Monitoring of **Internal Moisture Loads** in Residential Buildings

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Disclaimer

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FOREWORD

Relative humidity is an important factor in the quality of the built environment. It affects thermal and respiratory comfort, occupant perceptions of indoor air quality (IAQ), and the energy necessary for heating and air conditioning. High relative humidity also favors growth of biological contaminants such as dust mites and mold. Elevated moisture levels over a prolonged period of time may also result in physical damage to the home. However, data related to moisture levels and coupled building features of residential building are lacking. HUD undertook this project primarily to create a data set that engineers and building scientists could use to better understand those relationships. This report describes the data and presents preliminary analysis.

The study gathered a full year of indoor temperature and humidity data in a sample of sixty homes across three different climate regions – the hot/humid Southeast, the cold Northeast, and the marine Northwest. Multiple locations in each home were sampled every 15 minutes. This data set consists of over nine million individual temperature and humidity readings. To guide the study, HUD collaborated with members of the American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. (ASHRAE) committee for the Criteria for Moisture-Control Design Analysis in Buildings.

The data present information on the homes; including age, the air leakage rate, foundation type, heating and cooling equipment, and other observations from residents and evaluators. For example, while homes in the Northwest marine climates exhibited the highest average relative humidity levels (>50%), homes in the Northeast had the greatest occurrences of visible mold and musty smells.

This report addresses issues of interest to HUD's Office of Healthy Homes and Lead Hazard Control (OHHLHC) and the Office of Policy Development and Research (PD&R). OHHLHC concentrates on identifying and mitigating hazards to resident health and safety, while PD&R develops improved methods for the design and construction of affordable, durable homes. The valuable data collected during this research advances the interests and goals of both offices.

While this report provides a useful summary of the data, we expect the greatest value will occur when the data set is used to answer critical questions about ways to improve indoor air quality and building durability by designing homes to mediate indoor moisture levels.

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EXECUTIVE SUMMARY

An insufficient amount of measured data is available on actual indoor humidity levels in U.S. households, making it difficult to design durable homes. This research project has collected 1 full year of indoor temperature and humidity data for a sample of 60 homes across three different climate regions—the hot and humid Southeast (Zone 2), the cold Northeast (Zone 5), and the marine Northwest (Zone 4).

This research was in direct support of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc. Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*. A research methodology was developed with assistance from Oak Ridge National Laboratory (ORNL), a subcontractor and member of Standing Standards Project Committee 160 that acted in an advisory role. The monitoring protocol involved three site visits to each home to perform tasks such as collecting basic house and equipment characteristics, installing data loggers, performing testing to quantify envelope leakage and duct leakage, and collecting data recorded by the loggers. Data compiled in the field tests were analyzed to identify the potential relationships between certain household characteristics and the measured internal humidity levels.

This report presents significant findings from the study. Correlations between indoor moisture levels and climate, occupant density, and house characteristics are the focus of the results. Conclusions and recommendations for indoor moisture management or future research needs are also discussed.

Of the three climates in the study, the homes in the marine climate appear to consistently see indoor relative humidity levels above 50 percent, but the highest level of moisture problems occurred in climate Zone 5, the cold climate.

After the initial review of the data, it appears that major differences between the housing sets include the following:

- **Age.** Homes in the marine climate were much older than in the other two climates.
- **Air leakage.** The air-leakage rate (ACH50) was almost twice as high in the marine climate as in the other two climates.
- **Foundation type.** Several homes in the marine climate were built on vented crawlspaces with dirt floors. The homes in the hot, humid climate were all built on slabs and the homes in the cold climate were primarily built on partially finished basements that were conditioned.
- **Cooling equipment.** Only 20 percent of the homes in the marine climate had central air-conditioning units, whereas 75 percent of the homes in the cold climate and 100 percent of the homes in the hot and humid climate had central air-conditioning.
- **Heating equipment.** Only about 50 percent of the homes in the marine climate had forced-air heating. The other 50 percent had a mixture of boilers with baseboard radiators or electric heat.

In all three regions, the highest occurrence of visible mold or moisture damage was on or around the windows and in the bathrooms. In the hot-humid climate, mold was visible on several air handlers around the cooling coil, usually on air handlers located outside the conditioned space, such as in a garage.

