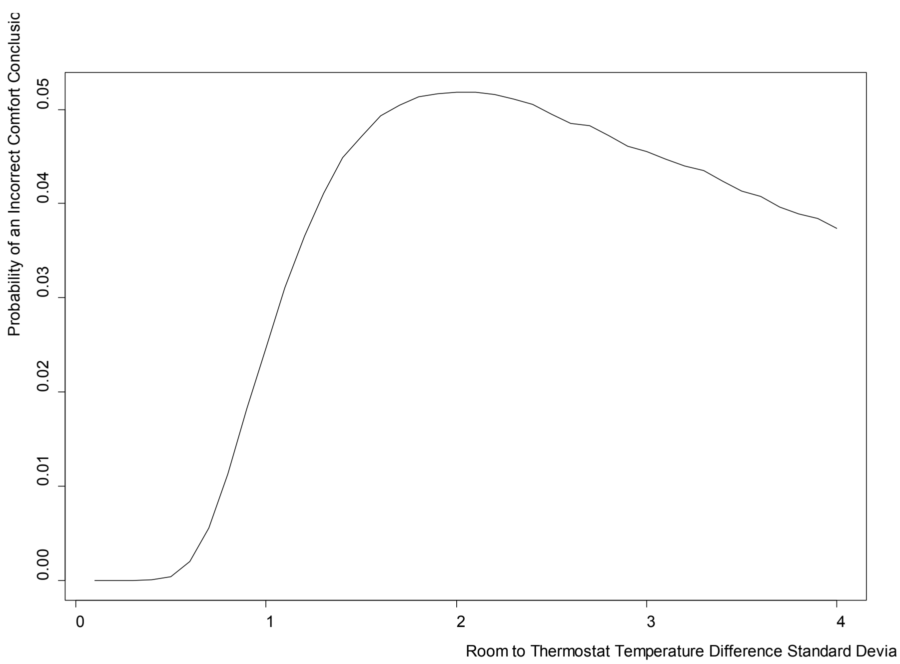

Figure 3. Probability of drawing an incorrect conclusion in the ACCA analysis for sensors with an error of 0.38°F

[8] R software. The R Foundation. www.r-project.org/.

3 Research and Experimental Methods

3.1 Home Identification and Selection

Initially, the project team planned to exclusively identify homes for this study through builder participation in the Environments For Living program. Environments For Living is a high-performance home program that, among other things, offers a home comfort and performance guarantee to homeowners. Difficulties in finding a sufficient number of volunteers meant the team broadened the search criteria to other acceptable high-performance homebuilders in the southeastern region of the United States. Homebuilders requested volunteers through several methods, including direct requests to employees living in builder homes, mass emails, and posting to community social media pages. The majority of homes were built within 2 years of the study period (one home was 7 years old). Table 1 contains a summary of the homes in the study. In total, 37 homes were monitored from three production homebuilders. The thermostat measurement device from one of the homes fell from the wall; therefore, data from only 36 homes were reported.

Table 1. Home Location Summary

State	City	Number of Homes	Number of Builders
Texas	San Antonio	11	2
Texas	Houston	7	1
Florida	Tampa	10	1
Florida	Orlando	9	1

IBACOS also solicited input from several homebuilders that were constructing high-performance homes that included comfort guarantees. Once the homebuilders were identified, questions were emailed directly to the homebuilder contacts. IBACOS then compiled the responses.

The Appendix contains a detailed list of the specifications of each home in the study as well as homeowner questionnaire results.

3.2 Sensor Selection

Low-cost, easy-to-use temperature and relative humidity data loggers were required for this project. IBACOS conducted a search for possible options. Based on price, accuracy, battery life, logging rate, data recovery, risk, and appearance, sensors from several manufacturers were rated. The team decided that sensors with Internet connectivity and the ability to send real-time data to the researchers were too expensive with uncertain logistics and may not significantly reduce the risk of losing data.

After evaluating the choices, IBACOS determined that the Onset HOBO UX100 would be the most appropriate data logger to use for this project, because it offers a reliable and cost-effective solution and provides highly accurate data. Metzger and Norton (2014) also recommend using the UX100-011 HOBO data logger at 1-h intervals. The preferred log interval for this study was 1 min to best characterize the maximum and minimum temperatures in each 15-min interval and to characterize system runtime. Because the capacity of the UX100-011 was limited to

84,000 measurements, that data logger would not allow for 1 year of data to be collected without replacing the logger during that time.

To provide a balance of cost, availability, and accuracy, the team decided to use a combination of three types of HOBO loggers. The HOBO U10-003 loggers collected temperature and humidity measurements from the perimeter rooms in each house at 10-min intervals. High-capacity HOBO UX-100-M loggers (346,795-measurement capacity) collected the temperature and humidity data at the supply register and thermostat of each house at 1-min intervals. The high-capacity HOBO UX-100-M loggers were supplemented with 20 HOBO UX100-011 loggers because of availability. IBACOS owned the HOBO UX100-011 loggers; all other loggers were rented for the project. Table 2 gives details about the sensors chosen for this project.

Table 2. Sensor Measurement Capacity and Accuracy

	Sample Capacity	Temperature Accuracy	Humidity Accuracy	Number
UX100-011	84,650	±0.38°F	±2.5%	20
UX100-M	346,795	±0.38°F	±3.5%	80
U10-003	52,000	±0.95°F	±3.5%	300

3.3 Sensor Installation and Survey Data Collection

IBACOS initially intended to find local contractors to install the monitoring equipment in test houses. Because of the close geographic location of groups of test houses and the shortened timeline due to slow partner involvement, IBACOS installed the equipment and collected survey data directly from the homeowners.

Sensors were installed with removable adhesive mounting strips in the subject houses at locations that were acceptable to the homeowners. These locations were 24–48 in. above the floor and closely followed the recommendations in Metzger and Norton (2014). Wall-mounted sensors were placed in each living space, away from the direct flow of HVAC equipment, and on interior walls. Each runtime logger was installed on the external face of a supply register close to the central air handling unit. Airflow direction was optimized across the sensor probe. Figure 4 shows an example of a logger placed on a supply register. Finally, a logger was mounted directly next to the thermostat.

Figure 4. A logger placed on a supply register

4 Results and Discussion

4.1 Summary of Data

As a starting point for this analysis, the team plotted all measured temperature data in a heat map (Figure 5). This figure shows the period of data collection by each sensor. Blacked-out regions on the left and right of the graph show sensor installation and removal times. Each measured data point is represented as a cell on the map; sensors are organized by house on the y axis and by time on the x axis. Individual sensors are not labeled; however, they are sorted such that the supply temperatures and then the thermostat temperatures are at the top of each home's strip. The color of each cell represents the temperature measured by the sensor. From this graphic, diurnal trends become apparent. Some homes have an obvious setback; others show an almost constant temperature for the duration of the study. Several vacation periods also are apparent, during which the indoor temperature rose for a period of several days. Supply temperature measurements appear at the top of each house as a dark purple band.

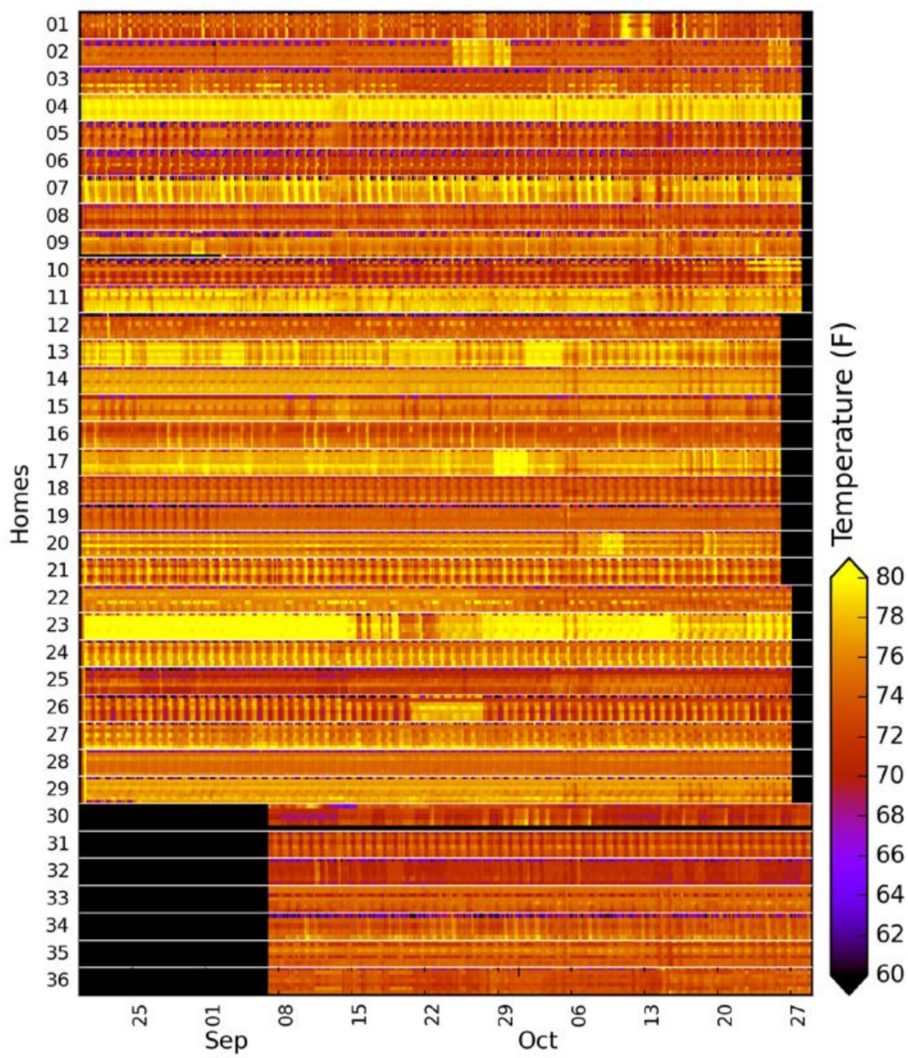

Figure 5. Heat map showing the period of data collection for each sensor

The team plotted humidity measurements in a similar fashion (Figure 6). Relative humidity values higher than 60% are shown in magenta. Supply temperature measurements again are shown as the first horizontal line for each house. Only two houses (House 02 and House 36) show humidity levels that are consistently higher than 60%. Other homes show brief periods of elevated humidity. According to industry standards such as ASHRAE Standard 55 (ASHRAE 2013), humidity levels should remain lower than 60% to provide conditions for a comfortable and healthy environment. Industry experts agree that the 60% humidity level presents a risk for comfort and health-related problems (Rudd 2014). The cause of these two houses having consistently elevated humidity is unknown; the houses were built and are occupied similarly to the other houses in the study. As listed in the Appendix, House 02 had a gas stove, whereas House 01, House 03, and House 04 had electric stoves. The excess moisture generated from combustion may have impacted the humidity levels.

