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The Building America Indoor Temperature and Humidity Measurement Protocol

Cheryn Engebrecht Metzger
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Technical Report
NREL/TP-5500-61040
February 2014

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In addition, the authors thank the following Building America research teams for their initial feedback and results into this report and protocol: Consortium for Advanced Residential Buildings (CARB), Advanced Residential Integrated Energy Solutions (ARIES), and Building Science Corporation (BSC).

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Executive Summary

When simulating energy use in homes, the assumed heating and cooling set points have a significant impact on the results. Even one degree Fahrenheit difference in heating set point can make a 5% difference in heating energy use. This is the single largest occupant-driven variable (Robertson et al., 2013) in residential simulations today.[1]

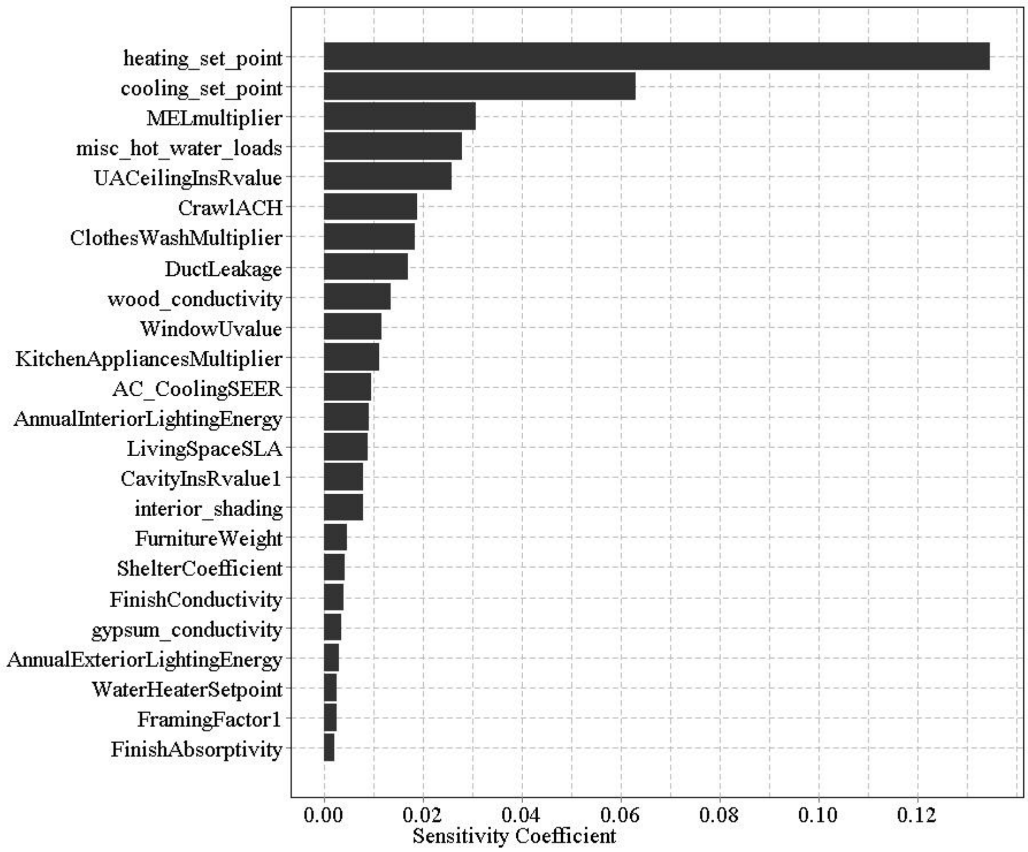

Figure 1. Relative sensitivity of 24 influential inputs in residential simulation tools.

The Building America House Simulation Protocols (HSP) (Hendron and Engebrecht, 2010) are used to help define the default heating and cooling set points for simulations related to compliance for the Building America Program. The set points for heating, cooling and humidity used in the HSP were established based on ASHRAE Standard 55-2004 (ASHRAE 2004b). This information was complimented by the data in the Residential Energy Consumption Survey (RECS) data from 2005. However, the RECS data is based on occupant surveys, which may not provide accurate set point information. In recent years, a few small samples have shown that the Building America asset heating set point of 71ºF may be too high (Roberts and Lay, 2013, Parker, 2013 and Appendix II). High uncertainty in the protocol set point, high sensitivity to set points, and data indicating the protocol set point may be high, all point to the need for a large-scale data set to be collected that informs the industry on this very influential matter.

[1] Relative sensitivity shows the relative influence that variables have on the outcome of a residential simulation

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Humidity was added midway through the development of this document as it became clear that many more research questions could be answered with a small additional investment in sensors. Some manufacturers of dehumidifiers recommend set points around 50% relative humidity (RH) to control dust mites, while ASHRAE recommends 60%. In an unpublished study in New Orleans, it was also found that some people are more comfortable at higher than 60% RH. Clearly, there is a need for more data on the humidity levels that people actually experience in their homes.

This new protocol document was created to help Building America researchers and other entities collect consistent data to help answer the question: ***How should the indoor temperature be represented in simulation tools to most accurately represent a home in an asset energy rating?*** An asset energy rating analyzes the energy performance of a home under a standard set of occupant and operational assumptions. After sufficient data (see Appendix I) is collected through this protocol format, the future study would ultimately inform the Building America HSP, as well as other asset rating bodies like RESNET, HES, etc.

This protocol document covers the decision-making process for researchers to determine how many sensors should be placed in each home, where to put those sensors, and what kind of asset data should be taken while they are in the home during a research project. The authors attempted to design the protocols to maximize the value of this study and minimize the resources required to achieve that value.

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Introduction and Background

When modeling homes using simulation tools, the accuracy of the output is strongly influenced by the accuracy of the information fed into the model. Some of these inputs are measurements or observations (building geometry, orientation, etc.), others are equipment performance characteristics, and some describe occupant behavior (heating and cooling set points, hot water use, miscellaneous electric loads, etc.). In Building America research projects, the inputs describing occupant behavior are dictated by the House Simulation Protocols (HSP). The HSP provides standardized values for occupant behavior inputs that are held constant for modeling homes within the Building America Program (Hendron and Engebrecht/Metzger, 2010). Using consistent inputs provides the ability to compare modeling results across the program. The heating and cooling set points, as well as the humidity set point, which is included in these standard inputs, can have a significant impact on home energy use.

This document outlines a protocol for collecting a large sample of temperature and relative humidity (T&RH) data in order to determine realistic standardized values for the HSP. In the future, the National Renewable Energy Laboratory (NREL) will collect data from Building America teams, labs and partners to enter into the Building America Field Data Repository (BAFDR). Once enough data is collected, NREL will analyze the set and report the findings. The raw data set will also be made available as a resource for other research projects.

The audience for this protocol includes Building America researchers as well as researchers, analysts and directors from other residential programs (ex: HERS, HES, BPI/HPwES, universities, etc.). The work outlined in this protocol is meant to compliment other research that is already being done in houses across the United States. In most cases, NREL will provide the equipment necessary to complete these tasks and will also provide the analysis. If a research or rating institution is already active in a group of homes at any given time, this exercise should only take a few extra hours of their time.

Temperature

When simulating energy use in homes, the heating and cooling set points have a significant impact on the results. Even one degree Fahrenheit difference in heating set point can make a 5% difference in heating energy use. Of all the occupant-driven assumptions in simulation tools, this variable has the most impact on the results (Robertson et al., 2013).

In the most recent version of the HSP in 2010, the modeled heating set point for new and existing homes is dictated to be 71ºF. This value was based on the ASHRAE Standard 55-2004 (ASHRAE 2004b) and backed up by an analysis conducted on 3,050 homeowner surveys from the Residential Energy Consumption Survey (RECS) of 2005 (the most recent information available at the time). Although the sample size for this survey is large, the information may not be very accurate. The questions are posed to homeowners verbally, and in many cases, the homeowners may not know the actual set point temperature. In some cases, like electric baseboard heating, and some older thermostats, the thermostat does not have a temperature scale (e.g. the user must choose a temperature between red for hot and blue for cold). This makes the question, “what is your set point temperature?” difficult to answer with any precision.

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Simulation tools like BEopt (Christensen, et. al. 2006) often include an input for the set point temperatures. These temperatures are then used to model the operation of the heating and cooling equipment. Many residential simulation tools model the home as a single conditioned zone. This assumes the set point temperature is maintained uniformly throughout the entire conditioned area of the house. The HVAC equipment in the simulation is operated to maintain the exact set point temperature every hour throughout the heating or cooling season (except for peak conditions where the equipment cannot meet the load). Of course, this idealized case does not exist in real homes. In reality, the temperature may vary throughout the home, or float three or four degrees during HVAC use. In addition, a room away from the thermostat may receive solar gain and be warmer than the rest of the house on sunny days. Faulty or poorly designed distribution systems, closed registers, closed doors with inadequate undercut, and variation in wall and ceiling insulation are other examples of possible contributors to uneven temperature distribution.

The thermostat is not necessarily the greatest predictor of a representative indoor temperature that should be used in simulations. For improving simulation accuracy, the *average indoor temperature* for asset ratings in homes will be more valuable than the thermostat set point that is widely used today in simulations.

Humidity

The recommendation from experts on the in-home humidity set point is 55% RH (Rudd, 2013) so that the actual humidity in a home does not exceed 60%. The motivation for this value is largely to minimize mold, mildew, dust mites and other allergens in a home. However, in a recent New Orleans study (results yet to be published), it was observed that some homeowners are actually more comfortable with higher than 60% RH humidity levels.

Humidity is not as well studied as temperature. However, in the New Orleans study, it was shown that the majority of indoor humidity levels varied from 40% to 70% RH. This protocol contains guidance for how to measure humidity in all climates for just a few additional dollars per sensor.

In the 2014 version of the HSP and version 2.1 of the BEopt software, there is not a pre-determined set point for humidity because recent findings have posed questions about whether or not separate (from air conditioning) humidity control should be required in the Building America Program. This protocol aims to eventually help answer that question. After data collection and analysis has occurred in future years, it will be much easier to make a determination about the real humidity levels in new and existing homes.

Once humidity levels are known, it will be determined if a humidity set point should be required in the HSP and input into BEopt.

Other Data Collection Opportunities

There are a number of other data collection opportunities that present themselves in a large study such as this. Possible collection points could include: room occupancy, appliance usage, miscellaneous electric load usage, etc. Due to the requirement for a much larger sum of money upfront to purchase these types of sensors, this type of information is not going to be required for

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this study. However, any extra information that the researcher can collect will certainly be added to the BAFDR along with the temperature, humidity and other house characteristic information.