In the cold climate, moisture problems included musty smells within the conditioned space that were reported by the occupants and confirmed on site. Several homes had water leakage problems in the basements. In a couple of instances these smells were noted on the upper floors of the home as opposed to the basements.

Strong correlations between house characteristics and indoor humidity levels were not possible due to the small sample size. After evaluating the data regionally and with respect to those homes that did and did not have moisture problems, trends that deserve further investigation are increased humidity levels due to—

- High air-change rates.
- High occupant densities.
- The presence of unfinished and unconditioned basements and crawlspaces.
- The use of materials with higher condensation and mold potential in climate Zone 2, hot and humid climate, such as metal windows, marble window sills, and so on.

PART 1. RESEARCH DESIGN AND EARLY FINDINGS

Introduction

A complete understanding of the influences certain factors have on a home's overall moisture content and moisture performance is not available. Which is more harmful to a home: showering without the fan on or having inefficient single-pane or metal windows? The U.S. Department of Housing and Urban Development (HUD) funded a research project that measured interior relative humidity. The purpose of the research was to identify and quantify moisture loads on a home, and it targeted three different regions in the United States—the hot and humid Southeast (Zone 2), the cold Northeast (Zone 5), and the marine Northwest (Zone 4). During an initial site visit, an engineer collected house and household characteristic data, including occupancy levels, insulation levels, equipment efficiencies, envelope leakage, and duct leakage. This information will aid researchers and engineers in developing construction standards and best practice guidance that will reduce the likelihood of new homes having moisture-related problems.

After obtaining yearlong exterior and interior moisture load data for the test homes, engineers conducted an analysis of the influence of various components of the home and occupant-related activity. This analytical activity should provide all the data required for the analysis. Engineers analyzed data compiled in the field tests with the intention of identifying relationships between the various household characteristics and the internal humidity levels.

Research Design

The following section introduces the objectives and goals of this study. The development of the monitoring protocol is also described in detail.

Objectives

Engineers focused on three major objectives for conducting this study.

1. **Research Support.** As noted in a Buildings VIII paper (TenWolde and Walker, 2001: 1), "computer models are increasingly used to make recommendations for building design in various climates. However, results obtained with these models are extremely sensitive to the assumed moisture boundary conditions." One intention of this HUD project was to provide the research community with critically important field data for defining boundary conditions for use in moisture models and, through that effort, help that community better understand the effect of moisture on the durability of homes.

2. **Support for Development of Design Criteria.** The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc., Standing Standard Project Committee 160 continues to maintain the relatively new standard, "Criteria for Moisture-Control Design Analysis in Buildings." This committee has formulated "performance design criteria for

predicting, mitigating, or reducing moisture damage to the building envelope, materials, components, systems and furnishings" (ASHRAE, 2009: 4). This moisture design standard will help make homes more moisture resistant and thus more durable. Data collected during this project provides documented support for the interior design loads adopted by the committee with the hope that the resulting design criteria will minimize durability problems associated with high moisture levels.

3. **Identify Influences on the Moisture Levels in Homes.** Residential interior moisture loads are influenced by a multitude of variables, including the following:

- Climate.
- Construction materials.
- Building envelope tightness.
- Type, size, and control of mechanical equipment.
- Size and configuration of the home.
- Number of occupants and their behaviors.
- Moisture capacitance of furnishings.
- Age of home.

Although the data set collected during this study is somewhat limited, it was intended that the proposed project analyses would identify correlations between interior and exterior conditions and moisture levels in typical single-family detached homes.

Goals

This project attempted to address a combination of two recommended research projects that each received a "very high" priority ranking in the HUD publication, *Building Moisture and Durability: Past, Present, and Future Work* (Dacquisto, Crandell, and Lyons, 2004):

- Characterize the moisture performance of existing homes through a monitoring protocol.
- Develop statistically validated procedures to assess internal moisture loads for use in hygrothermal analyses and related engineering studies.

The scope of the proposed research project was not sufficient to monitor several hundred homes around the country, however, and statistical validation is unlikely. What this project has provided is a sound monitoring protocol and start at developing a critically important database of information for moisture modeling and standards development.