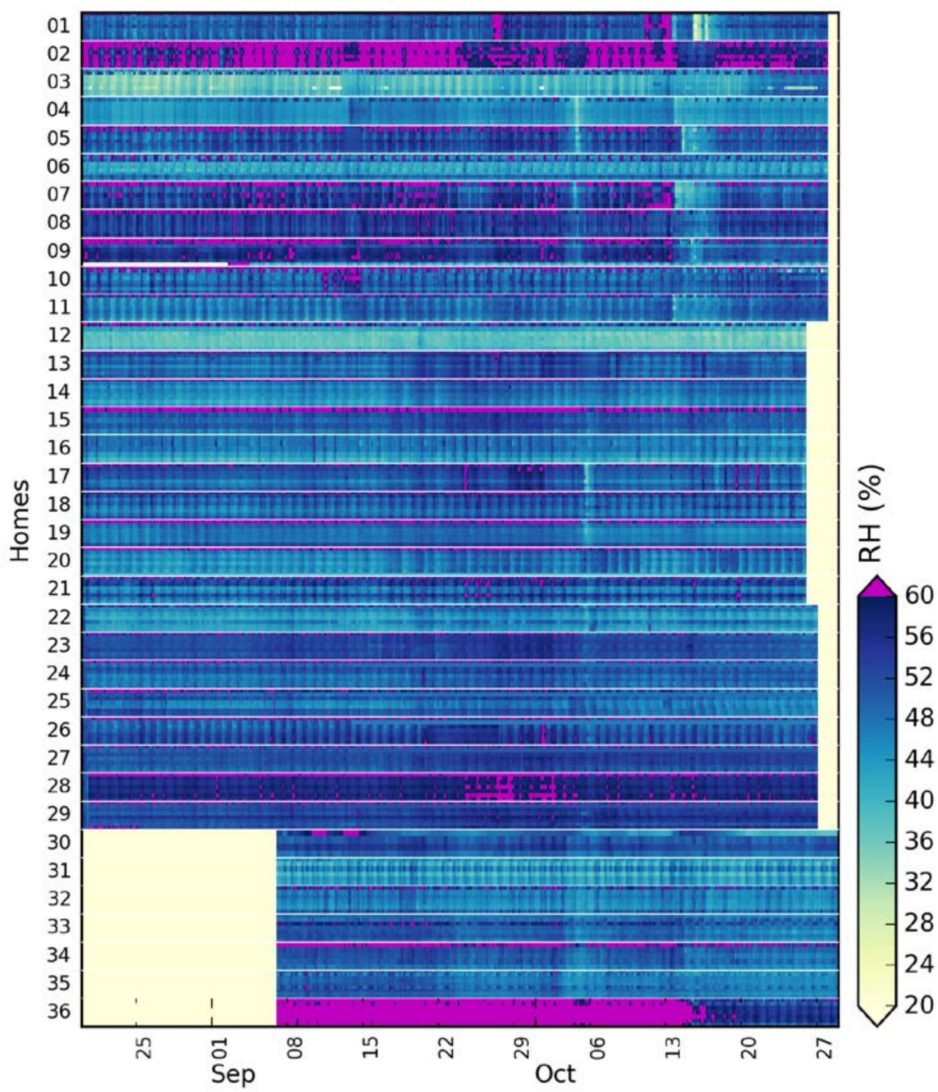

Figure 6. Heat map showing humidity measurements for each sensor

To understand the average room-to-room temperature variability among all houses, the team created a cumulative summation plot (Figure 7). For this plot, the maximum room-to-room temperature difference was calculated at each time step for each house. (All data were resampled to 1-min intervals.) Using 6°F as the maximum allowable temperature difference, it is apparent that more than 95% of the data are lower than this threshold, meaning that for 95% of the time, the room-to-room temperature variability in all homes was within an acceptable limit. Furthermore, the room-to-room temperature variability is less than 4°F for 80% of the time.

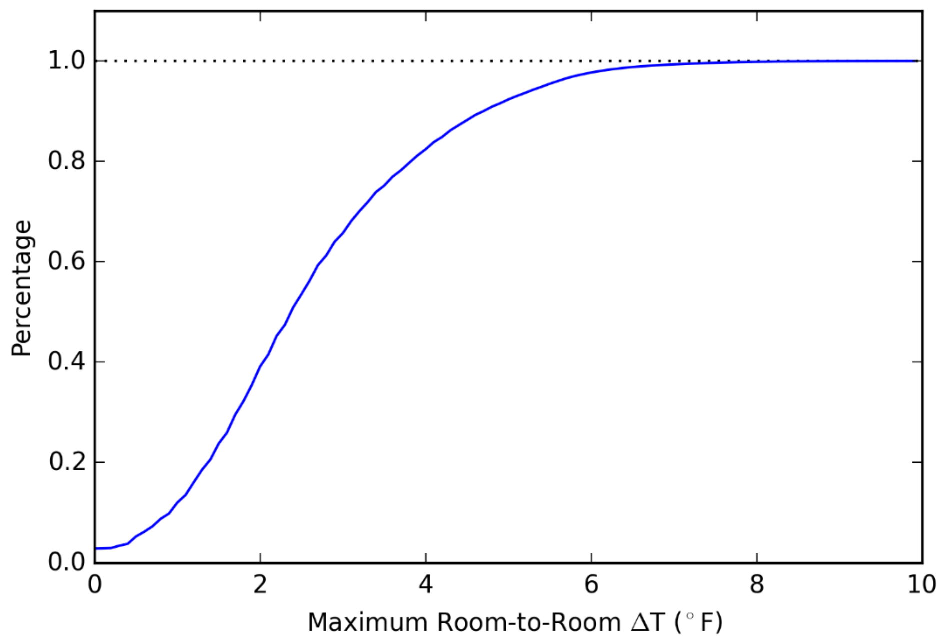

Figure 7. Cumulative summation of room-to-room temperature differences for all homes based on 1-min data

To further break out the data, the cumulative summation has been subset by hour of the day (Figure 8). The early morning hours (6–10 a.m.) show the best room-to-room uniformity, whereas the evening hours (4–6 p.m.) show the worst uniformity. This may be explained by several factors. The morning hours typically are associated with the lowest outdoor temperature and the lowest cooling demand on the house. Outdoor temperatures typically are still elevated in the evening hours, and at this time, solar heat gains can be at their worst because of lower sun angles. The evening also is associated with many occupants returning home and setting the thermostats in their homes to a lower temperature after a setback. As shown in later figures, system runtime may increase room-to-room temperature variations in some houses.

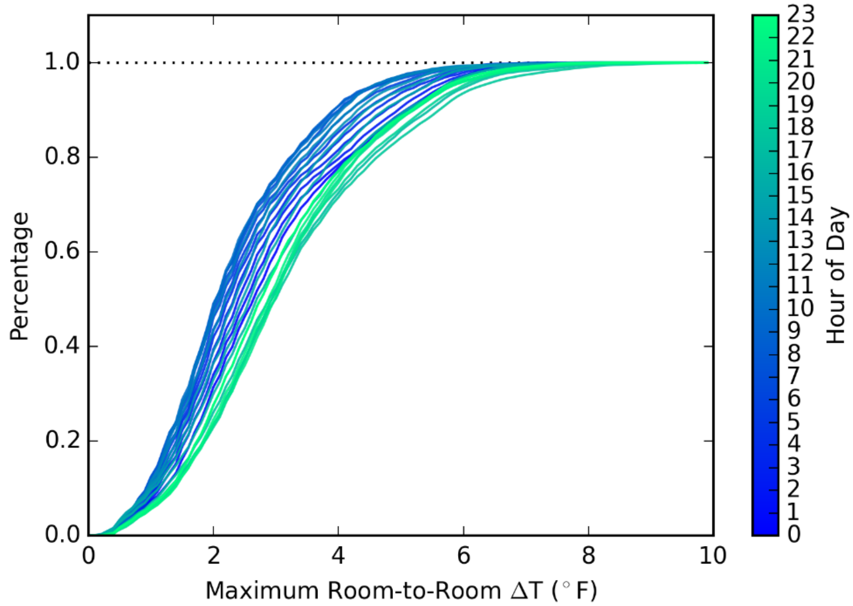

Figure 8. Cumulative summation of room-to-room temperature variability by hour of the day

4.2 Indoor Temperature Variability with Time

To better understand the room-to-room temperature variability and its potential causes, the team created a number of colored line plots (Figure 9 through Figure 13). In each figure, the average daily room-to-room temperature variability[9] is plotted against time for each house. To help understand trends in uniformity, the color of each line is based on one of several parameters.

According to ACCA Manual RS (Rutkowski 1997), each room of the house should be within 6°F of every other room during the cooling season. Based on daily averages, all except one house in the study maintained this level of uniformity. This single house showed a period of elevated temperature difference between September 18, 2014, and September 30, 2014, which likely was the result of a vacation setback.

As a starting point, Figure 9 represents with a different color the city in which each house was located. This figure shows no apparent trend based on city.

[9] The average daily room-to-room temperature variability was calculated as follows: For each time step, the temperature of the coolest room was subtracted from the temperature of the warmest room. This calculation always yields a positive number because all sensors never read the exact same number. These values then were averaged for the entire day.

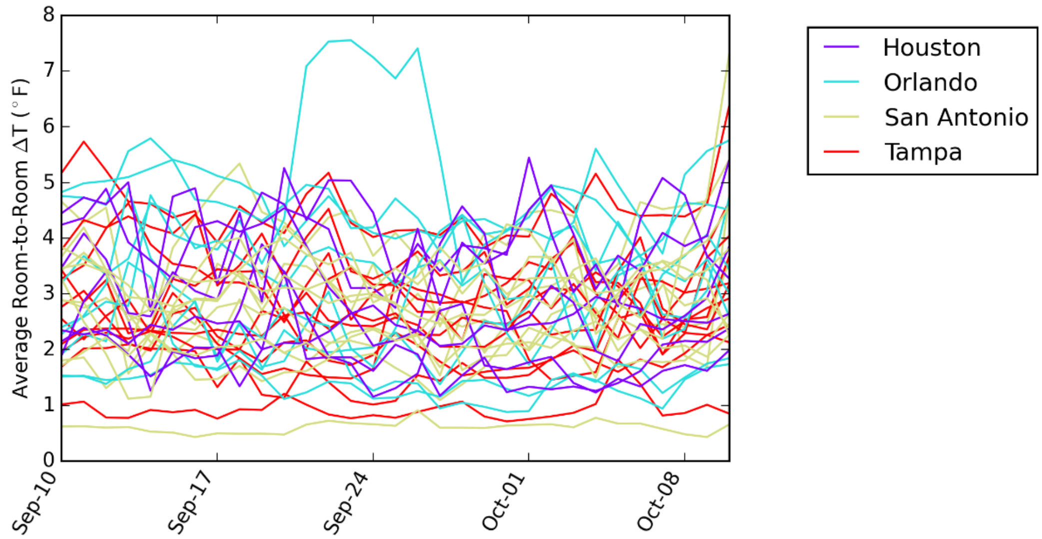

Figure 9. Average daily room-to-room temperature variability by city

The team found that the strongest trend in determining uniformity was based on the number of stories of construction. As expected, single-story homes provided a more uniform temperature (Figure 10). This trend was caused by thermal stratification between floors. Based on the data in Figure 10, the average temperature difference between rooms for the two-story houses was 3.3°F, whereas the average temperature difference between rooms for single-story houses was 2.2°F.

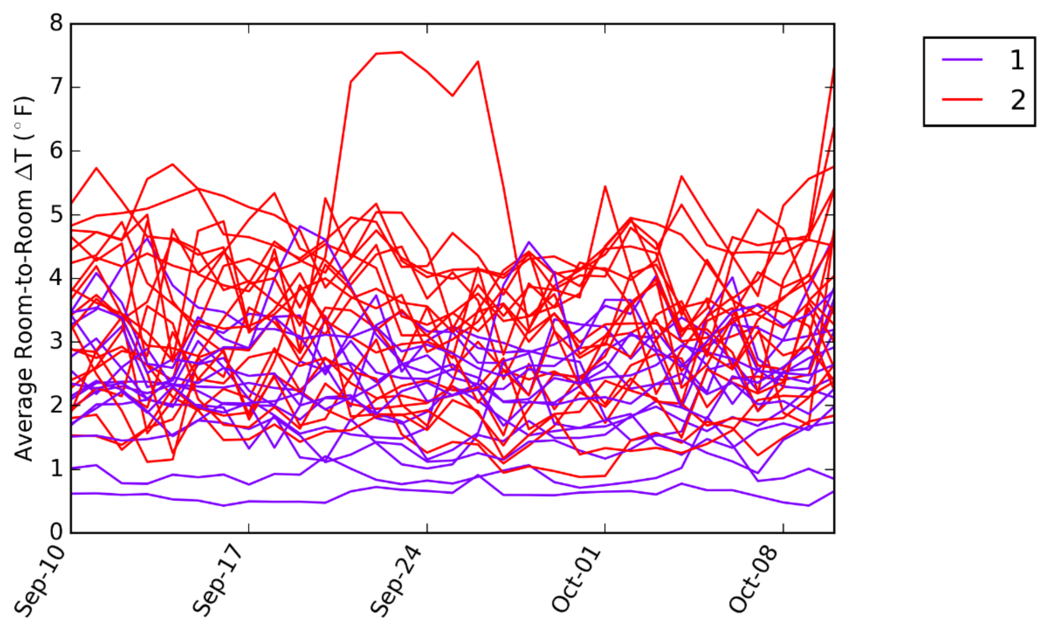

Figure 10. Average daily room-to-room temperature variability by number of stories

Occupant behavior can have a significant influence on temperature variations. One measure of occupant behavior—job status—was collected as part of the study. Data in Figure 11 show that retired homeowners generally had more uniform temperatures within their homes, which may be the result of their preference for single-story homes and a constant thermostat set point. On the other hand, occupants with full-time job schedules, and thus the greatest opportunity for a thermostat setback, tended to show the most variability.