Protocol Design Method

The approach to developing this protocol was as follows:

1) Determine the need for a large indoor temperature dataset via literature review, discussions with Building America Program members and conversations with industry stakeholders.
2) Research past findings to determine the accuracy and house characteristic range required for the final data set to be collected in the future.
3) Determine the average standard deviation of data to date (Appendix II.A and II.B).
4) Calculate the sample size required for the future data set, based on the standard deviation and accuracy required for the model input based on a 95% confidence interval (Appendix I).
5) Test a preliminary Indoor Temperature and Humidity Protocol with a few practice scenarios in order to address any questions that come up during installation, documentation, or removal of sensors.
6) Document the final Indoor Temperature and Humidity Protocol.

The following sections of this report outline the intentions for how to determine the equipment needed, install sensors, collect asset data, report to NREL, and recover equipment.

In the future, when the Indoor Temperature and Humidity Study is complete, the authors will analyze the data and publish the findings.

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Step-By-Step Protocol

Step 1: Identifying Opportunities and Registering the New Project with NREL

NREL will monitor the industry for opportunities to recruit homes for the Indoor Temperature and Humidity Study. In addition, the authors ask to be notified when potential opportunities arise. In the ideal situation, the Indoor Temperature and Humidity Study data logging will be synergistic to the research projects and can be installed when staff members are already in the home for the primary project.

It is important that the lead researcher on each project contact Chuck Booten at NREL (chuck.booten@nrel.gov) before planning this part of a project. NREL will keep track of the housing characteristics and locations of all the projects across the county and will only encourage collecting this data if it adds to the overall diversity of the dataset.

To assure the sample of homes included in the study represents national trends as closely as possible, a diverse set of homes must be included. This includes a mix of: homes from all climate zones; home types (one-story, multistory, single family, multifamily, etc.); housing characteristics (vintage, enclosure construction, foundation type, heating fuel type, air tightness, house size, etc.); and variation in fuel costs..

Of course the choice of homes in the study will be constrained by practical considerations. The authors expect many of the homes recruited for the study will be new and retrofit projects being pursued by the Building America teams or other home energy programs. The authors also expect that the sample will be somewhat clustered with a few to dozens of homes being located in one project or community rather than the entire sample of homes being evenly distributed across the country. Projects and individual homes within projects will be chosen based on the considerations above and their similarity and differences to other homes in the study.

When a home has been recruited for the study, the equipment will likely be provided by NREL unless the primary institution conducting the research already has the equipment in stock. If the loggers are provided by NREL, they will be preprogrammed before delivery to the Building America team or other participating program. The Building America team or program participant will place the loggers, remove them after the logging period, and mail them back to NREL.

Discussion of the removal strategy will be required before sensors are delivered. There is no value in installing the sensors if the data cannot be obtained at the end of the monitoring period.

Step 2: Measurements and Equipment Needed

The following measurements will be made in each home in the study:

- Indoor T&RH in multiple locations in the home
- The runtime of the space conditioning equipment (furnace, air conditioner, heat pump, etc.).

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The outdoor T&RH will also be measured in at least one location for each community of study homes. All measurements will be taken at a minimum interval of one hour, at the top of the hour. Shorter intervals are acceptable but not recommended. Shorter intervals reduce the duration the loggers can operate before filling their memory. Consistent use of a one-hour interval also simplifies data handling and analysis. Most building energy simulation programs use one-hour intervals for analysis.

Step 2a: T&RH Loggers

NREL will use wall-mounted HOBO data loggers made by Onset to measure and store the data for the study. These loggers are small (about 2 in. by 3 in.) battery-powered, self-contained sensors with on-board storage. They can be programmed to log at a variety of time intervals and can store 84,650 measurements (5 years of T&RH data at one-hour intervals). For this study, NREL will use the UX100-011 HOBO loggers (Accuracy - Temp: ±0.38°F,RH: ±2.5%) for T&RH measurements. When using the UX100 series loggers, NREL will uncheck the "Push Button" box in the "Stop Logging" section of the "Launch Logger" window when launching the logger to prevent the accidental termination of data logging by the home occupants.

Other types and brands of loggers with similar accuracy may also be used. Also, in rare cases, homes will be monitored with more sophisticated equipment than what is discussed in this section by other institutions besides NREL. In those cases, NREL will gladly accept this data; but requests that the institution that collected the data upload it to the BAFDR. All of the other data and information requested in this protocol must be uploaded as well so that the data can be aggregated correctly in the future.

Step 2b: Outdoor T&RH Loggers

Outdoor T&RH loggers are very similar to the indoor loggers. The loggers that are rated for outdoor spaces are simply able to measure humidity levels up to 100% RH without breaking the internal components of the data logger. The authors have had good results using the Onset U23 logger for outdoor data collection in the past.

Step 2c: Runtime Equipment

The set points in simulations determine when the heating and cooling equipment use energy. Therefore, the data that will provide the most value to simulation tools is specifically during the time periods when heating or cooling is intentionally maintained at a set point by operation of a space conditioning system. Although space conditioning equipment operation may be inferred from indoor/outdoor temperature measurements in many cases, this approach may be problematic, especially in attached housing. The most straightforward way to unambiguously identify periods of space conditioning operation is to measure the runtime of the equipment.

The type and number of runtime loggers depends on the space conditioning equipment present and access to this equipment, so this information must be available prior to ordering the loggers. Table 1 describes the Onset HOBO loggers that have been successfully used by the authors to measure equipment runtime.

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Table 1. Equipment Used for Various HVAC Scenarios.

HVAC System	Suggested Logger Type
Central forced air heating and/or air conditioning systems *WITHOUT* fan cycling ventilation systems	UX90-004
Central forced air electric heating, heat pumps and/or air conditioner *WITH* fan cycling ventilation	UX90-004 or U12-006 or UX120-017 logger with appropriate current transformer Use U12-008 or H21-002 if installation is outside of the home
Central natural gas, oil, or propane heating systems *WITH* fan cycling ventilation And Boilers with hydronic distribution	UX90-004 with 24V AC solenoid
Distributed heating and/or air conditioning systems *WITH* forced convection (including window air conditioning units and mini-split heat pumps)	UX90-004 or U12-006 or UX120-017 logger with appropriate current transformer Use U12-008 or H21-002 if installation is outside of the home
Natural convection furnace	U10 or UX100-001 internal or external sensor

NREL Installation Kit

NREL will provide an Install Kit for any project that meets the needs of the study. The kit will include loggers for the indoor and outdoor T&RH, as well as for the runtime equipment. Depending on the type of HVAC system at the site, safety equipment may be recommended to the installer. NREL may be able to provide this equipment, depending on availability.

Step 3: Placement Guidelines

The success of the study will depend on careful and consistent placement of the sensors in each house. Inconsistencies in placement among the homes or poorly placed individual sensors (such as in direct sunlight or in direct line of a supply register air flow) will greatly reduce the usefulness of the data and may lead to a skewed result. This step defines a set of placement guidelines and an Indoor Temperature and Humidity Study Information spreadsheet form to assure consistency in the number and placement of sensors in each home regardless of the individual installer. These guidelines should be carefully adhered to whenever possible.

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Number and location of T&RH loggers

Installers should follow instructions outlined below when determining the number and location of the T&RH loggers in each home:

1. Place one T&RH logger in each bedroom.
2. Place at least one T&RH logger on each conditioned level of the home. (The bedroom loggers may satisfy this requirement.)
3. Place at least one T&RH logger in the basement if the home has a basement—conditioned or unconditioned.
4. Place one T&RH logger by each thermostat in the house.
5. For open-plan living space over 500 ft^2, use an additional logger for each additional 500 ft^2 of floor space.
6. DO NOT place any loggers in the kitchen or any bathroom (because large swings in temperature are likely not due to the conditioning system).
7. Although additional loggers not prescribed by the above guidelines are not required, they may be placed at the discretion of the installer if the above requirements will clearly leave a significant fraction of the conditioned space unrepresented.

Individual loggers may satisfy several of the placement rules. For example, a logger next to a thermostat in a second floor bedroom may simultaneously satisfy rules 1, 2, and 4. Due to the wide diversity in home types and design, the rules stated above may contradict each other in some homes. In that case, the placement of the loggers should default to the lowest numbered rule above. For example, if for some reason there are two thermostats in an open floor plan space that is smaller than 500 ft^2, then two loggers would be placed in that space. In all cases, engineering judgment will be required and assumptions should be documented in the Indoor Temperature and Humidity Study Spreadsheet.

Step 3a: Specific Placement of the T&RH Loggers Within Rooms

The specific logger location within a room should be chosen to best represent the air temperature and RH in the room while remaining out of the way of (and approved by) the occupants.

The following specific placement protocol applies to all T&RH loggers:

1. Choose the specific logger locations in partnership with the occupant whenever possible. The occupant should be present to consent to each specific location.
2. Mount the loggers on an ***interior*** wall.
3. Mount the loggers between 4 ft and 5 ft from the floor.
4. DO NOT place the loggers in the direct path of supply register airflow.
5. DO NOT place the loggers above, or within 4 ft horizontally of any heating or cooling appliance including, but not limited to baseboard heaters, space heaters, radiant panels, and window air conditioners.

6. DO NOT place the loggers where they will receive direct sunlight. Take the change of sun angles during the day and during the anticipated test period into consideration.
7. DO NOT place the logger within 4 ft of TV/entertainment centers, aquariums, large appliances, or other devices that may consume a larger amount of electricity and produce heat.
8. DO NOT place any loggers in the kitchen or any bathroom.
9. Use a removable mounting system such as 3M Command damage-free hanging strips. (When using Command Strips, leave at least one foot of space for the strip to be removed at the end of the logging period. It is easier to position the Command strip so it is pulled down (not up or sideways) when removed. One should wear one work glove when removing the Command Strips. Start pulling Command Strip with ungloved hand. Finish pulling with gloved hand so that if it snaps off, it doesn't bruise your hand.)