Review of Existing Research

The monitoring protocol was developed with the help of an advisory panel composed of experts from different segments of the building industry, most of whom are members of the ASHRAE Standing Standard Project Committee (SSPC) 160.

In addition to receiving the input from the SSPC 160 committee, this study was supported by Oak Ridge National Laboratory (ORNL), which has been directly funded by the U.S.

Department of Energy to support the ASHRAE Standard 160 process. In an effort to determine what information was most critical, subcontractor ORNL reviewed copies of 10 hygrothermal models. During the past two decades, a number of computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building envelope. In addition to using these forensic tools to investigate building failures, engineers increasingly use these computer models to make recommendations for building design in various climates.

The SSPC 160 committee realized that requiring the use of multidimensional models was inconsistent with its goal of creating a standard that could be easily used by the design community. In Section 5 of the standard, however, the committee listed a series of criteria that any computer tool needed to satisfy.

For those models that met the requirements, engineers examined the input variables and data format requirements to ensure that the data generated by this HUD project would be compatible and useful to each of these simulation models.

Results obtained with this type of model are extremely sensitive to the assumed moisture boundary conditions. For instance, during winter in cold climates, the moisture conditions in walls depend greatly on the indoor humidity conditions. Moisture capacitive walls, such as brick-clad walls, will have their performance vary greatly based on the quantity of wind-driven rain. The SSPC 160 committee correctly realized that a consistent approach to moisture design demands a consistent framework for design assumptions or assumed loads.

The ASHRAE Standard 160 describes three options for estimating the interior conditions. These options contain varying amounts of input data to calculate; however, the options are missing a database of typical temperature and humidity loads that the user of the standard can apply to compare with his or her estimations. Although great strides have been made to quantify and standardize meteorological data, such as wind-driven rain, insufficient data exist on typical indoor conditions. The primary purpose of this HUD project was to generate some of these data.

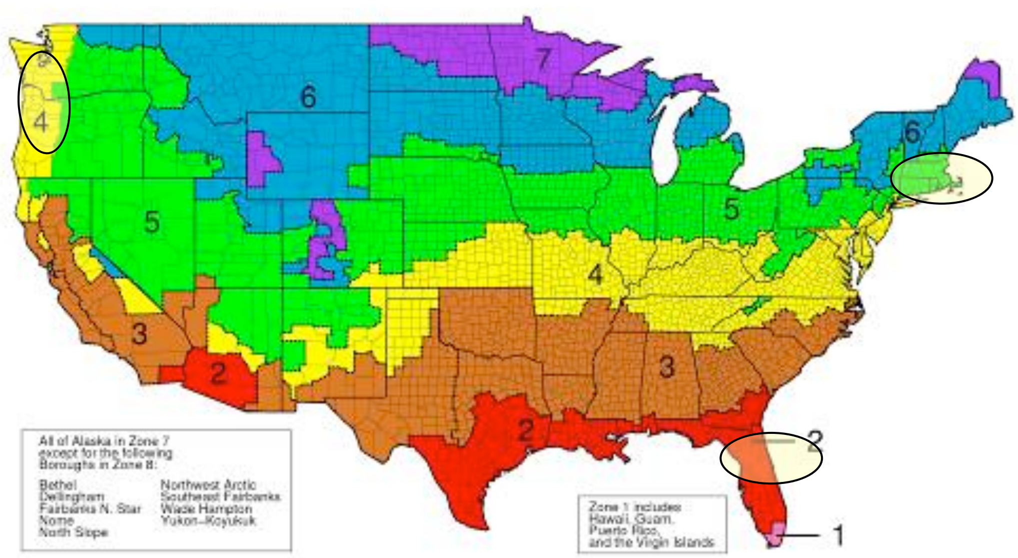
Engineers conducted a review of data from other research studies similar in nature to this one to aid in the study design; address unanswered questions, if possible; and to potentially supplement the data collected during this HUD study. Although these data sets proved useful in determining characteristics that should be recorded, climate zones on which to focus, and desired length of the collection period, they could not be used to supplement the data set from this study. Engineers determined during this review that vital information was missing from each study in one form or another. For instance, several studies produced numerous data points on relative humidity and temperature but had not collected detailed information about the house characteristics (Piggs, 2003), had been conducted only in one climate (Aoki-Kramer and Karagiozis, 2004; Kalamees, 2006), had collected data for only one month (Kumaran and Sanders, 2008), and so on.