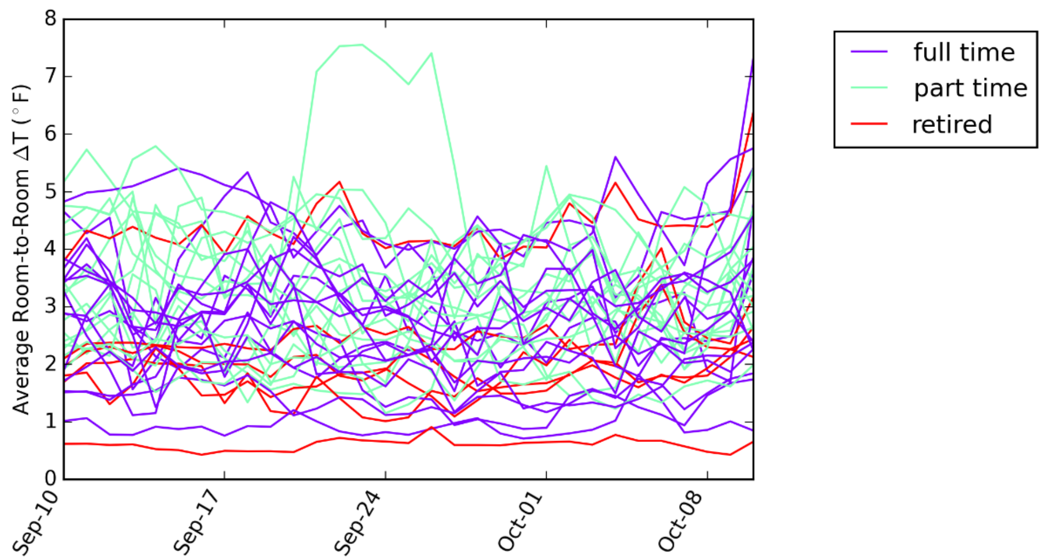

Figure 11. Average daily room-to-room temperature variability by occupant employment

The number of thermostats, or the number of thermal zones, also can have a significant impact on comfort in a house. Having more thermostats can allow occupants to have more uniform comfort in their house or to selectively condition spaces based on occupancy. In Figure 12, the widest degree of variability, as measured by room-to-room temperature difference, is apparent for homes with a single thermostat.

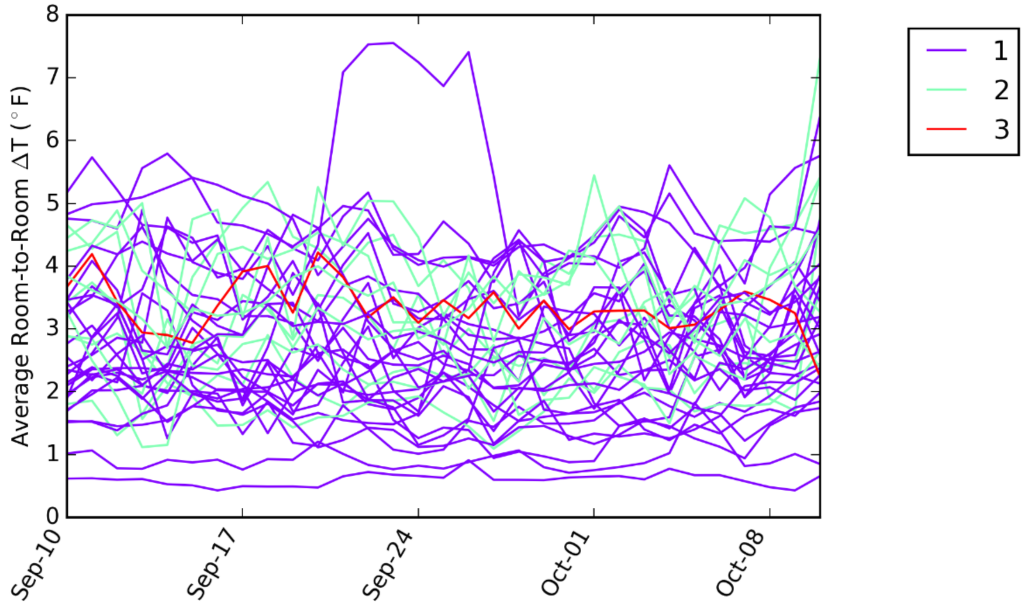

Figure 12. Average daily room-to-room temperature variability by number of thermostats

Another factor impacting the comfort of each house is the choice of a thermostat setback schedule. In this study, 26 respondents stated that they did not program their thermostats with a regular schedule, whereas 11 respondents stated that they used their programmable thermostats for a regular setback. The data shown in Figure 13 display no generalized comfort improvement between occupants who program their thermostats and those who do not.

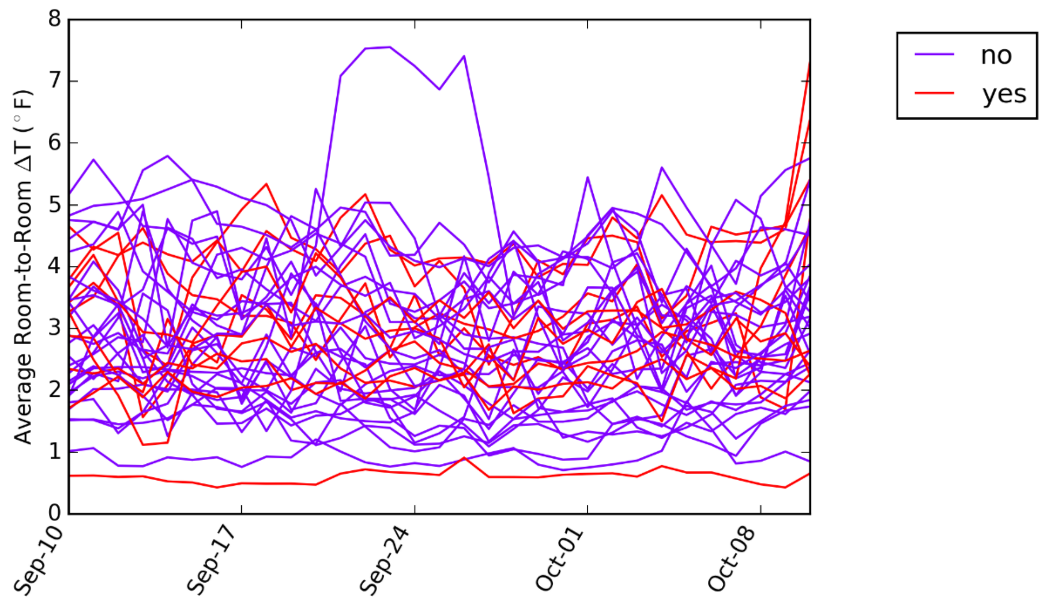

Figure 13. Average daily room-to-room temperature variability by use of programmable thermostat

4.3 Indoor Temperature Variability with Outdoor Temperature

Figure 14 and Figure 15 were created to determine if room-to-room temperature variability and outdoor temperature correlated. In these plots, the daily average temperature difference versus the daily average outdoor temperature are plotted for all homes for data between September 10, 2014, and September 15, 2014. The data in Figure 14 are colored based on the number of stories in each house and continue to show the trend that multistory houses have greater temperature variability. Outdoor temperature data were obtained from Weather Analytics' historical database[10] for each city.

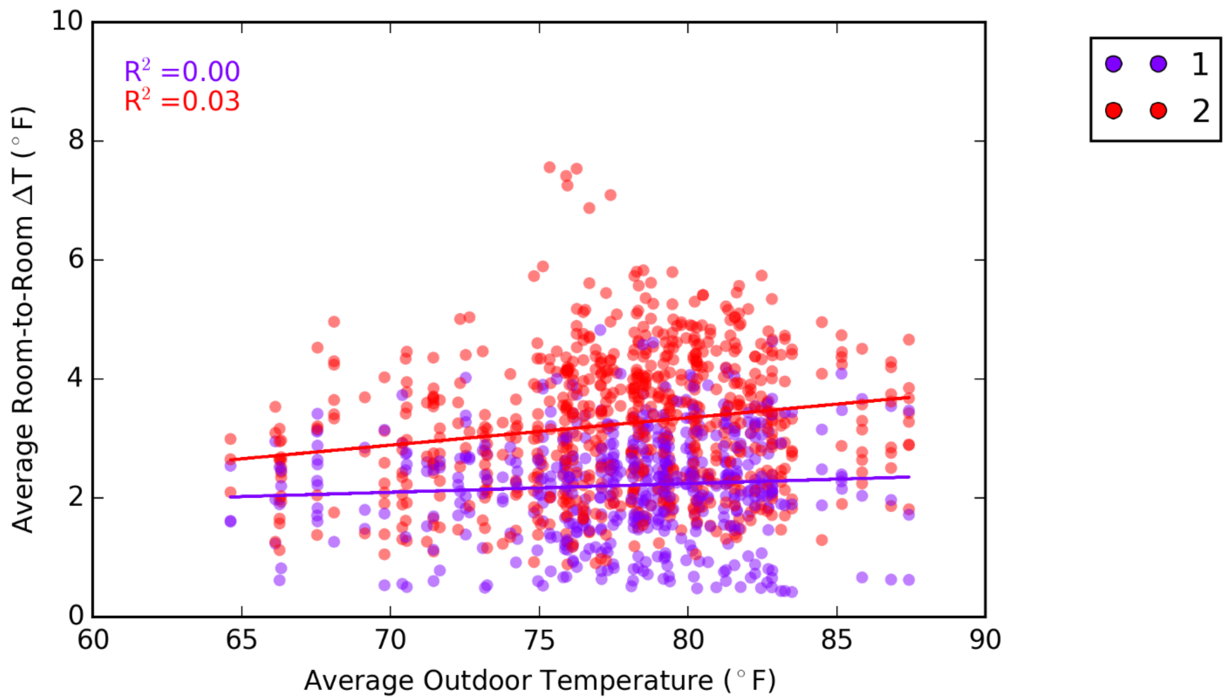

Figure 14. Room-to-room temperature variability by number of stories

The calculated trend line shows no correlation between outdoor temperature and room-to-room temperature difference for these houses. Many more factors are influencing the temperature uniformity but are not captured using a simplistic linear model. Visually it appears as if there may be a slight trend; however, this is likely due to the concentration of samples at warmer temperatures. Because there were many more measured occurrences at the warmer temperatures, the probability of randomly sampling from the extremes of the room-to-room temperature difference was higher.

The data in Figure 15 are colored by the location of the homes. Data for Tampa and Orlando show the smallest variation in outdoor temperature, whereas Houston and San Antonio show wider variations in temperature. The indoor temperature difference appears to be greatest in Orlando; however, this may be the result of a tendency toward two-story houses in that location.

[10] Weather Analytics. Bethesda, MD. http://www.weatheranalytics.com/wa/.

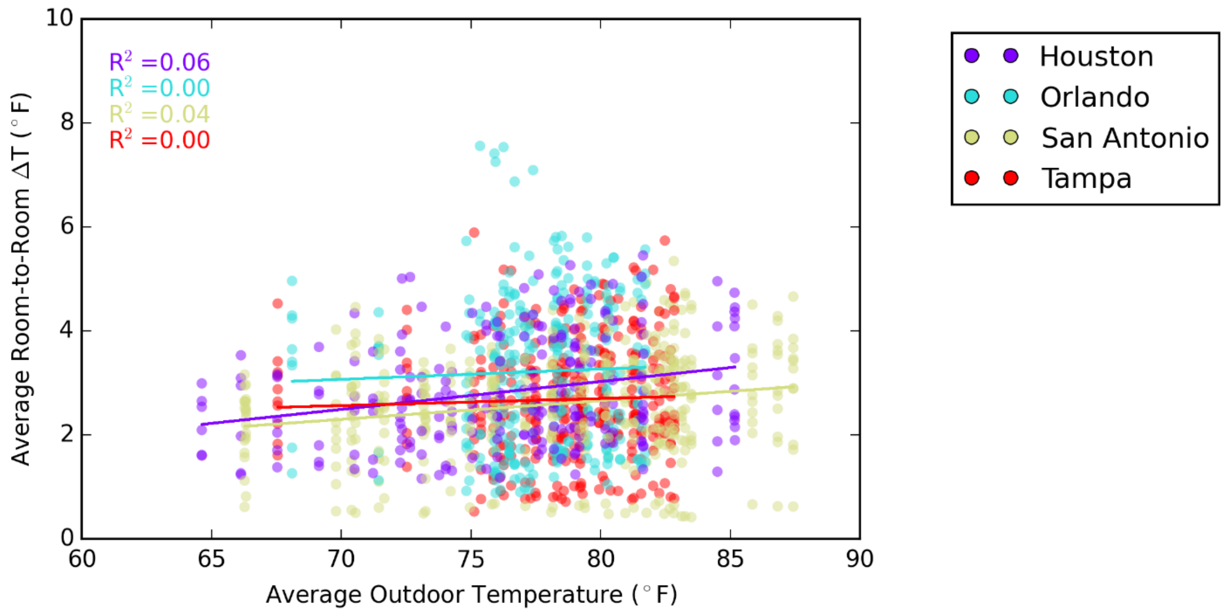

Figure 15. Room-to-room temperature variability by city where the houses were located

4.4 Thermostat Temperature

An additional benefit of this study to the homebuilding industry is a better understanding of the set point used in each house. The National Renewable Energy Laboratory is interested in these data to improve thermostat set point modeling in simulation programs such as its Building Energy Optimization software.[11] The Building America House Simulation Protocol assumes a 76°F indoor set point during the cooling season, with no setback (Metzger and Norton 2014).