For all T&RH loggers being deployed, the following settings must be initiated via the Onset software by either NREL or the researcher in charge of the project:

1. A logger location description should be put in the Onset software and printed on the logger (or a label on the logger) with a permanent marker.
    a. The logger location description should be: zip code, street address number, unit number (if applicable), room name
2. Check to make sure the current battery level is at 100%.
3. Sensor on/off state: Do not measure the logger battery voltage during the field test.
4. A time step between one minute and one hour. A one-hour time step is recommended for this project.
5. Start logging: "At interval" (aka the next hour). Note the logger timestamp matches your computer's timestamp, so make sure your computer's timestamp is consistent with the time zone of the site to be analyzed (there are often delays and problems when trying to initiate the loggers on site).
6. Stop logging: "When memory fills."

Most of these settings may also be used for other types of Onset loggers, with a few minor modifications depending on the logger type.

Placing a sensor on the wall behind the entry door is often a good location for bedroom sensors.

There may be instances where it is impossible to follow all of the above placement guidelines. In these cases, the installer should use his/her judgment to choose a location that will best represent the average room temperature and make note of the situation in the Indoor Temperature and Humidity Study Information Spreadsheet.

Step 3b: Outdoor T&RH Logger

There will be one outdoor T&RH sensor for each community of study homes. If homes are within the same city or geographical area and can reasonably be expected to experience very

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similar outdoor conditions, they may share a common outdoor T&RH sensor. The placement of the outdoor T&RH sensor should follow this protocol:

1. Mount the loggers where they will be shaded 100% of the time in all seasons. An example of a location that may satisfy this requirement is on an exterior wall tucked under a porch roof. When placing the outdoor logger, be sure to consider the daily sun path, the change in sun path during the anticipated test period, and reflective surfaces that may reflect sunlight onto the logger.
2. If a fully shaded location is not available, choose a location that minimizes exposure to direct sunlight and mount the sensor in a solar radiation shield (such as the Onset M-RSA Solar Radiation Shield).
3. DO NOT mount the sensor in any enclosure other than a solar temperature radiation shield.
4. DO NOT mount the sensor near the outside unit of an air conditioner or the exhaust of any combustion appliance.

If placing an outdoor T&RH sensor is not possible, weather data from a nearby weather station can be collected and submitted with the data. This option is often undesirable due to the distance between the homes and the weather station, the level of effort required to locate and download the data, and the frequency of data gaps in weather station data.

Step 3c: Runtime of Space Conditioning Equipment

To help interpret the temperature data, the runtime of the space conditioning equipment will also be logged. A runtime logger should be placed on each piece of space conditioning equipment expected to operate during the logging period. Table 2 provides suggestions on logger placement for different HVAC scenarios.

In homes with forced air circulation systems, it may also be possible to use a temperature logger such as the HOBO U10 or UX100-001 placed in a supply register to determine run time. Alternative logger types with similar capabilities and accuracy and other measurement approaches can be used. Document the approach and equipment to be used and discuss with NREL before installation.

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Table 2. Placement of HVAC On/Off State Sensors.

HVAC Scenario	Placement Notes
Central forced air heating and/or AC systems *WITHOUT* fan cycling ventilation systems	Place on off state motor sensor on or near the air handler fan motor or attached to the power wire leading to the air handler fan motor. A temperature logger placed in a supply register may also be used.
Central forced air electric heating, heat pumps and/or AC *WITH* fan cycling ventilation	UX90-004 placed on the wire to the heating, heat pump outdoor unit, or AC outdoor unit or U12-006 with CT on the same wires. (Strategy above may also be used).
Central natural gas, oil, or propane heating systems *WITH* fan cycling ventilation And Boilers with hydronic distribution	Connect 24V AC solenoid in parallel with the thermostat wires and use the UX90-004 as a pulse counter on the solenoid switch
Distributed heating and/or AC systems *WITH* forced convection (including window AC units and mini-split heat pumps)	Monitor each piece of equipment expected to operate during the test period. Can use the UX100-011 and place near the air stream of the distributed heating system.
Natural convection furnace	A temperature sensor should be placed in the supply air register to indicate the furnace runtime.

Step 4: Documentation of Pertinent Information

A detailed record of the loggers and the home are essential to assure correct interpretation of the temperature, RH, and runtime data. The spreadsheet entitled *Indoor Temperature and Humidity Study Information* must be used for recording the relevant logger and home characteristics information before data loggers are supplied. The information required is listed in Table 3.

Table 3. General Information To Be Documented.

Project Name	**Format of the project name should be: "Building America climate region.Zip code.Institution conducting research.House ID number". The House ID number will be distributed by NREL upon acceptance into the study.**
Brief description of project	
Installer's name(s) and contact info	Name, phone number, and email address of those actually installing the loggers
Building America Team/Research Organization	Name of the Building America team involved in the project, if any.
Project partners contact info	Name, phone number, and email address of other people associated with the project.
Documents associated with the project	Please include a full reference and/or link to any previous reports on the project.

Step 4a: House Information

The information related to the house itself will be documented in the *Indoor Temperature and Humidity Study Information* spreadsheet (details shown in Table 4). This information is

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important so that data aggregation can be done according to various house components. It is possible that an unexpected trend will arise, but won't be known until all the data is collected.

Table 4: House Information To Be Documented.

Street address	Street number and street name
City	
State	
Zip code	
Home type	Single family detached, duplex, townhome, apartment or condo, etc.
Apartment number	If applicable
Number of bedrooms	
Number of bathrooms	Count each bathroom as one. Bathrooms with no bathtubs or with only a shower are each counted as one bathroom.
Interior or corner apartment	If the home is an apartment, please indicate if it is an interior or corner unit. If the configuration does not fit these descriptions, please list the walls in the apartment that are exterior walls.
Estimated total conditioned square footage	Total square footage of the conditioned portion of the home.
Basement Conditions (if applicable)	Is the basement conditioned? For forced air systems, does the basement have a supply register? Is a dehumidifier used in basement? If the basement is partially conditioned or conditions are ambiguous, please record your observations.
Installed heating equipment and fuel type	Gas furnace, gas boiler, central air-source heat pump, ground source heat pump, electric resistance, oil furnace, ductless minisplits, etc. Include as much information as available, such as rated output.
Heating distribution type	Forced air, radiant floor, baseboards, distributed, point source, etc.
Installed cooling equipment	Central AC, central air-source heat pump, ground source heat pump, ductless minisplits, central evaporative cooler, window air conditioners, etc.
Primary heating/cooling equipment location	Is the equipment in conditioned space, attic, garage, closet, etc?
Supplemental heating or cooling equipment	Make note of any plug-in portable heating or cooling equipment present in the home and in what room it was found. Examples include electric space heaters, kerosene space heaters, portable air conditioners and evaporative coolers, temporarily installed window air conditioners, etc. Make note of the rated output, if possible.
Dehumidifier? (if applicable)	Type and location of dehumidifier? Central or point source? In operation with air conditioner? In operation with occupancy? In basement only? Settings at time of sensor installation?
Fireplace or woodstove?	If there is a fireplace or woodstove, please provide a short description included the floor and room where it is located and the fuel type (wood or gas).
Year constructed	

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Have energy upgrades been installed since the year of construction?	Yes or No. Provide details, if possible
Window types	Single or double pane? Air or argon filled? Frame type?
Infiltration	If measured, please report the ACH50 for the home
Duct Leakage	Report if measured (preferably in CFM25)
Number of heating/cooling zones	(i.e. number of thermostats)
Heating and cooling settings at time of installation	Temperature? Is the thermostat programmed?
Is the home intentionally passive solar?	
Enclosure construction	Wood frame, CMUs, ICFs, SIPs, other
Foundation type	List all that are applicable: Unconditioned full basement, conditioned full basement, conditioned garden-level basement, crawlspace, slab, partial basement, combination of the above, etc.
Large solar gains	Please make note of rooms with window areas larger than 40 ft^2 on south or west side of the house. Note the directions that the large windows face.
Notes	Please include any notes that may be helpful in interpreting the data from this house. Note any peculiarities of the home.

Step 4b: Logger Information

The information in Table 5 must be recorded for each indoor temperature and T&RH logger.

Table 5. Logger Information to be Documented.

Logger Name	The convention for naming loggers is as follows: [zip code]-[street address number]-[unit number if applicable]-[room or equipment type] Example 1: A temperature logger in an west apartment bedroom: 80303-2905-211-WBR Example 2: A runtime logger in a detached house: 80305-1290-furnace
Logger Serial Number	As assigned by the manufacturer. HOBO loggers have this on a sticker on the back of the logger
Floor	On what floor of the home is the logger located? Examples: Basement, first, second, etc. For apartments, this is the floor of the apartment, not of the building. For example, the floor in a one-story apartment on the third floor of a multifamily building would be called the first floor.
Room	In what room is the logger located? Examples: Bedroom, Great Room, Living Room, Basement, etc. For multiple bedrooms on the

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	same floor, use cardinal directions to distinguish between bedrooms. Examples: N Bedroom, SW Bedroom, E Bedroom, etc.
Is there a thermostat in the room?	Yes or No. (If Yes, the logger should be located next to the thermostat.)
Detailed location	Where in the room is the logger located? This information will help the person downloading the data or removing the logger. Examples: behind the door, on the west wall, etc.
If not wall mounted, where is the logger located?	If the logger is not mounted on the wall but instead placed in another location such as the top of a bookcase or on a shelf, record the location so the logger can be found by another person.
Estimated weighted floor areas*	Estimate the floor area (in square feet) of the space being represented by the temperature measurement.
Notes	Record any information about the logger or room where it is located that may be useful in understanding its placement or interpreting its data. Examples: "There was a plug-in electric heater in the room." "Logger may receive some direct sunlight near summer solstice." "There was a plug-in evaporative cooling in the room."

* If a kitchen is part of a great room (no doors can close between them), count that area for that sensor. If the kitchen is separate from the great room, do not count that floor area for a sensor. The estimate need not be precise, but a reasonable estimate needs to be made and recorded for each temperature logger placed in a home. The weighted floor areas will not add up to 100% of the actual square footage of the home due to the fact that loggers will not be placed in bathrooms, kitchens and some hallways.

Step 4c: Researcher Contact Information

In order to maintain an accurate record of NREL equipment, NREL will need to contact each project's point of contact (POC) from time to time. Information in Table 6 will be collected for each project, in case specific questions arise regarding the project details.

Table 6. Occupant Information To Be Documented.

Name	Name of POC for project—the person who coordinated the installation
Phone number	
Email address	

Step 4d: Questions for House Occupants

The occupants of the house know its operation better than any researcher could. For that reason, the team asks the occupants to provide some high-level information about the house and how it operates. Several of the following questions are taken from the International Energy Agency's RECS. Comparison of our results to the answers generated by these questions may also help correlate survey responses to measured temperature. Good correlation between survey results and measured temperatures will provide higher confidence in the much larger survey data sample.