The thermostat temperature for each house was averaged by the hour of day for each day in a 5-day work week (Monday through Friday) period (September 15, 2014 through September 20, 2014). This provides an average indoor thermostat profile for each house. These profiles are shown in Figure 16, as well as whether the homeowners indicated they use a programmed thermostat setback. Almost all homes with a setback showed a warmer thermostat temperature during the daytime hours; however, several homes with nonprogrammed setbacks showed cooler temperatures during the day. This may result from atypical occupancy patterns, such as the growing trend of individuals working from home.

[11] Building Energy Optimization software. Golden, CO: National Renewable Energy Laboratory. https://beopt.nrel.gov/.

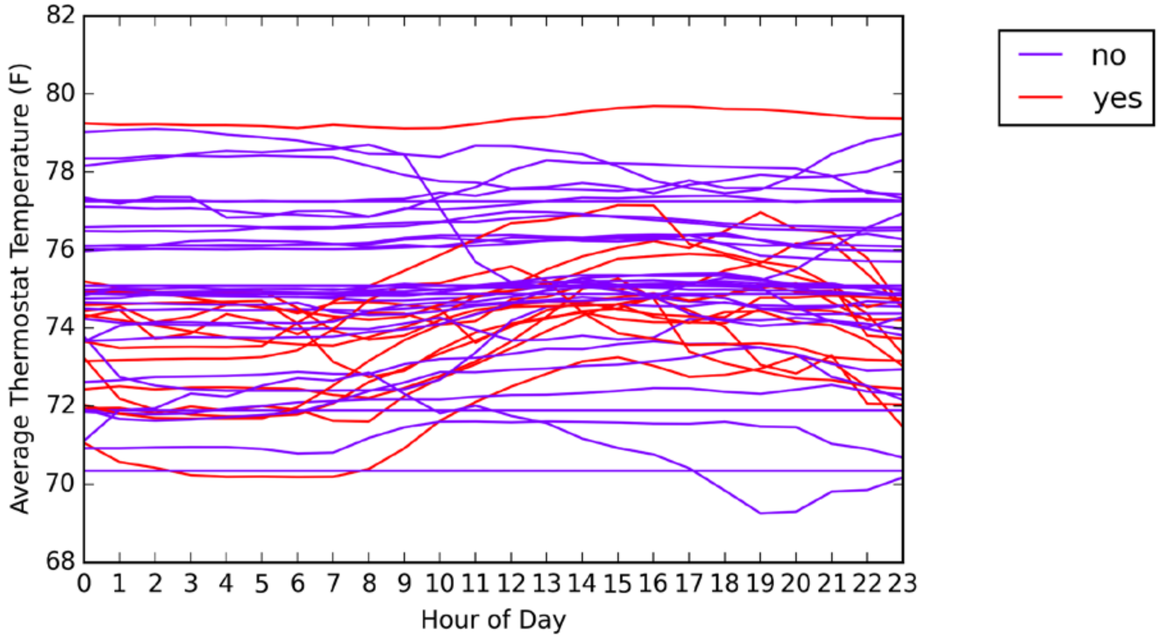

Figure 16. Average thermostat temperature over 1 week of data with programmable thermostats used

Data for occupants who did or did not claim to use a programmed setback then were aggregated into two typical profiles. The profiles were calculated by determining the median set point value for each hour of the day and then calculating the 10th and 90th quantiles to provide a determination of the range in set points. The two profiles are apparent in Figure 17; the setback population shows increased indoor temperatures through the afternoon. The median change in thermostat setting was from 74° to 75°F during evening and morning hours. To provide an idea of the setback for individual houses, additional data are presented in the next section. An interesting takeaway is that for the houses without a setback, their median set point was a continuous 75°F. It may be that the occupants use the setback to achieve better comfort relative to the baseline of 75°F.

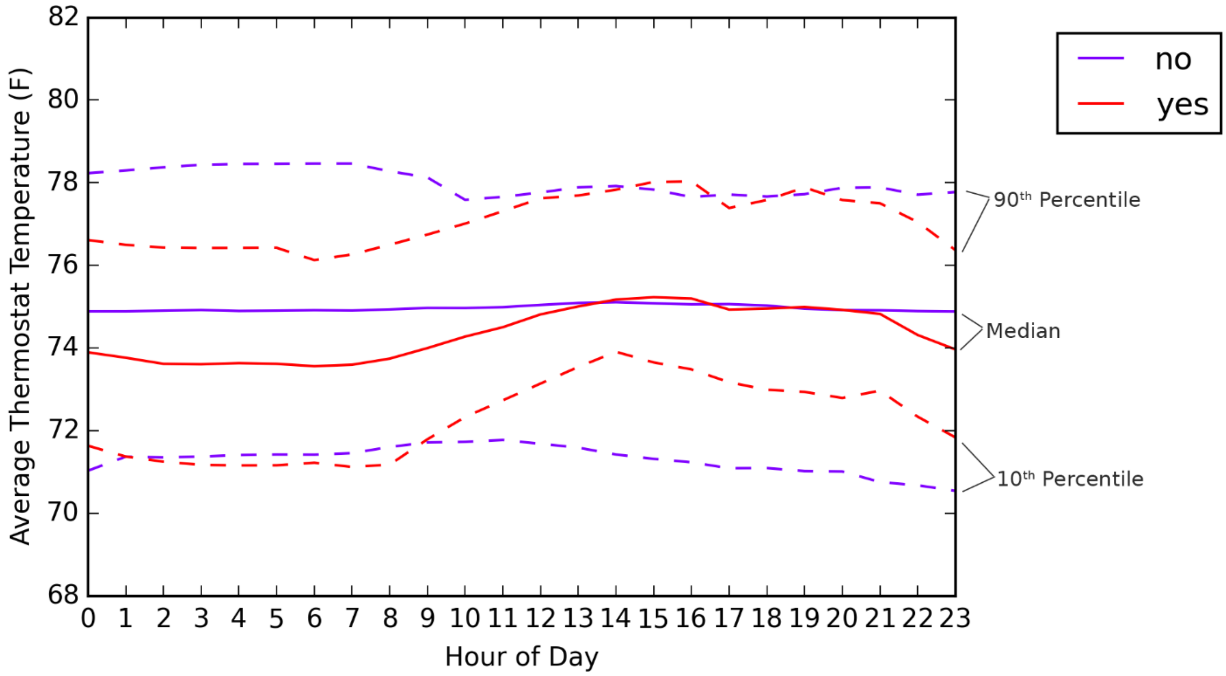

Figure 17. Aggregated median thermostat temperature with programmable thermostat used

Raw thermostat measurements from several interesting and comparable houses are presented in Figure 18 through Figure 22. The team plotted the thermostat measurements for the entire monitoring period by the hour of day, along with the average profile for weekdays and weekends. Differences in occupant behavior can be inferred from these graphics.

Figure 18 shows the thermostat profile of the occupant of House 28; this occupant appeared to make no set point changes throughout the duration of the monitoring period. There is a slight hump in the middle of the day, possibly caused by a few factors. In the middle of the day, during periods of highest heat gain, the thermostat tends to spend more time at the upper end of the dead band. Through the night, the opposite is true.

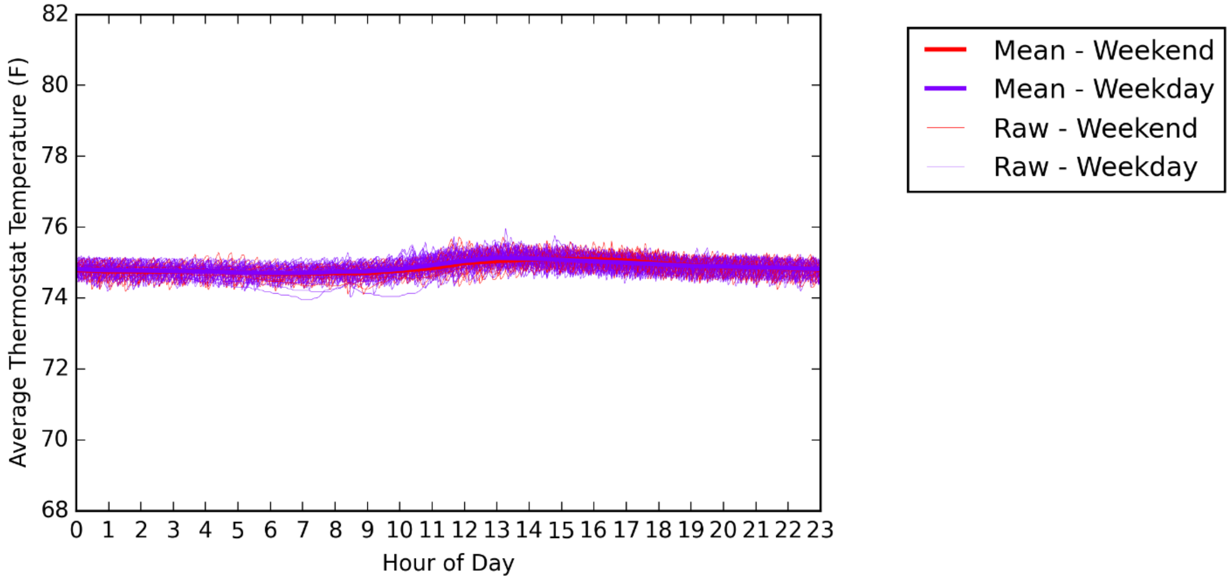

Figure 18. Thermostat trend, House 28

Data for House 24 and House 26 (Figure 19 and Figure 20, respectively) show a uniform setback period. The occupants in both of these houses reported that they did not use a programmed thermostat setback. However, it is apparent that they used a manual setback ranging from 3°F to 6°F. These occupants had very predictable behavior.

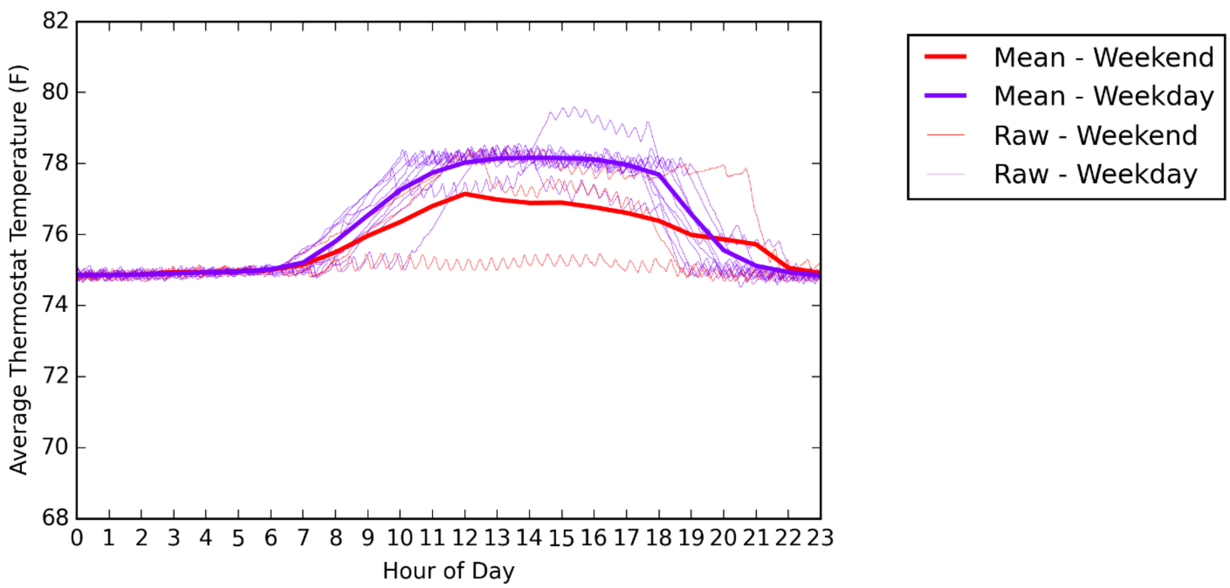

Figure 19. Thermostat trend, House 24

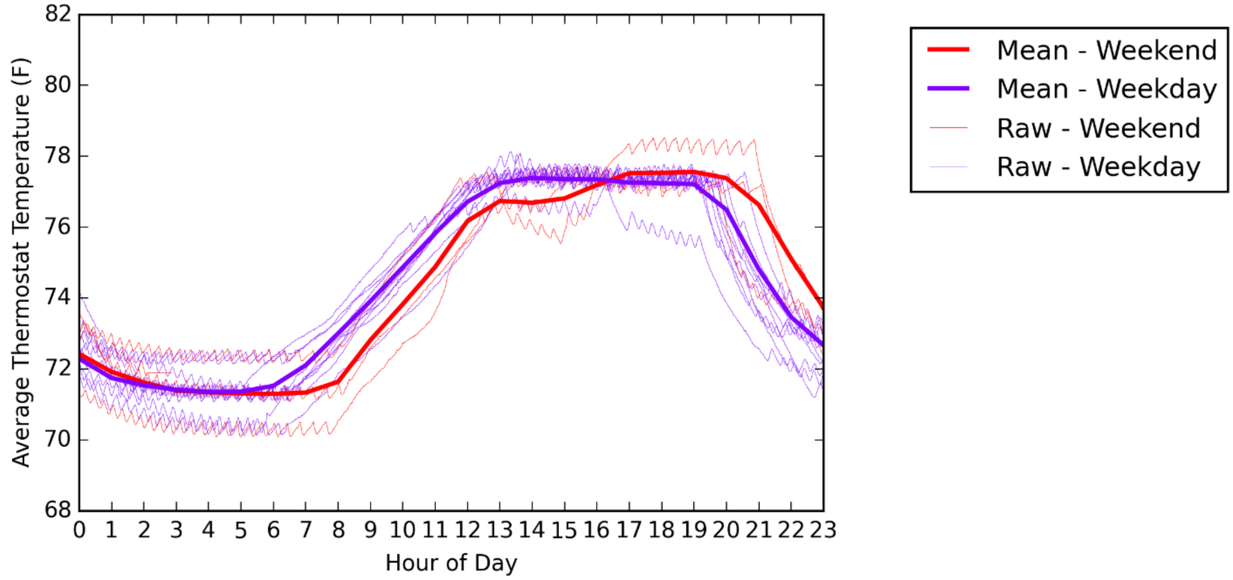

Figure 20. Thermostat trend, House 26

The data for House 23 (Figure 21) show three distinct set point periods. Analysis of the data indicates these different set points may be entirely arbitrary and do not follow any external factor, such as ambient air temperature. This kind of occupant behavior is unpredictable, based on the information available.

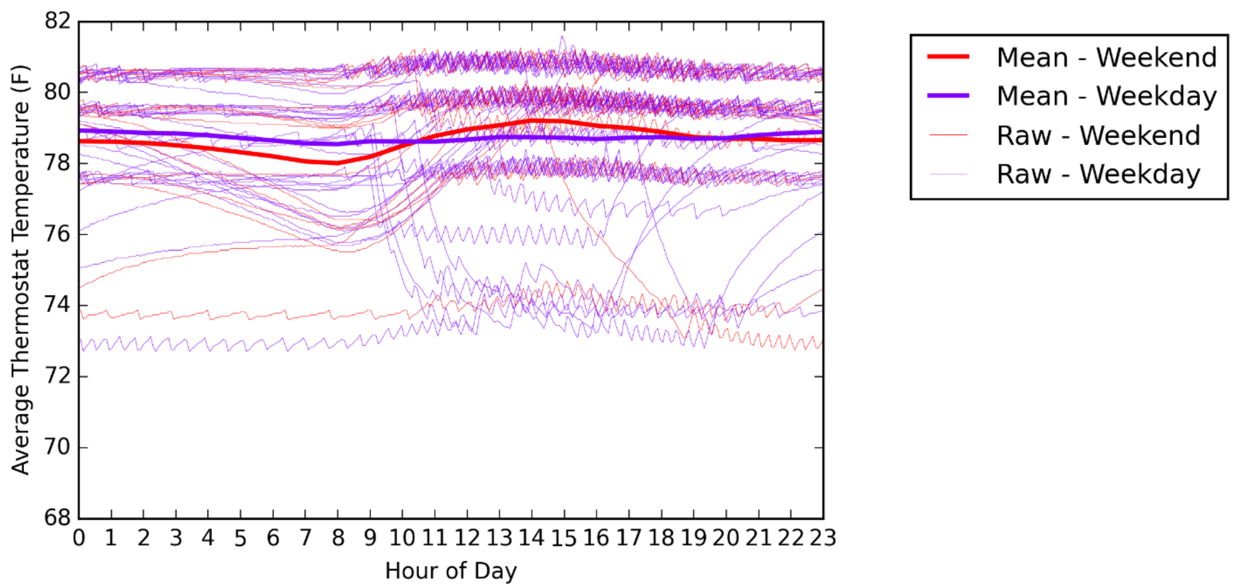

Figure 21. Thermostat trend, House 23

Figure 22 is shown as an interesting case in which the occupant of House 21 reported a programmed thermostat setback; however, the actual behavior, especially the weekday response, shows the users may have frequently intervened. Regardless, the return from setback (76°F to 74°F) follows a very regular time (hour 21), whereas the return from setback for House 24 and

House 26 shows a deviation of several hours, supporting the idea that the setback is user controlled.

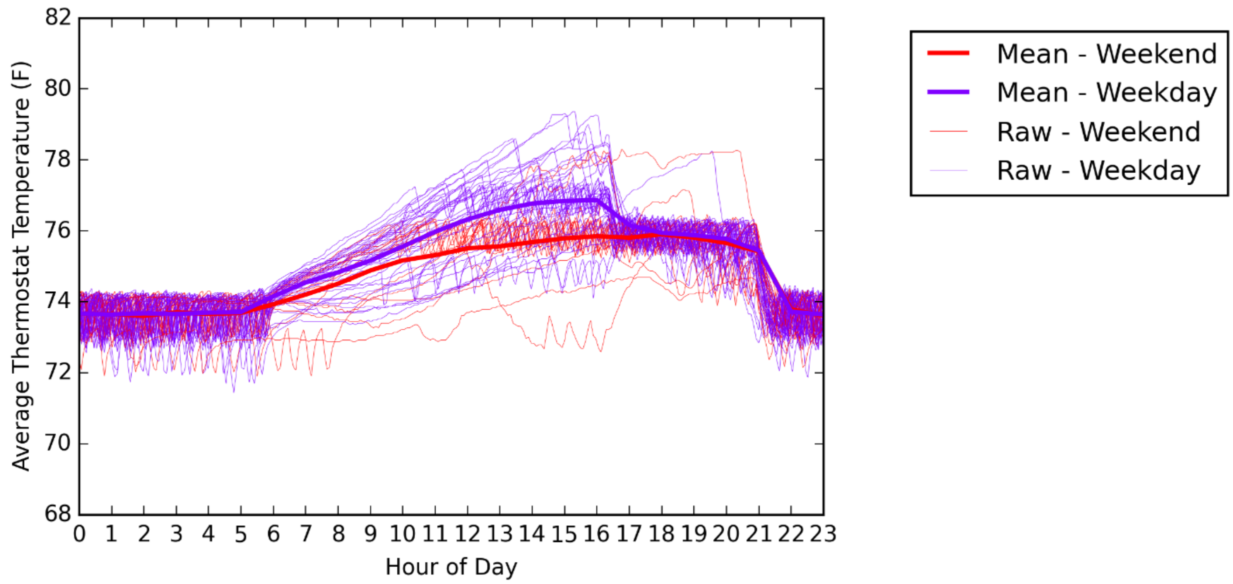

Figure 22. Thermostat trend, House 21

4.5 System Run Impact on Uniformity

The team used the runtime calculation algorithm outlined in Section 2 to create a plot to show the change in indoor temperature uniformity during system run. This "hair plot" shows each system off and on cycle for a period of several days between September 15, 2014, and September 18, 2014. System off periods are represented by lines leading up to the 0-min marker. System on periods then are shown as minutes increasing from 0. The starting and ending temperatures for each period are marked with a small vertical line. For periods longer than the x axis boundary, the line has been truncated. Lines showing a positive slope represent periods with worsening room-to-room uniformity, whereas periods of negative slope represent periods of improving room-to-room uniformity. The color of each line represents the change in starting and ending uniformity. Magenta lines show periods of large decline in room-to-room uniformity; light blue lines show an improvement in uniformity.

All homes represented in Figure 23 through Figure 25 are located in the same neighborhood and on the same street, with similar house geometries and orientations. All respondents indicated that they do not use programmable thermostats. Three very different behaviors are apparent. House 24 and House 26 appear to have a manual setback, with long run and drift periods. House 25 does not appear to have any adjustments to the thermostat set point, with very regular and relatively short on/off cycles. Of note is the apparent behavior that, during long periods when the system is off, the temperatures of rooms in the house tend to float away from each other; during shorter off periods, the temperatures of rooms tend to drift closer. When the system cycles on after a long off period, the room-to-room uniformity tends to improve, whereas the system on cycles after short system off cycles tend to show worsening room-to-room uniformity. This trend is most apparent in House 24 (Figure 23). A possible explanation for this behavior is the temporal nature of manual system overrides. Typically, the system will be off for longer periods during the day, when the house is unoccupied, and certain rooms will be subject to unbalanced solar heat gains. Houses that show worsening thermal uniformity during system on periods may have poorly balanced register airflows.