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Is the home occupied by the primary owner?
Are the home's utility bills paid for by the occupants?
How many bedrooms are occupied?
In general, is the home occupied all day during the weekdays?
Are different parts of the home intentionally maintained at different temperatures?
Are the bedroom doors generally open or closed during the day? At night?
Are the windows commonly open while the home is being heated or cooled?
Questions if HEATING season temperatures are being measured Is the thermostat that controls the main heating equipment programmable? *(RECS D-10b)* • Is the thermostat usually programmed to automatically lower the heating temperature setting during sleeping hours? (RECs D-10b1) • Is the thermostat usually programmed to automatically lower the heating temperature setting *during the day*? (RECs D-10b2) Now, please think about the temperature inside the home when central heating equipment was used last winter. • During the winter, what is the temperature when the house is occupied *during the day?* (RECS D-11a) • During the winter, what is the temperature when the house is not occupied *during the day*? (RECS D-11b) • During the winter, what is the temperature inside the home *at night*? (RECS D-11c)
Questions if COOLING season temperatures are being measured Is the thermostat that controls the central air conditioning equipment programmable? *(RECS F-9a)* • Is the thermostat usually programmed to **adjust the cooling temperature setting** during sleeping hours? (RECs F-9a1) • Is the thermostat usually programmed to **adjust the cooling temperature setting** *during the day*? (RECs F-9a2) Now, please think about the temperature inside the home when central air conditioning equipment was used last summer. • During the summer, what is the temperature when the house is occupied *during the day?* (RECS F-10a) • During the summer, what is the temperature when the house is not occupied *during the day*? (RECS F-10b) • During the summer, what is the temperature inside the home *at night*? (RECS F-10c)

Step 5: Log Time Duration and Removal

Whenever possible, loggers should be left in place for at least a full year to record the complete seasonal variation of indoor temperatures. However, this may not be possible for some projects. The heating and cooling set point and the effect on actual indoor temperature can be inferred from the most extreme two or three weeks of each season fairly easily. Ultimately, the logging

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duration is likely to be affected most by factors including access to the homes, occupant scheduling and project scheduling (when piggybacking the temperature measurements onto projects with additional objectives). At the very least, data for this study should be taken for a minimum of two weeks near the peak of the heating or cooling period.

If the project's POC will be visiting the home for their primary project, they will be expected to remove the loggers and send them back to NREL.

If the POC is not going to be re-entering the house(s) after the monitoring period, the loggers can be removed by the occupants and sent back to NREL in a pre-addressed package (coordinate with NREL to have this sent to the house(s)). All loggers will be labeled with permanent marker and their serial numbers will be recorded in the *Indoor Temperature and Humidity Study Information* spreadsheet, so it will be easy to determine which logger was installed in what location when they return to NREL. If a logger is in a location other than easy-to-access, safe spaces, NREL will likely have to collect the loggers. However, this will be considered prior to the installation and acceptance of the house to this study.

Step 6: Data Collection and Aggregation

If NREL provided the sensors and will be receiving them after the project, NREL will upload all information from the *Indoor Temperature and Humidity Study Information* spreadsheet to the BAFDR (http://buildings.nrel.gov/BAFDR).

If the institution provided their own sensors, they will be responsible for uploading their project information to the BAFDR. Please contact Mike Gestwick at NREL (Michael.Gestwick@nrel.gov) for questions related to the use of the BAFDR.

It is expected that the data collection for the required number of homes (and variety of data) will be completed in 2015, with the aggregation of the data completed in FY 2016.

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Looking Ahead

The main goals of the future Indoor Temperature and Humidity Study are to answer the following questions:

How should the indoor temperature be represented in simulation tools to most accurately represent a home in an asset rating?

What is the average relative humidity in homes with and without dehumidifiers and how is the relative humidity distributed between rooms?

The authors recognize that actual thermostat set points in occupied homes will likely vary substantially and in a potentially quirky manner with specific occupants. Therefore, this study is not seeking agreement between modeled and actual energy use in individual specific occupied homes. The information gathered using this protocol will be applied to asset analyses where the average effect of thermostat set-point behavior is modeled. The research questions are intentionally stated very generally to allow for creativity in approaching the representation of indoor temperature and humidity in simulations.

Many simulation tools only have a single heating, and cooling (and sometimes humidity) set point at this time. To accommodate this reality, a primary objective of the future study will be to determine the most representative average indoor temperatures and humidity during heating, cooling and swing seasons to use in current models constrained to this type of limited input.

The current Building America HSP prescribes the heating and cooling set point temperature as follows (Hendron and Engebrecht, 2010):

Set point for cooling: 76°F with no setup period
Set point for heating: 71°F with no setback period

The data from the Indoor Temperature and Humidity Study will be used to update these set point temperatures. In addition, it is anticipated that a more sophisticated and effective approach to simulating the effect of indoor temperature and humidity on energy use may be possible based the study data. Some examples of possibilities include:

- Set point schedules that are designed based not only on the average indoor temperatures from the study, but also on the statistical frequency of setbacks and setups
- Look-up tables of heating and cooling set points (or hourly schedules) based on factors such as climate zone, type of distribution system, fuel cost, home vintage, etc.
- Monte Carlo methodology in which the results of multiple simulations, each using different set points, are combined according to the probability density of each set point
- Better representation of multizone temperature distributions for multiple zone modeling tools that provide a more realistic analysis of indoor temperatures in homes
- More accurate relative humidity profiles based on large data set of real humidity levels (and distribution) in homes.

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The data from this study may also be of interest to other researchers to answer research questions. Therefore, when the final analysis report is published, the raw data set will be as accessible as possible. However, to maintain the privacy of the homeowners, some data, such as specific address, may need to be hidden/ unpublished.

Future Study Snapshot

The following bullet points provide an overview of the scope of the Indoor Temperature and Humidity Study that will be conducted, including**:**

- More than 350 homes of different types in a variety of climates and house types (possibly more as data disaggregation occurs for different climate regions, etc.)
- Stand-alone battery powered sensor/loggers
- Hourly temperature and humidity measurements in the living room, all bedrooms, and outdoors
- On/off state sensors for heating and cooling equipment
- At least two weeks of data near the peak of the heating or cooling season.

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Appendix I: Calculating Sample Size

In order to calculate the number of homes needed for the Indoor Temperature and Humidity Study, we must first assume that the average indoor temperature is distributed normally. Given this assumption is satisfied, we calculate the sample size, *n*, using the following:

$$Margin\ of\ Error = Z_{\alpha}\frac{\sigma}{\sqrt{n}}$$

where Z_{α} is a factor based on the level of desired confidence and σ is the standard deviation[2]. For this project, we would like the margin of error to be no larger than 0.5° F. In other words, we want to be at least 95% confident that the true mean lies in the interval X +/- the margin of error, where X is the sample mean. For a 95% confidence level, the factor Z_{α} is 1.960 (for 99% confidence level, $Z_{\alpha} = 2.575$).

Given this information, Table 7 indicates the number of homes, *n*, that are needed to have a margin of error of 0.5 ° F for a possible range of standard deviations. This range was chosen based on the sample standard deviations seen in previous studies outlined in Appendix II.

Table 7. The Number of Homes Needed for a Given Level of Confidence (CI) at a Range of Possible Standard Deviations.

Standard Deviation (°F)	n_i (CI: 95%)	n_i (CI: 99%)
4.00	246	425
4.25	278	480
4.50	312	538
4.75	347	599
5.00	385	664
5.25	424	732
5.50	465	803

Table 7 shows that the sample size requirement could grow or shrink depending on the findings of the study. As data comes in, it will be analyzed every 8-10 months and the sample size requirements will be adjusted accordingly. Sample size may change depending on disaggregation techniques for data acquired. For example, the standard deviation for a given climate region could be much smaller than 5, in which case the sample size for that region would be much smaller than 385 for a 95% confidence interval.

[2] Margin of Error. http://stattrek.com/estimation/margin-of-error.aspx. Accessed December 4, 2013.

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Appendix II: Summary of Preliminary Indoor Temperature Studies

A: New York, Florida, and Oregon Study – 2009

The Consortium for Advanced Residential Buildings (CARB) Building America team collected hourly indoor temperature data for a total of 60 homes located in New York, Florida, and Oregon. Three sensors were placed inside each home, measuring the temperature of the living room, master bedroom, and main bathroom. This data was collected in 2009, but was analyzed by Roberts and Lay in 2013 (Roberts and Lay, 2013). The additional analysis below focuses only on the heating season, using the time period Dec 15. 2008—Feb 28. 2009. Observations from the three sensors were used to calculate the mean indoor temperature, standard deviation, and the temperature difference between each room and the mean for the heating season. The difference between each room's temperature and the mean was calculated as follows:

$$\Delta\ Room = mean\ temp\ of\ room - mean\ temp\ of\ home$$

Additionally, only homes located in New York and Oregon were used for this analysis since they have a distinct heating season.

Table 8. The Mean Indoor Temperature, Standard Deviation, and Difference Between Room and Mean Temperature for Each Home Located in New York.

State/Home ID	Records	Mean Temp	Standard Deviation	ΔLiving Room	ΔMaster Bedroom	ΔBath
NY/21	5,472	62.9	6.0	4.5	-5.7	1.4
NY/22	5,472	64.0	4.7	-6.1	2.6	3.4
NY/23	5,472	68.0	3.1	-1.5	1.4	0.0
NY/24	5,472	67.6	4.5	5.4	-2.5	-3.0
NY/25	5,472	69.7	2.5	-1.6	1.0	0.7
NY/26	5,472	66.0	2.4	-0.8	-0.1	0.8
NY/27	5,472	63.4	3.5	-3.8	2.7	0.9
NY/28	5,472	63.6	3.0	1.8	-1.4	-0.3
NY/29	5,472	67.8	2.9	1.0	-1.6	0.5
NY/30	5,472	61.7	3.7	-0.5	0.3	0.3
NY/31	5,472	64.5	5.2	-2.7	2.2	0.6
NY/32	5,472	64.1	4.1	-3.0	-0.5	3.5
NY/33	5,472	64.6	2.9	3.1	0.0	-3.2
NY/34	5,472	67.5	2.7	-0.1	0.3	-0.3
NY/35	5,472	62.8	2.5	1.3	-3.0	1.7
NY/36	5,472	62.2	3.2	-3.0	0.6	2.4
NY/37	5,472	68.2	2.3	-0.7	-1.2	1.7
NY/38	5,472	65.1	2.4	-1.1	1.3	-0.3
NY/39	5,472	63.5	1.9	0.6	-0.5	0.0
NY/40	5,472	66.2	2.8	-2.7	1.7	0.9
All NY	**109,440**	**65.2**	**4.1**	**-0.5**	**-0.1**	**0.6**

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Table 9. The Mean Indoor Temperature, Standard Deviation, and Difference Between Room and Mean Temperature for Each Home Located in Oregon.