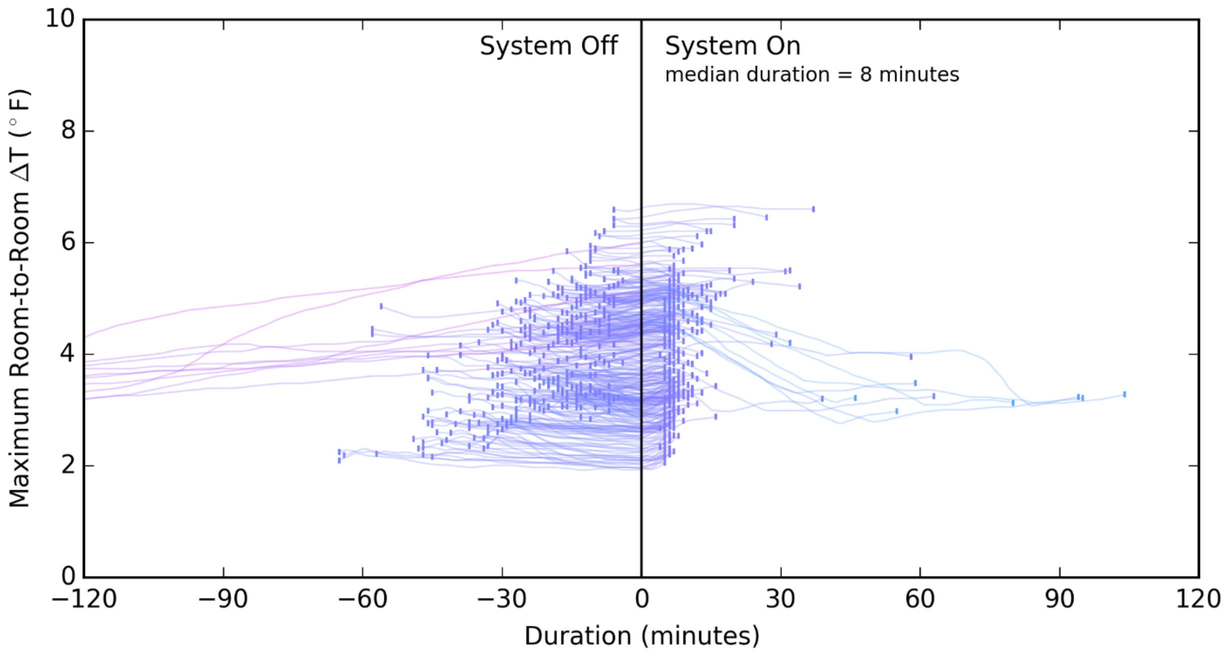

Figure 23. HVAC system off and on periods, House 24

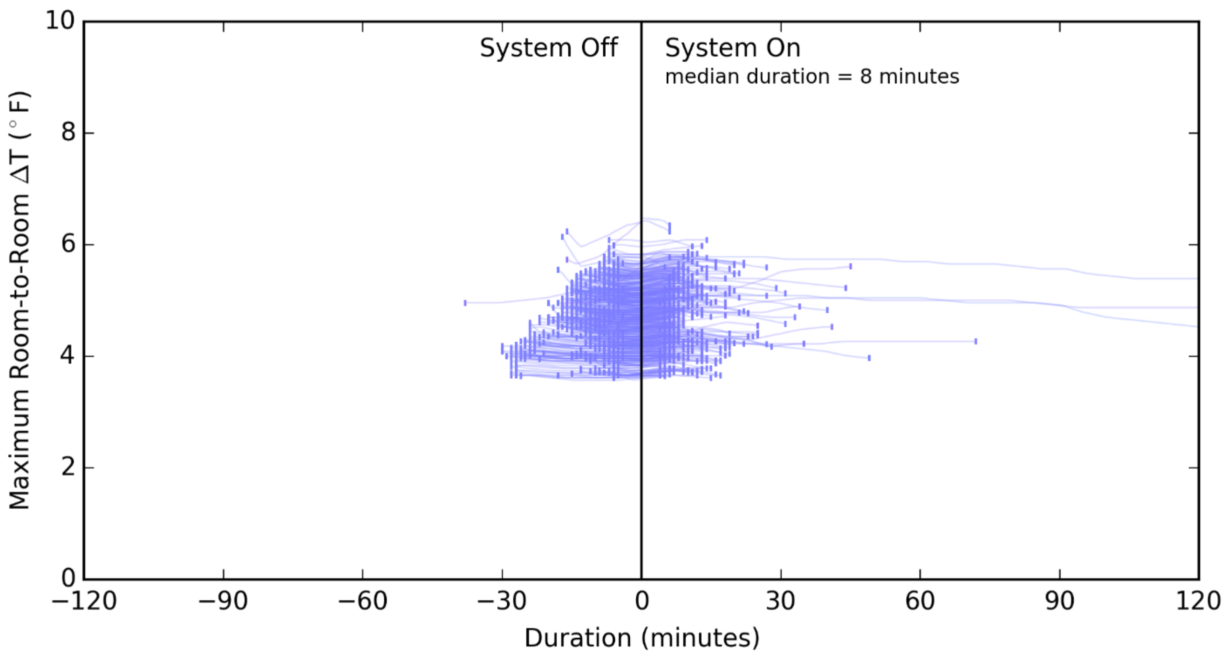

Figure 24. HVAC system off and on periods, House 25

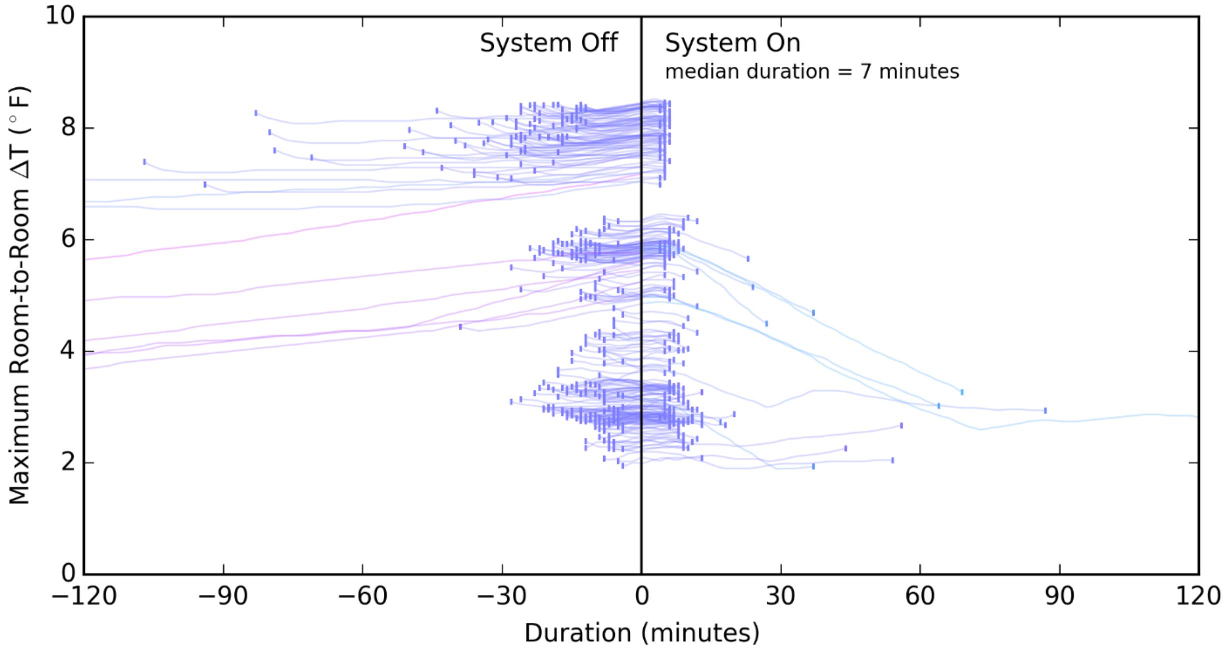

Figure 25. HVAC system off and on periods, House 26

4.6 Psychrometrics

Data for the period of September 7, 2014, through September 9, 2014, for House 24 through House 26 as examples have been plotted on psychrometric charts in Figure 26 through Figure 28, respectively. Each zone is plotted in a different color and with a 10% opacity value to begin showing relative density. In addition to the measured data, the ASHRAE Standard 55 comfort box for an occupant with 0.5 CLO and 1.0 MET has been drawn for reference (ASHRAE 2013). A value of 0.5 CLO is typical of a person wearing an ensemble of a shirt, pants, and shoes. An MET rate of 1.0 is typical of a person sitting still—for example, watching TV. Conditions within the box are thought to satisfy 80% of people. The percentage of data points that fall inside the box has been calculated and is shown on each chart for easy reference.

Figure 26 shows the highest compliance with the comfort zone; Figure 27 shows the highest number of occurrences outside the comfort zone. Figure 28 shows the greatest variation of the three houses, which corresponds to the conclusion of the hair plot shown in Figure 25. Further analysis could be done to determine the optimum CLO value for each house, which maximizes the amount of time each house spends within the comfort box.

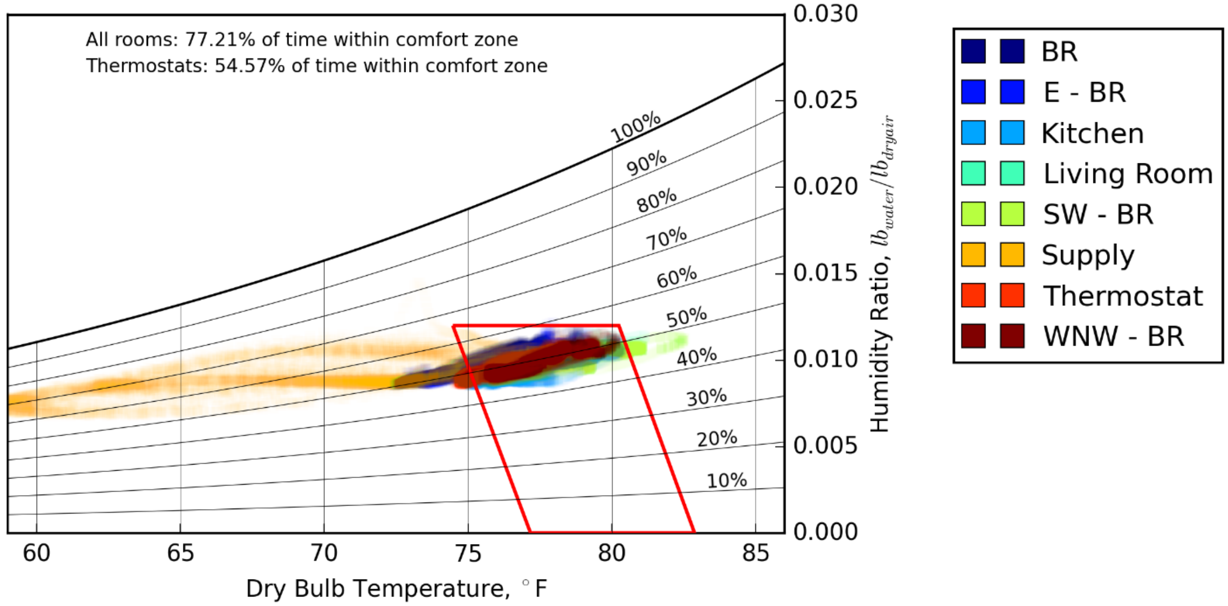

Figure 26. Psychrometric chart, House 24

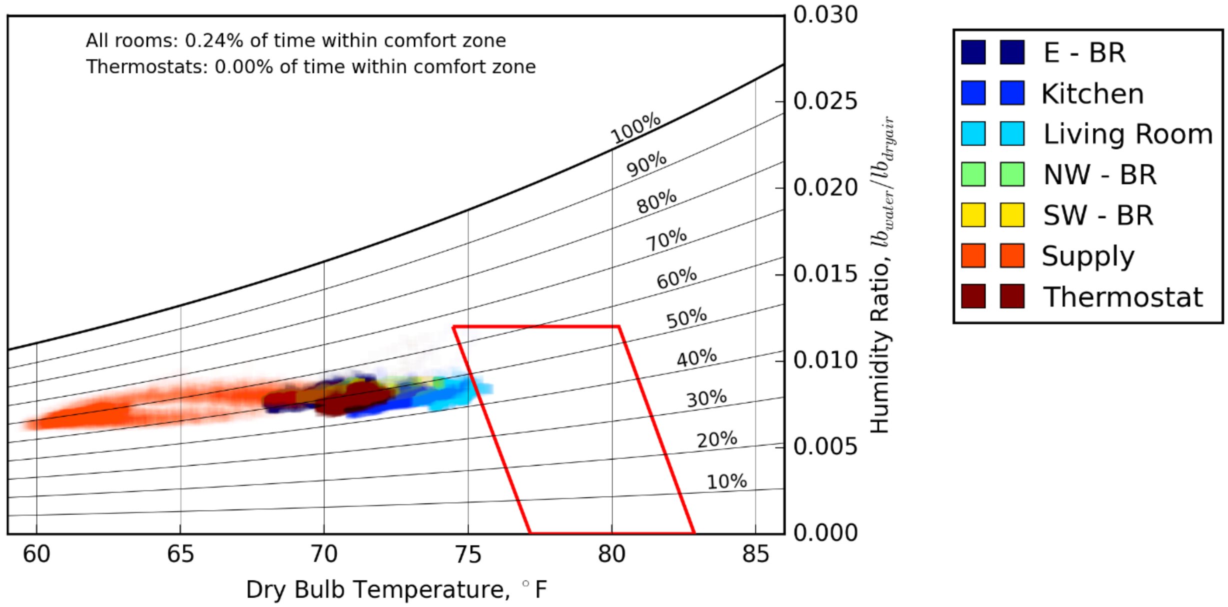

Figure 27. Psychrometric chart, House 25

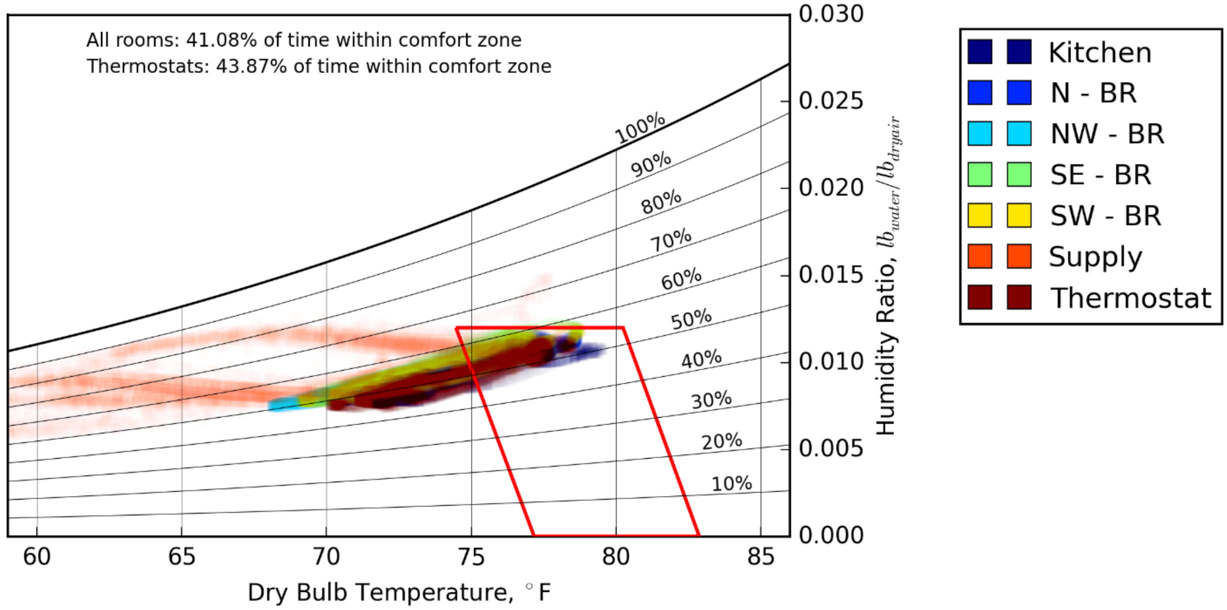

Figure 28. Psychrometric chart, House 26

As a final summary of all the measured temperature and humidity data, a density psychrometric chart is shown in Figure 29, containing more than 2 million data points. In this chart, data from each room in each house (excluding the supply registers) have been tabulated into a two-dimensional density plot. Contour lines show areas of more frequent occurrence. An extreme peak in the data is visible around 75°F and 50% relative humidity. One house is seen as an "island" with temperatures that consistently exceed 80°F.

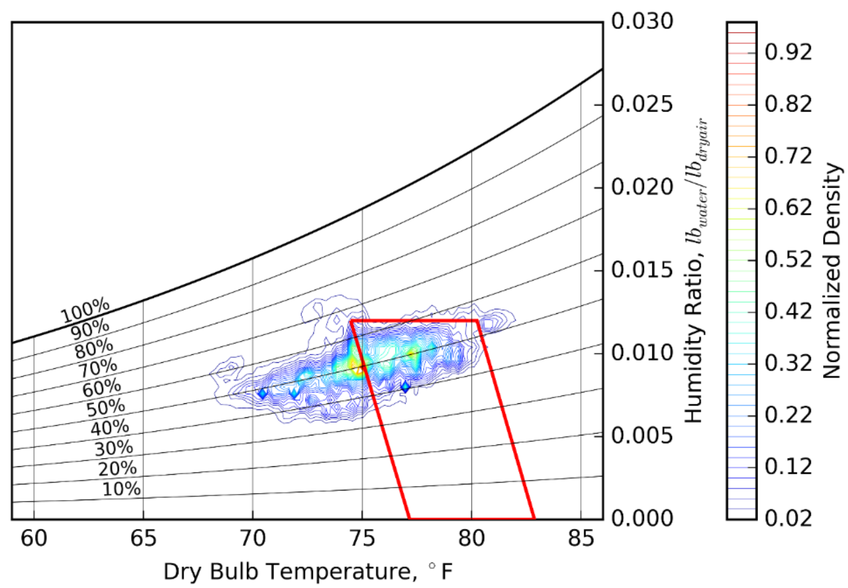

Figure 29. Psychrometric plot of data from all measured rooms in all houses

In Figure 29, the assumed CLO value of 0.5 may not be an indication of actual clothing worn in a house. The results suggest that a CLO value closer to 0.75 may be more representative of the average residential occupant in hot-humid climates. Another factor that may influence the comfort band is activity level. The comfort box assumes a 1.0 MET rate; however, occupants may have higher MET rates for various household activities such as cooking or exercising.

4.7 Builder Metrics

Summaries of the homebuilders' responses to each survey question are listed below. At times, some disagreement arose about the impact of providing a comfort guarantee on the specific business metric, and this is discussed.

Do you offer any comfort guarantee, either an internal warranty or an external program such as Masco Environments For Living?

> Comfort guarantees can be perceived by buyers as valuable in higher market groups such as the move-up market or active adult market. How the guarantee is presented can have a direct impact on the buyer's perception of the value. Some respondents noted that misunderstandings have occurred about how the guarantee was calculated, leading to confrontation. All builders have at least explored the idea of offering a comfort guarantee.

Since implementing the comfort guarantee, have you seen a change in the rate of comfort callbacks?

> Respondents noted fewer callbacks related to comfort in the homes that were built to receive a comfort guarantee and a generally higher level of customer satisfaction; however, they acknowledged that real data numbers to support the general perception of higher customer satisfaction are not available.

What impact has the comfort guarantee had on the HVAC design and installation process and costs?

> Higher costs have been associated with HVAC and with insulation and air sealing. A higher level of attention has also been given to the installation quality.

What impact has the comfort guarantee had on referral sales?

> No data are available to back up the opinion that the comfort guarantee benefits sales. However, the consensus is that comfortable homeowners are referring new buyers and that the program is another component of market differentiation.

What impact has the comfort guarantee had on market share?

> The comfort guarantee has helped maintain market share through the market downturn, but the specific impact is difficult to measure.

What impact has the comfort guarantee had on sales velocity?

The comfort guarantee is one part of the overall high-quality product that helps maintain sales velocity.

What impact has the comfort guarantee had on warranty service?

Again, although difficult to measure, the impact of the comfort guarantee has played a role, along with all other quality items, in reducing service tickets. Mechanical contractors, and not builders, often see the direct impact from warranty service costs; however, the perception is that the comfort guarantee indeed has lowered the number of warranty claims.

5 Conclusions

The following research questions were addressed in this report:

1. How much do temperatures and relative humidity vary from room to room in houses constructed in the last 7 years to meet comfort guarantee program requirements—assuming the occupants consider their homes to be comfortable?

   Measured data indicate that on average the temperature uniformity in these homes is within the 6°F boundary specified by ACCA Manual RS (Rutkowski 1997). The aggregate of all homes in this study showed that 95% of the time, the room-to-room temperature difference was less than 6°F. Some homes showed higher levels of room-to-room variability. A temporal analysis of these data shows that room-to-room temperature uniformity was worse during the late afternoon and evening hours. This is when solar heat gains tend to have the most impact on southwestern- and western-facing glazing and when most systems were returning from setback. Uniformity was best in the early morning before the sun had risen and after most of the HVAC systems had been in an unadjusted state for many hours.

2. How do occupants use their space-conditioning equipment controls for scheduled setbacks and nonscheduled adjustments?

   The team plotted the average thermostat temperatures over a day for each thermostat in the 37 homes; the team focused on average patterns over the weekdays and weekends separately. After analyzing the data for each thermostat, the team determined approximate occupant behavior as defined by each thermostat. Each thermostat was classified in one of the following five categories: no adjustments were made, a regular setback was used, a sporadic setback behavior was observed, a random behavior was observed with no pattern, or it was a Nest thermostat.[12] The results are presented in Table 3, which shows that almost half the thermostats were not adjusted. Note that 10 of the houses had two thermostats; there were a total of 47 thermostats in 37 houses. The average room-to-room temperature difference was 2.8°F for homes with a setback and 2.8°F for homes without a setback. So based on the data collected in this study, a setback had no observed impact on thermal uniformity.

Table 3. Observed Thermostat Behavior

No Adjustment	Setback	Sporadic Setback	Random	Nest
21	7	7	10	2

3. How do builders feel that participating in a comfort and performance guarantee program has impacted their business? What business metrics are associated with their involvement in terms of cost, marketing, and performance?

   Through communication with builders in Texas and Florida who participate or have participated in programs offering a comfort guarantee, the research team gained the

[12] Nest. Palo Alto: CA. https://nest.com/thermostat/life-with-nest-thermostat/.

following insights. No builders surveyed keep numeric records or were willing to share specific values relating to the impact that a comfort guarantee has had on their businesses. In higher market groups such as the move-up market or active adult market, comfort guarantees can be perceived by buyers as valuable. How the guarantee is presented can have a direct impact on the buyer's perception of the value.

Some respondents noted that misunderstandings occurred over how the guarantee was calculated, which led to undesirable confrontation. Higher costs have been associated with HVAC and with insulation and air sealing. Also, a higher level of attention has been given to installation quality. Again, no data are available to back up the opinion that there is a benefit to sales, but the consensus is that comfortable homeowners are referring new buyers and that the program is another component of market differentiation. Comfort guarantees helped maintain market share through the downturn. Although it is difficult to measure the impact, the comfort guarantee has played a role—along with all other quality items—in reducing service tickets.

Some additional and interesting conclusions were reached in this study.

Homes that did not use programmable thermostats had a median cooling set point of 75°F. Homes that used programmable thermostats had a median baseline temperature of 74°F and a setback temperature of 75°F. These values suggest that the assumed 76°F cooling set point in the Building America House Simulation Protocols (Wilson et al. 2014) may be high for new-construction homes in a hot-humid climate.

Relative humidity can be maintained at or lower than 60% by operating the air conditioner alone. Additional dehumidification was not required in any of these homes. This observation should be taken with a grain of salt, however, because the data collection period did not extend through the entire shoulder season. A complete year's worth of data may show elevated humidity during cooler months when the air conditioning is not cycling as often.

5.1 Future Work

Given the nature of this data set, many follow-up questions could be considered with additional analysis. Collecting data for a longer period also would allow for additional conclusions to be drawn. Ideally, a whole year of data could be collected to understand peak conditions and the impact of humidity during shoulder seasons.

The team noted wide variability in the supply air temperature. Some of this may have been the result of sensor placement; however, duct length and insulation are likely to have played a significant role. Additional analysis could look at the impact of duct insulation and attic type on supply temperature.

Based on the system-runtime algorithm, an analysis of cycle duration compared to outdoor temperature would help researchers to better understand the appropriate sizing of each HVAC system. Observed behavior indicated short cycling for some homes. The impact of short cycling on dehumidification also could be analyzed. Despite the short cycling, the measured results indicate that the indoor air humidity was maintained at or lower than 60% most of the time.

The measured data were specific to a hot-humid climate region. These data could be compared to measured data from homes in other climate regions, and regional assessment of preferred thermostat settings may be observed.

References

Arena, L., P. Mantha, and K. Achilles. 2010. Monitoring of Internal Moisture Loads in Residential Buildings. Prepared for the U.S. Department of Housing and Urban Development, Washington, DC. Steven Winter Associates and Oak Ridge National Laboratory, December 2010.

ASHRAE. 2013. ANSI/ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: ASHRAE.

de Dear, R.J., T. Akimoto, E. Arens, G. Brager, C. Candido, K.W. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, and Y. Zhu. 2013. "Progress in Thermal Comfort Research over the Last Twenty Years." Indoor Environmental Quality Series. Berkeley, CA: University of California at Berkeley. https://escholarship.org/uc/item/92z5q2qb#page-4.

Fanger, P.O. 1970. *Thermal Comfort*. Copenhagen, Denmark: Danish Technical Press.

Herk, A., A. Poerschke, and R. Beach. 2015. *Brookfield Homes Passive House Performance Evaluation*. Golden, CO: National Renewable Energy Laboratory (in publication).

Metzger, C., and P. Norton. 2014. *The Building America Indoor Temperature and Humidity Measurement Protocol*. Golden, CO: National Renewable Energy Laboratory. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/indoor_temp_humidity_protocol.pdf.

Rittelmann, W. 2008. "Thermal Comfort Performance—Field Investigation of a Residential Forced-Air Heating and Cooling System with High Sidewall Supply Air Outlets." Presented at the BEST1 Conference, Minneapolis, MN, June 1–12, 2008. http://best1.thebestconference.org/pdfs/045.pdf.

Rudd, A. 2014. *Measure Guideline: Supplemental Dehumidification in Warm-Humid Climates*. Golden, CO: National Renewable Energy Laboratory. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/measure_guideline_dehumidification_warmhumid.pdf.

Rutkowski, H. 1997. *Manual RS—Comfort, Air Quality, and Efficiency by Design*. Arlington, VA: Air Conditioning Contractors of America. www.acca.org/technical-manual/manual-rs/.

Ueno, K. and H. Loomis. 2014. *Long-Term Monitoring of Mini-Split Ductless Heat Pumps in the Northeast*. Golden, CO: National Renewable Energy Laboratory, NREL/SR-5500-63079. www.nrel.gov/docs/fy15osti/63079.pdf. Revised 2015.

Wilson, E., C. Engebrecht-Metzger, S. Horowitz, and R. Hendron. 2014. *Building America House Simulation Protocols* (Technical Report, NREL/TP-5500-60988). Golden, CO: National Renewable Energy Laboratory. http://energy.gov/sites/prod/files/2014/03/f13/house_simulation_protocols_2014.pdf.