State/Home ID	Records	Mean Temp (°F)	Standard Deviation	ΔLiving Room	ΔMaster Bedroom	ΔBath
OR/42	5,319	61.7	3.5	-1.7	-0.4	2.1
OR/43	3,648	64.4	4.9	-0.6	0.5	-
OR/44	5,472	61.7	5.6	5.7	-3.2	-2.6
OR/45	3,648	57.4	5.1	2.3	-2.3	-
OR/46	5,472	66.0	3.3	3.4	0.1	-3.5
OR/47	3,648	60.9	3.9	1.9	-2.0	-
OR/48	5,472	64.5	3.2	-1.1	-1.4	2.3
OR/50	5,472	60.1	3.5	0.5	-1.7	1.3
OR/51	5,472	62.5	2.9	1.4	0.2	-1.8
OR/52	5,472	65.6	1.6	0.1	-0.3	0.2
OR/53	5,472	55.7	8.3	-2.2	1.4	0.7
OR/54	3,720	67.1	4.2	-1.0	-0.1	1.1
OR/55	5,472	67.4	1.1	0.4	0.2	-0.7
OR/56	3,648	64.6	4.6	-0.1	0.2	-
OR/57	5,472	60.5	3.1	-2.1	-1.0	3.1
OR/58	5,472	62.6	2.1	1.1	-0.8	-0.3
OR/59	5,472	63.4	1.8	0.9	-1.1	0.1
OR/60	3,648	68.1	3.7	1.0	-1.0	-
OR/61	5,472	65.9	3.5	-2.0	0.7	1.4
All OR	**92,943**	**63.1**	**5.1**	**0.4**	**-0.6**	**0.2**

Table 10. The Mean Indoor Temperature, Standard Deviation, and Difference Between Room and Mean Temperature for Oregon and New York.

State	Records	Mean Temp (°F)	Standard Deviation	ΔLiving Room	ΔMaster Bedroom	ΔBath
NY	109,440	65.2	4.1	-0.5	-0.1	0.6
OR	92,943	63.1	5.1	0.4	-0.6	0.2
Total	**202,383**	**64.2**	**4.7**	**-0.1**	**-0.4**	**0.6**

Results: From Table 10, we see that the mean indoor temperature in New York is approximately 2º F higher than the mean temperature in Oregon and the sample standard deviation differs by 1º F. Furthermore, we see in Table 8 and Table 9 that there is not a uniform difference between the mean home temperature and each room. Therefore, more than one sensor is needed to calculate an average temperature for each home.

Lessons Learned:

1) Homes that use wood burning as their primary heat source should not be part of the study. Wood stoves do not have adequate control functions to manipulate house temperatures within a few degrees.
2) It is very important to avoid putting the sensors in locations that are strongly affected by point-source-type heat (i.e. fireplaces, direct sunlight/solar gains, vent air streams, major appliances, media centers, space heaters, etc.).

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3) There is too much noise in data taken near bathrooms or kitchens; therefore, it is not worth the cost of the sensor to get data in these locations.

Results from this study are summarized in Appendix II A. Temperatures in different rooms can vary significantly from the overall mean home temperature, hence confirming the need to use multiple temperature loggers. The overall mean temperature was 64.2°F with a standard deviation of 4.7°F.

B: Maryland Study – 2011

The Partnership for Home Innovation (PHI) team conducted a study in Greenbelt, Maryland, in 2011. The Maryland study collected daily indoor temperature data for a total of 10 apartment units. Three to four sensors were placed inside each home, measuring the temperature of the living room, dining room, bedroom 1, and bedroom 2. The additional analysis below focused only on the heating season, using the time period December 15, 2010—February 28, 2011. Observations from the sensors were used to calculate the mean indoor temperature, standard deviation, and the temperature difference between each room and the mean for the heating season. The difference between each room's temperature and the mean was calculated as follows:

$$\Delta\ Room = mean\ temp\ of\ room - mean\ temp\ of\ unit$$

Table 11. The Mean Indoor Temperature, Standard Deviation, and Difference Between Room and Mean Temperature for All Ten Units.

Building	Unit	Records	Mean Temp (°F)	Standard Deviation	ΔBedroom1	ΔBedroom2	ΔDining Room	ΔLiving Room
GHI-1	B1	300	69.9	1.9	-0.7	-1.1	1.5	0.1
GHI-1	B2	225	68	2.2	-1.3	0.5	-	0.8
GHI-1	B4	300	70	5	1.8	-6.9	2.3	2.7
GHI-2	FB5	280	64.6	3.3	-1.5	-1.6	1.3	1.5
GHI-2	FB6	210	64.4	2.7	-1.8	2.3	-	-0.3
GHI-2	FB8	210	63.8	4.2	3.7	-	-3.1	-0.8
GHI-3	FV5	244	69.5	2.5	-0.3	0.2	-	-
GHI-3	FV6	183	64.5	2.4	-0.4	0.4	-0.2	0
GHI-3	FV7	183	65.8	2.6	0.1	-1.3	-	0.7
GHI-3	FV8	183	62.1	2.9	-3.5	0.2	0.5	2.4
All	**-**	**2318**	**66.5**	**4.2**	**-**	-	**-**	**-**

Results: From Table 11, we see that the mean indoor temperature of all units is 66.5º F and the sample standard deviation is 4.2º F. Furthermore, we note that there is not a uniform difference between the mean unit temperature and each room. Therefore, more than one sensor is needed to calculate an average temperature for each apartment unit.

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C: Colorado Study – 2013

Nine apartments were instrumented in the Phoenix Apartments complex in Boulder, Colorado. Installing loggers, collecting the data, and analyzing the data from the Phoenix Apartments homes provided early temperature data as well as direct feedback on the draft Indoor Temperature Measurement Protocol. This appendix documents the temperature data collected as well as lessons learned in the process.

The Phoenix Apartments: The apartments in the Phoenix complex range in size from 470 ft^2 to 800 ft^2. They are rented primarily by students of the University of Colorado. The apartment complex underwent renovations in 2011 to bring it into compliance with the Boulder's residential energy conservation ordinance, dubbed "SmartRegs". A Building America Program's research project led by the CARB team is evaluating how realized energy savings compare to predicted savings and is conducting a cost benefit analysis on the retrofit package. NREL staff and contractors coordinated with CARB to piggyback the temperature measurements onto the existing research project.

A range of units were chosen for this study, including: corner and end, first and second story, and 1-3 bedroom units (up to 800 ft^2). The draft Indoor Temperature Measurement Protocol was used to determine the number and placement of sensors in each apartment. Data was collected with battery powered temperature and T&RH loggers with data recorded every 15 minutes. The data used in this analysis spans from January 7, 2013 to March 26, 2013.

The team was prepared to install run time sensors in the air handlers of the furnaces in the apartments. However, upon arrival at the apartments, the team discovered that the furnaces were all natural convection units without air handlers. We were, therefore, unable to log furnace on/off state for the project.

Research Questions: The following research questions provided guidance for conducting this preliminary study:

1) What is the Weighted Average Indoor Temperature (WAIT) in each of the Phoenix apartments when the furnace is providing heat to the space?
    a. How sensitive is the average temperature to changes in weighting factors?
2) How does the WAIT compare to the average temperature at the thermostat?
    a. Do we have to measure all bedrooms in addition to the living room (thermostat) to accurately determine average indoor temperature?
3) Does the Indoor Temperature Measurement Protocol provide adequate information on sensor acquisition, installation and retrieval?
4) How does the data from this study compare to other studies? Are there any discernible trends?

Results: The mean temperature of each apartment, the standard deviation, and the temperature difference between the mean and each room are shown in Table 12.

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Table 12. The Mean Apartment Temperature (°F), Standard Deviation, and Difference Between Room and Mean Temperature for All Phoenix Apartments.

Building	Apt #	Records	Mean Temp (°F)	Standard Deviation	ΔBedroom1	ΔBedroom2	ΔLiving Room
2905 E. College Ave	103	3766	71.9	1.9	2.0	NA	-1.4
2905 E. College Ave	106	3766	68.7	2.6	0.8	NA	-0.5
2905 E. College Ave	108	5649	67.2	3.2	0.6	-1.8	0.8
2905 E. College Ave	208	5649	68.7	2.9	-0.9	2.3	-1.0
2905 E. College Ave	211	3766	68.7	2.2	0.6	NA	-0.4
2905 E. College Ave	117	3766	68.6	3.9	-1.7	NA	0.3
2905 E. College Ave	119	5649	69.9	4.0	-3.7	3.4	-2.7
2905 E. College Ave	121	3766	68.5	2.7	0.3	NA	-0.2
2905 E. College Ave	215	3766	67.4	4.0	1.1	NA	-0.7
All		39543	68.8	3.2	-	-	-

In order to determine the accuracy and precision of the HOBO sensors that were used for this project, a lab test was conducted after the sensors were recovered from the field. The sensors were placed in the lab with four thermocouples over two days and the results showed that the precision of HOBOs was +/-0.36ºF. In addition, on average, the HOBOs were 0.4 degrees above the temperatures of the thermocouples (similar to the expected uncertainty of the sensors). This means that the average mean temp shown above was likely actually 68.4ºF, which doesn't significantly change the results of the Colorado project.

The following results correspond to the numbered research questions:

1) *What is the WAIT in each of the Phoenix apartments when the furnace is providing heat to the space?*

The average weighted indoor temperature is calculated by using the square footage of each bedroom and the total square footage of the living room area. The kitchen and bathrooms are not monitored in this study because their external sources of heat (cooking and showers) would create too much noise in the data when focusing on temperatures related to calls for heating or cooling.