Appendix: Specifications for the Homes in the Study and the Homeowner Survey Results

	State	City	Occupants	Adults	Children	Home During Weekday	Employment
1	Texas	San Antonio	4	2	2	1	full time
2	Texas	San Antonio	2	2	0	1	retired
3	Texas	San Antonio	4	2	2	0	full time
4	Texas	San Antonio	1	1	0	1	retired
5	Texas	San Antonio	2	2	0	1	full time
6	Texas	San Antonio	5	2	3	0	full time
7	Texas	San Antonio	2	2	0	1	full time
8	Texas	San Antonio	2	2	0	1	full time
9	Texas	San Antonio	4	2	2	0	full time
10	Texas	San Antonio	3	2	1	0	full time
11	Texas	San Antonio	4	2	2	0	full time
12	Florida	Tampa	3	2	1	1	0
13	Florida	Tampa	2	2	0	1	part time
14	Florida	Tampa	2	2	0	1	0
15	Florida	Tampa	3	2	1	1	0
16	Florida	Tampa	2	2	0	1	part time
17	Florida	Tampa	2	2	0	1	0
18	Florida	Tampa	2	2	0	1	0
19	Florida	Tampa	2	2	0	0	0
20	Florida	Tampa	2	2	0	1	0
21	Florida	Tampa	4	2	2	1	0
22	Florida	Orlando	3	2	0	1	0
23	Florida	Orlando	4	1	3	0	0
24	Florida	Orlando	5	2	3	1	0
25	Florida	Orlando	2	2	0	0	0
26	Florida	Orlando	4	2	2	1	0
27	Florida	Orlando	4	2	2	1	0
28	Florida	Orlando	2	2	0	0	0
29	Florida	Orlando	3	2	1	1	0
30	Texas	Houston	3	2	1	1	0
31	Texas	Houston	3	2	1	1	0
32	Texas	Houston	4	2	2	1	0
33	Texas	Houston	4	2	2	1	0
34	Texas	Houston	2	2	0	0	0
35	Texas	Houston	2	2	0	1	0
36	Texas	Houston	3	1	2	0	0

	Year of Constr.	No. of Stories	Front Door Orient.	No. of Tstats.	Prog. Tstat. Used	House Changes	Cond. Square Footage	Foundation Type
1	2014	2	E	2	yes	0	3,656	slab
2	2014	2	SW	2	no	0	3,420	slab
3	2013	2	SW	2	yes	0	3,070	slab
4	2009	1	S	1	yes	0	1,532	slab
5	2013	2	SW	2	yes	0	3,656	slab
6	2013	2	E	3	yes	0	3,120	slab
7	2013	1	S	1	yes	0	1,921	slab
8		1		1	no	0		
9		2		2	no	0		
10		2		2	yes	0		
11		2		2	no	0		
12	2013	1	W	1	no	0	2,681	slab
13	2014	1	W	1	no	insulation	2,154	slab
14	2014	1	E	1	no	0	2,154	slab
15	2014	1	W	1	no	0	1,818	slab
16	2013	1	S	1	yes	0	1,710	slab
17	2013	1	N	1	no	0	1,573	slab
18	2013	1	S	1	no	ceiling fans	1,953	slab
19	2013	1	E	1	no	pool; ceiling fans	2,300	slab
20	2013	2	W	1	no	ceiling fans	3,326	slab
21	2014	2	SE	1	yes	ceiling fans	2,681	slab
22	2014	2	S	1	no	ceiling fans	2,318	slab
23		2		1	no	ceiling fans		slab
24	2014	2	W	1	no	ceiling fans	2,638	
25	2014	2	W	1	no	ceiling fans	1,707	
26	2014	2	E	1	no	ceiling fans	2,318	
27	2013	2	W	1	no	ceiling fans; insulation	2,443	
28	2014	1	S	1	no	0	1,847	
29	2013	2	S	1	no	ceiling fan	3,070	
30		1		1	no	ceiling fan		
31		1		1	yes	ceiling fans		
32		1		1	no	0		
33		2		2	no	0		
34		1	SW	1	no	0		
35		2	N	2	no	ceiling fans		
36		2		1	no	ceiling fans		

	Bedrooms	Bathrooms	Master Bdrm. Door	Bdrm. 2 Door	Window Vent.	Zones	Fireplace
1	4	3.5	closed - night	closed - night	no	1	no
2	4	3.5	open	open	no	1	yes
3	4	2.5	open	open	no	1	no
4	3	2	open	open	yes	1	no
5	4	3.5	open	open	no	1	yes
6	4	3.5	open	open	yes	1	yes
7	3	2.5	open	closed	no	1	no
8			open	closed	no		
9			open	closed - night	no		
10			open	open	no		
11			open	open	no		
12	4	2	open	open	no	1	no
13	3	2	open	open	winter	1	no
14	3	2	open	open	winter	1	no
15	3	2	closed	0	no	1	no
16	3	2	open	0	no	1	no
17	3	2	open	0	winter	1	no
18	3	2	open	0	October-summer	1	no
19	3	2	open	0	winter	1	no
20	4	4	open	0	winter	2	no
21	4	2	closed - night	closed - night	late October, onward	1	no
22	4	2.5	open	closed - night	winter	1	no
23			0	0	no		no
24	4	2.5	closed - night	open	winter	1	no
25	3	2.5	open	0	no	1	no
26	4	2.5	open	0	winter	1	no
27	5	3	open	0	no	1	no
28	3	2	open	0	no	1	no
29	4	2.5	open	0	no	1	no
30			closed - night	0	no		
31			open	0	no		
32			open	open	no		
33			open	closed	no		
34			closed	0	no		
35			closed	closed	no		
36			open	0	no		

	Enclosure	Insulation Type	Wall R-Value	Ceiling R-Value	Solar Panels/Capacity
1	Wood frame	OC foam+0.5" cont. XPS	13+3	22	yes/1.94 kw
2	Wood frame	OC foam+0.5" cont. XPS	13+3	22	yes/1.94 kw
3	Wood frame	OC foam+0.5" cont. XPS	13+3	22	yes/1.94 kw
4	Wood frame	OC foam+0.5" cont. XPS	13	22	yes/unknown
5	Wood frame	OC foam+0.5" cont. XPS	13+3	22	yes/1.94 kw
6	Wood frame	OC foam+0.5" cont. XPS	13+3	22	yes/1.94 kw
7	Wood frame	Cellulose+0.5" cont. XPS	13+3	22	yes/1.94 kw
8					
9					
10					
11					
12	CMU	blown	4.1	R-38	no
13	CMU	blown	4.1	R-38	no
14	CMU	blown	4.1	R-38	no
15	CMU	blown	4.1	R-38	no
16	CMU	blown	4.1	R-38	no
17	CMU	blown	4.1	R-38	no
18	CMU	blown	4.1	R-38	no
19	CMU	blown	4.1	R-38	no
20	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-38	no
21	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-38	no
22	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-30	no
23					no
24	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-30	no
25	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-30	no
26	1-CMU,2-wood	batt & blown	up-11;down-4.1	R-30	no

27	**1-CMU,2-wood**	**batt & blown**	**up-11;down-4.1**	**R-30**	**no**
28	**CMU**	**batt & blown**	**4.1**	**R-30**	**no**
29	**1-CMU,2-wood**	**batt & blown**	**up-11;down-4.1**	**R-30**	**no**
30					
31					
32					
33					
34					
35					
36					

	Window Type	Infiltration	Duct Leakage	Ductwork Location	Ductwork Insulation
1	dbl. – vinyl	1,581	112	sealed attic & midfloor	R-6
2	dbl. – vinyl	1,264	87	sealed attic & midfloor	R-6
3	dbl. – vinyl	1,290	97	sealed attic & midfloor	R-6
4	dbl. – vinyl	830	unknown	sealed attic	R-6
5	dbl. – vinyl	1,396	94	sealed attic & midfloor	R-6
6	dbl. – vinyl	980	172	sealed attic & midfloor	R-6
7	dbl. – vinyl	1,133	73	sealed attic & midfloor	R-6
8					
9					
10					
11					
12	dbl. - alum	5.0936	0.026		
13	dbl. - alum	5.0588			
14	dbl. - alum	5.9275	0.019		
15	dbl. - alum	5.0742	0.046		
16	dbl. - alum	5.1277	0.041		
17	dbl. - alum	4.1742	0.037		
18	dbl. - alum	5.457	0.034		
19	dbl. - alum	4.9984	0.03		
20	dbl. - alum	4.5761	0.032		
21	dbl. - alum	4.4901	0.018		
22	dbl. - alum	4.2438	0.022		
23					
24	dbl. - alum	4.2429	0.022		
25	dbl. - alum	4.572	0.016		
26	dbl. - alum	4.3178	0.016		
27	dbl. - alum	4.1816	0.011		
28	dbl. - vinyl	3.5793	0.016		
29	dbl. - vinyl	3.65	0.021		
30					
31					
32					
33					
34					
35					
36					

	AHU Location	Fuel Source	Fuel Source Range	Fuel Source Oven	Fuel Source Heating	Adtnl. Htg/ Clg	Space Heater	Humidifier/ Dehumidifier
1	sealed attic	both	electric	electric	gas	no	0	0
2	sealed attic	both	gas	electric	gas	no	0	0
3	sealed attic	both	electric	electric	gas	no	0	0
4	sealed attic	both	electric	electric	gas	yes	2	2
5	sealed attic	both	gas	gas	gas	no	0	0
6	sealed attic	both	electric	gas	gas	no	0	0
7	sealed attic	both	gas	electric	gas	no	0	0
8						no	0	0
9						no	0	0
10						no	0	0
11						no	0	0
12	closet	electric	electric	electric	electric	no	0	0
13	closet	electric	electric	electric	electric	no	0	0
14	closet	electric	electric	electric	electric	no	0	0
15	closet	electric	electric	electric	electric	no	0	0
16	closet	electric	electric	electric	electric	no	0	0
17	closet	electric	electric	electric	electric	no	0	0
18	closet	electric	electric	electric	electric	no	0	0
19	closet	both	electric	electric	electric	yes	0	0
20	closet	both	gas	gas	gas	no	0	0
21	closet	electric	electric	electric	electric	no	0	0
22	closet	electric	electric	electric	electric	no	0	0
23	closet					no	0	0
24	closet	electric	electric	electric	electric	no	0	0
25	closet	electric	electric	electric	electric	no	0	0
26	closet	electric	electric	electric	electric	no	0	0
27	closet	electric	electric	electric	electric	no	0	0
28	closet	electric	electric	electric	electric	no	0	0
29	closet	electric	electric	electric	electric	no	0	0
30						no	0	0
31						no	0	0
32						no	0	0
33						no	0	0
34						no	0	0
35						no	0	0
36						no	0	0

	Heating Equipment	Heating Capacity	Heating Distribution	Cooling Equipment	Cooling Capacity
1	gas furnace	112 kBtuh	forced air	AC	46 kBtuh
2	gas furnace	76 kBtuh	forced air	AC	44.5 kBtuh
3	gas furnace	57 kBtuh	forced air	AC	41 kBtuh
4	gas furnace	56 kBtuh	forced air	AC	29 kBtuh
5	gas furnace	92 kBtuh	forced air	AC	45 kBtuh
6	gas furnace	92 kBtuh	forced air	AC	40.5 kBtuh
7	gas furnace	57 kBtuh	forced air	AC	29 kBtuh
8					
9					
10					
11					
12	heat pump	46 Btu	forced air	AC	46
13	heat pump	26.2	forced air	AC	28.6
14	heat pump	26.2	forced air	AC	28.6
15	heat pump	26.2	forced air	AC	28.6
16	heat pump	26.2	forced air	AC	28.6
17	heat pump	26.2	forced air	AC	28.6
18	heat pump	26.2	forced air	AC	28.6
19	gas	28.8	forced air	AC	28.8
20	gas & pump	28.8 & 35	forced air	AC	28.8 & 35
21	heat pump	46	forced air	AC	46
22	heat pump	8.0 HSPF	forced air	AC	14 SEER
23			forced air	AC	
24	heat pump	8.0 HSPF	forced air	AC	14 SEER
25	heat pump	8.0 HSPF	forced air	AC	14 SEER
26	heat pump	8.0 HSPF	forced air	AC	14 SEER
27	heat pump	8.0 HSPF	forced air	AC	14 SEER
28	heat pump	8.3 HSPF	forced air	AC	15 SEER
29	heat pump	8.3 HSPF	forced air	AC	15 SEER
30					
31					
32					
33					
34					
35					
36					

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