In the case of the Phoenix apartments, the weighted indoor temperatures were determined by the following equation 1:

$$WAIT = \left[\left(\frac{LR}{Tot}\right)_{sf} \times T_{LR}\right] + \left[\left(\frac{BR1}{Tot}\right)_{sf} \times T_{BR1}\right] + \left[\left(\frac{BR2}{Tot}\right)_{sf} \times T_{BR2}\right] + \left[\left(\frac{BR3}{Tot}\right)_{sf} \times T_{BR3}\right] + \left[\left(\frac{B}{Tot}\right)_{sf} \times T_{B}\right] \quad (1)$$

Where:

$WAIT$ = Weighted Average Indoor Temperature

$(\ )_{sf}$ = square footage

LR = Living Room (square footage should include kitchen if open concept)

Tot = Total square footage of rooms with temperature measurements

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BR = Bedroom (BR1= 1st bedroom, BR2= 2nd bedroom, etc)
B = Basement
T = temperature
where BR2, BR3 and B are only used if applicable.

The average temperatures for each apartment are represented in Table 13. The WAIT of all nine apartments was about 69°F.

Table 13. Weighted Average Indoor Temperatures.

Apt. Num.	# of Bedrooms	Total Area	Middle or End Unit	Floor	Average Indoor Temperature (°F)	
					All Rooms Equally Weighted	Weighting Based on Plans
#103	1 Bedroom	490 ft^2	End Unit	1st	71.6	72.1
#106	1 Bedroom	490 ft^2	Middle Unit	1st	68.6	68.8
#108	2 Bedrooms	680 ft^2	End Unit	1st	67.3	67.1
#208	2 Bedrooms	630 ft^2	Middle Unit	2nd	68.6	68.9
#211	1 Bedroom	490 ft^2	End Unit	2nd	68.6	68.7
#117	1 Bedroom	490 ft^2	Middle Unit	1st	68.6	68.6
#119	3 Bedrooms	800 ft^2	End Unit	1st	70.2	70.9
#121	1 Bedroom	490 ft^2	End Unit	1st	68.4	68.5
#215	1 Bedroom	490 ft^2	Middle Unit	2nd	67.2	67.4
Averages of All Nine Apartments					**68.8**	**69.0**

1) a. How sensitive is the average temperature to changes in weighting factors?

It depends on the size of the rooms. If the rooms are under 200 ft^2 each, it doesn't make a significant difference in the result to change the weighting factors as described below. If the rooms are larger, it has been calculated that these weights matter more and should be used as stated in equation 1.

In the current draft of the Indoor Temperature Measurement Protocol, installers are required to estimate the square footage of the rooms where the sensors are located. These estimates are then used to create weighting factors for calculating the WAIT. In small housing units such as the Phoenix Apartments, weighting may not be necessary. To test its sensitivity to weighting factors, we calculated the average indoor temperature using two different sets of factors:

1. Equal weighting of each measurement
2. Weighting factors based on area taken from floor plans of the apartments.

The results are given in Table 13. For these small apartments, the weighting factors had only a small (about 0.2°F) effect on the WAIT for the asset rating. The resolution goal in this study is 1°F. A 0.2°F difference in this case proves that the variation in room size for small apartments such as the ones in this study, do not affect the outcome of the results. In situations where the room sizes are somewhat similar, researchers can save time and resources by not having to measure the dimensions exactly.

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2) How does the WAIT compare to the average temperature at the thermostat?

The difference between the WAIT (with weighting based on the floor plans) and the average temperature at the thermostat is shown in Table 14 for each apartment. The average absolute difference for all nine apartments was nearly 0.8°F[3]. A positive difference in Table 2 implies that the bedrooms were cooler on average than the thermostat in that apartment. This was true in seven of the nine apartments. The WAIT and the average thermostat temperature differed substantially more in end units (1.1°F absolute difference) than in middle units (0.4°F absolute difference).

Table 14. Weighted Average Indoor Temperatures Compared to Average Thermostat Temperatures.

				Average Temperature (°F)			
Apt. Num.	**# of Bedrooms**	**Middle or End Unit**	**Floor**	**Thermostat**	**All Rooms Weighted**	**Difference**	**Absolute Difference**
#103	1 Bedroom	End Unit	1st	73.3	72.1	1.2	1.2
#106	1 Bedroom	Middle Unit	1st	69.2	68.8	0.5	0.5
#108	2 Bedrooms	End Unit	1st	66.4	67.0	-0.7	0.7
#208	2 Bedrooms	Middle Unit	2nd	69.68	68.9	0.8	0.8
#211	1 Bedroom	End Unit	2nd	69.09	68.7	0.4	0.4
#117	1 Bedroom	Middle Unit	1st	68.72	68.6	0.1	0.1
#119	3 Bedrooms	End Unit	1st	72.63	70.9	1.8	1.8
#121	1 Bedroom	End Unit	1st	68.68	67.4	1.3	1.3
#215	1 Bedroom	Middle Unit	2nd	68.15	68.5	-0.4	0.4
Averages of All Nine Apartments				**69.5**	**69.0**	**0.6**	**0.8**

2) a. Do we have to measure all bedrooms in addition to the living room (thermostat) to accurately determine average indoor temperature?

Yes.

The maximum temperature difference between the living room and one of the bedrooms was calculated for each time step in each apartment. The frequency distribution of the temperature difference is shown in Figure 1. A negative difference indicated that a bedroom was warmer than the thermostat temperature; a positive difference indicates a bedroom was cooler than the thermostat temperature. As in Table 2, there is a clear trend for the bedrooms to be cooler than the temperature at the thermostat. On the average, the bedrooms were about 1.6°F cooler than the living room. However, this difference varied greatly (standard deviation = 3.1°F). Taking the absolute value of the temperature difference, the bedrooms differed from the temperature at the thermostat by an average of 2.6°F.

[3] Although the uncertainty for the HOBOs is on the order of 0.8 degrees, calibration tests were performed both before and after the study. All HOBOs were within 0.1 °F of each other for these calibrations. So, the relative difference between them should be accurate in this case.

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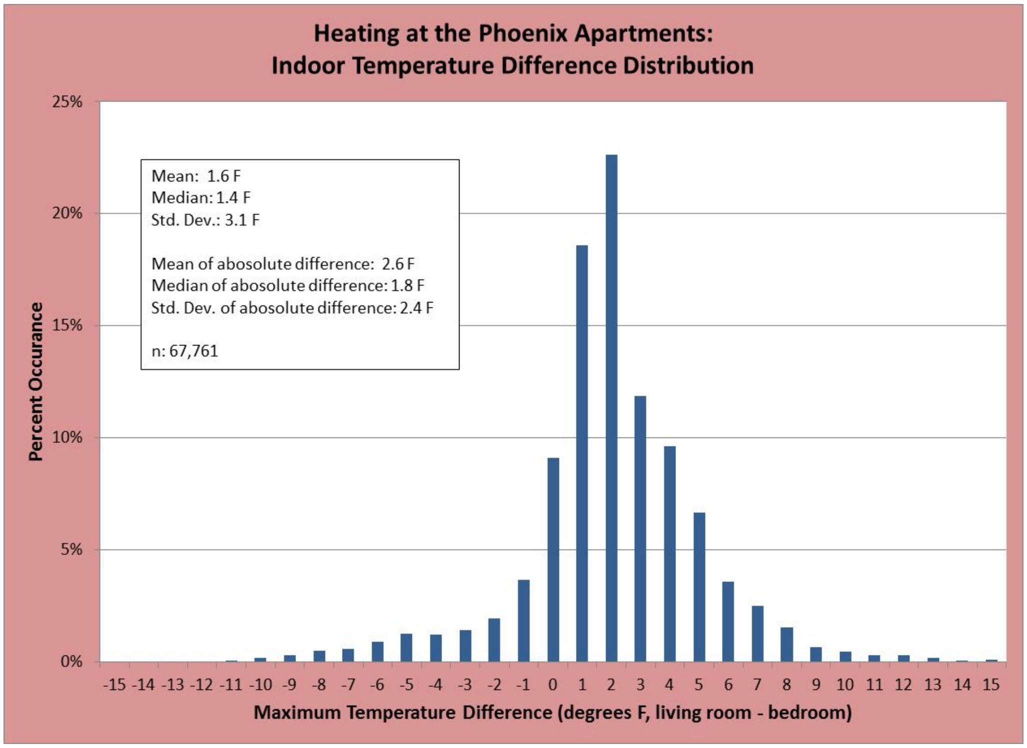

Figure 1. Frequency distribution of the maximum temperature difference between the living room and a bedroom in all nine apartments.

Even in these small apartments, the differences shown in Table 14 and Figure 1 are large enough to justify measuring bedroom temperatures and using an average temperature rather than simply measuring the temperature near the thermostat. In older homes with larger conditioned areas, the room-to-room temperature differences would likely be greater than measured in this study.

3) *Does the Indoor Temperature Measurement Protocol provide adequate information on sensor acquisition, installation and retrieval?*

A primary objective of the Phoenix Apartments installation was to vet the previous version of the Indoor Temperature Measurement Protocol. The project fulfilled this objective and led to several revisions in both the protocol document and supporting data spreadsheet templates:

- Rewriting the minimum logger requirement: Changed from 3 with one redundant in the living room, to a minimum of 2 without redundancy in the living room. (Note: HOBO calibration before and after this study showed that all HOBOs were recording the same/correct temperatures throughout the study.)
- Development of more comprehensive runtime logger recommendations that address a wide array of space conditioning equipment:
    - Furnaces or air conditioners with air handlers (on/off state motor HOBOs)
    - Electric baseboards (circuit HOBO)

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- Furnaces without air handlers/ducts (initial temperature reading when system is operating and ongoing hobo at outlet throughout field test)
  - Mini-split system (TBD)
- Addition of a recommendation: The type and access to space conditioning equipment be investigated before ordering logging equipment.
- Addition of information to, and reorganization of the Data Collection Spreadsheet template: Added documentation of HOBO serial numbers and documentation of supplemental heat sources.
- Modification of the required period of data collection: several weeks of data during the peak of a heating or cooling season is sufficient.

Additional practical advice on the attachment of loggers: Leave at least a foot of space for the Command strip to be pulled off. It is easier to position the Command strip so it is pulled down (not up or sideways) when removed. One should wear one work glove when removing the Command Strips. Start pulling command strip with ungloved hand. Finish pulling with gloved hand so that when it snaps, it doesn't bruise your hand. Also, the LED light on the HOBO should face away from occupants or be covered with electrical tape as the light could be a nuisance in a dark room.

4) How does the data from this study compare to other studies? Are there any discernible trends?

The average living room temperature was 4.5^{o}F higher in Colorado than that in New York. There are no discernible trends.

Table 15 and Figure 2 compare this data to similar data reported for 40 homes in Oregon, Washington, and New York (Roberts and Lay, 2013). At the Phoenix Apartments, the thermostat was located in the living room, so the term "living room" temperature is used interchangeably with "thermostat temperature". The average of the living room temperatures in the Phoenix apartments in Boulder, Colorado was several degrees higher than that in the other states and the standard deviation was somewhat lower. The average living room temperature in Colorado was 4.5^{o}F higher than that in New York. One hypothesis for why New York temperatures are different from Colorado (both in climate zone 5/cold climate zone), is that energy costs for heating in New York are higher than in Colorado. Another possibility is that the cost of heating a multifamily home or more well-insulated home is lower than larger, less insulated single family homes and occupants adjust set points accordingly.

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Table 15. Comparison of Phoenix Apartment Living Room Temperature Statistics to Similar Temperature Data Collected in Oregon/Washington and New York (Roberts and Lay 2013).

	Colorado	Oregon/Washington	New York
Number of Homes	9	20	20
Number of Temperature Readings	67,761	66,733	72,931
		Temperatures (°C)	
Mean	20.9	17.7	18.3
Median	20.8	18.2	18.3
Standard Deviation	2.0	2.7	2.6
		Temperatures (°F)	
Mean	69.5	63.9	65.0
Median	69.5	64.8	65.0
Standard Deviation	3.7	4.9	4.7

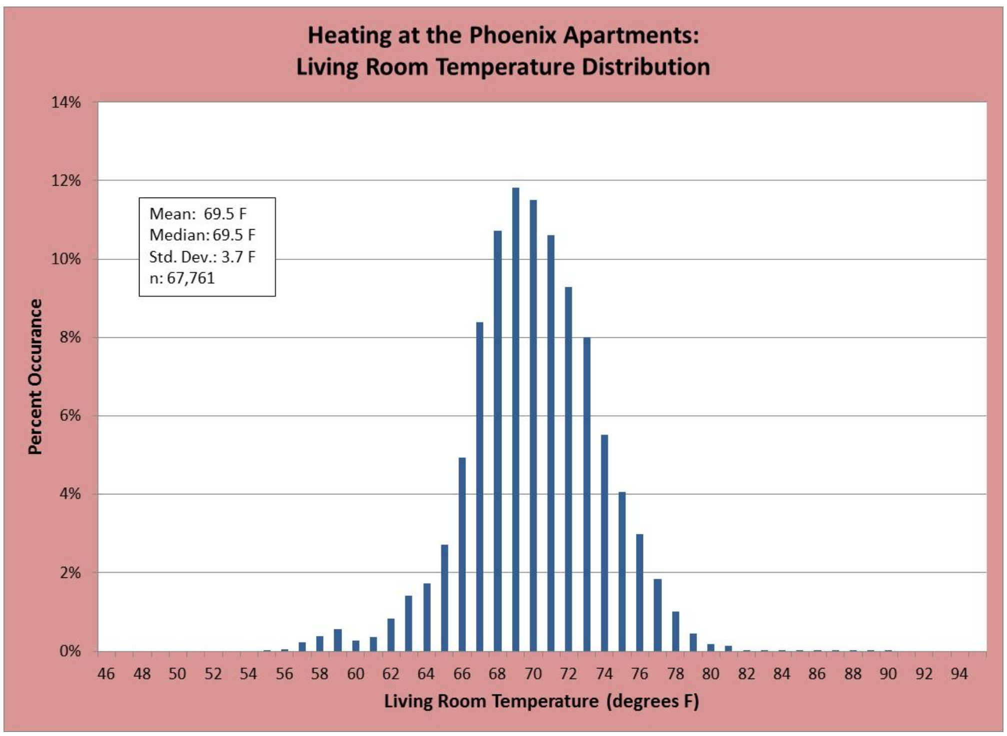

Figure 2. Frequency distribution of the living room temperatures in all nine apartments.

Conclusions: The room-to-room temperature variations measured in the Phoenix Apartments confirms the need for measuring more than just the temperature near the thermostat. However, in these small apartments, the WAIT was not particularly sensitive to the accuracy of the weighting factors.

The Phoenix Apartments project provided an excellent opportunity to apply the draft Indoor Temperature Measurement Protocol. Many lessons learned from the project have been incorporated into the improved protocol (see response to question #4 above).

In addition, the following lessons learned did not directly affect the protocol document:

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- Confirmation that the use of Command Strips leaves no mark on or damage to painted walls upon removal.
- Development of a philosophy for dealing with warm days during heating season when the furnace runtime is not available.
- Removal of equipment should be planned and negotiated with project partners at the time of equipment installation or earlier. With the help of a facility manager who has access to all apartments, this can take as little as one-half hour for all retrieval.

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Appendix III: Example Floor Plans

This appendix contains examples of where T&RH sensors are recommended to go based on the protocol. The red stars represent the T&RH sensors and the blue boxes represent the thermostats.

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HOUSE 1

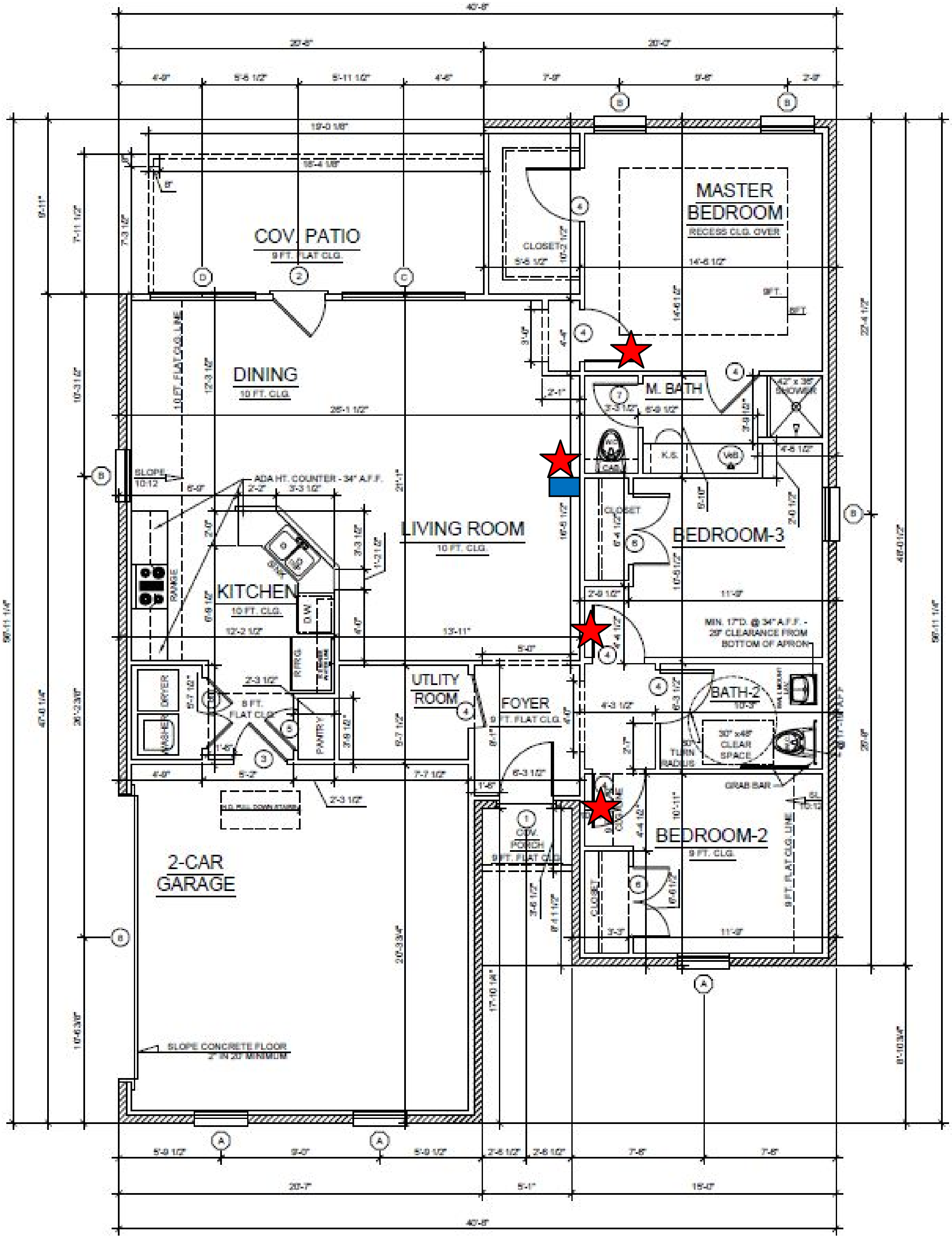

Figure 3. TXAIRE Lab Home Floor Plan. ***Courtesy: University of Texas at Tyler***

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HOUSE 2

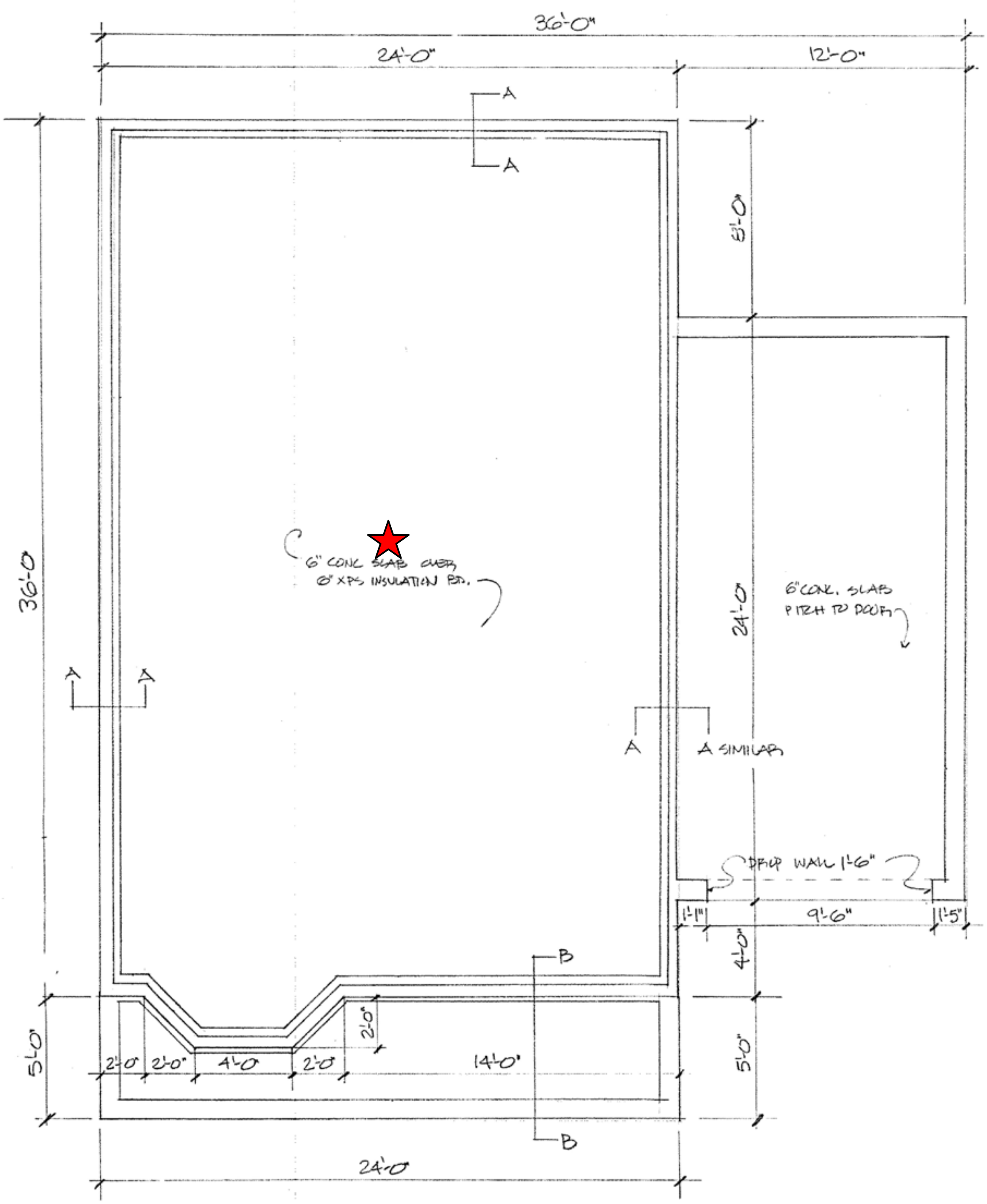

Image Courtesy of Transformations, Inc.

Figure 4. Basement of The Victorian ***Credit: Transformations, Inc.***

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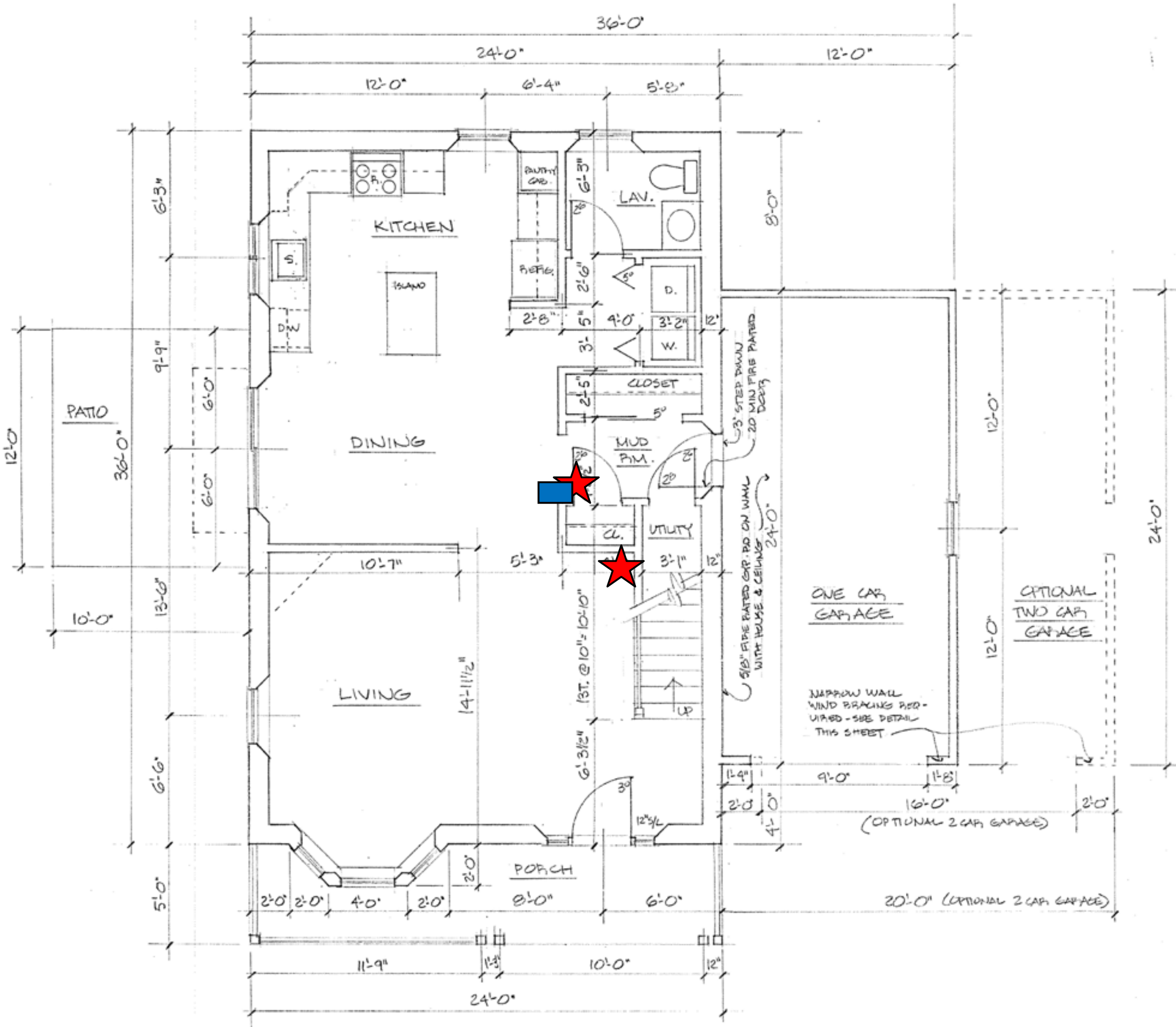

Image Courtesy of Transformations, Inc.

Figure 5. First floor of The Victorian ***Credit: Transformations, Inc.***

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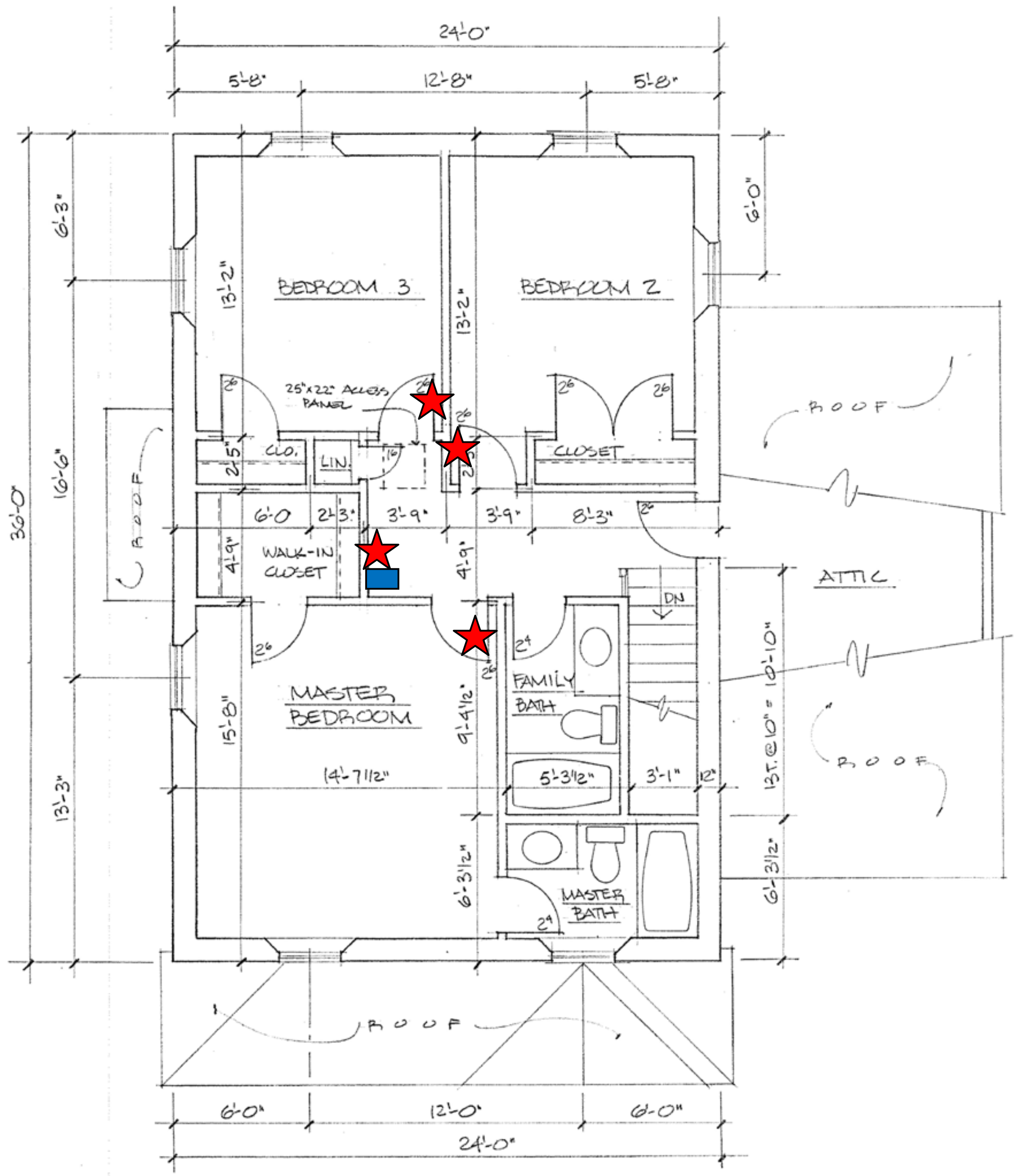

Image Courtesy of Transformations, Inc.

Figure 6. Second floor of The Victorian ***Credit: Transformations, Inc.***

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