Climates Evaluated

In this HUD study, engineers emphasized three climate regions of the country that are the focus of moisture and related durability studies. The plan as proposed was to have a greater sample of homes for a smaller sample of climates. It was hoped that the greater sample size would better characterize the variability within a climate region and enable the researchers to develop maximum, minimum, and average profiles for modeling and design studies. The three important climate regions are, for different reasons, the marine Northwest, the cold Northeast, and the hot and humid Southeast. (See figure 1.)

Zone 4, the marine Northwest, is an area of high to extreme rainfall amounts. It is also an area of rather moderate temperatures, minimizing the potential drying influence of heating or air-conditioning system operation. Building envelope failures in this region are known, and numerous moisture design studies have been performed with internal load assumptions, based on very limited data.

Figure 1. IECC Climate Zone Map of the United States



For residences in Zone 5, the cold Northeast, the internal moisture load assumptions are extremely important, because the primary cause of durability problems is moisture-laden internal air entering into the envelope system and the subsequent condensation of the moisture on cold surfaces. TenWolde (2000) documents this problem well and describes how design criteria, such as that developed by ASHRAE Standard 160, would have alerted builders to the potential problem.

Moisture issues in Zone 2, the hot-humid Southeast, are more influenced by ambient humidity levels, but the extent to which the exterior humidity influences interior humidity levels is not well understood. Factors such as envelope tightness, the presence and operation of a mechanical ventilation system, and the dehumidification performance of the home's air-conditioning system can significantly affect the indoor humidity conditions. Rudd and Henderson have conducted relevant monitoring studies and research in this climate region (Rudd and Henderson, 2007). Engineers thoroughly reviewed Rudd and Henderson's research, which served as guidance for the monitoring protocol.

Desired House Characteristics

After evaluating existing research and discussing goals with the SSPC 160 committee, engineers decided that homes with the following characteristics would provide the most useful data sets:

- Single-family homes (preferably detached).
- More than 1 year old.
- Less than 3,000 square feet.
- At least two occupants (preferably more) with no plans to move within the next year.
- No major renovation or remodeling work planned within the next year.
- Engineers wanted a range of characteristics and occupant densities.

Identifying and selecting test homes for this project was a critically important task. Simply put, without the homes, the study would have no data. Researchers were careful to ensure that the recruitment process avoided selective biases that might occur. For instance, occupants who were having problems or concerns about moisture and humidity problems in their homes may have been more inclined to participate.

Engineers found test homes through the following sources:

- Building America builder partners.
- Local agencies and institutes, such the Florida Energy Extension Service.
- Steven Winter Associates (SWA) employees' relatives and friends.
- Study participants.

Critical Parameters Measured and Recorded

In addition to determining the number of climate zones and the types of homes to be monitored, researchers used two key elements to the monitoring protocol:

- The test home characterization (short-term data collection).
- The internal moisture load monitoring (long-term data collection).

Short-Term Data Collection

As noted previously, the internal moisture load can be dependent on a multitude of home characteristics. An assessment of these characteristics for each test home would be important to subsequent analyses to help understand variability and key relationships. One critical task during the development of the monitoring protocol was to determine which house characteristics were vital to assessing internal moisture loads. The result of that analysis was translated to the Field Data Collection Form (see appendix B). Engineers developed this form to ensure consistency and completeness in the data collection process. They completed the form for each home during the initial site visit.

Short-term testing and data collection, which engineers conducted at the time of monitoring equipment installation, included the following:

- A blower door test to quantify envelope tightness.
- A test to quantify duct leakage to the exterior.
- A description of the envelope detail, including insulation type and quantity, siding materials, flooring materials, and so on.
- A description of the heating, ventilation, and air-conditioning equipment, including the type; capacity; and presence and description of humidifiers, dehumidifiers, and mechanical ventilation systems.
- Documentation of the house size and configuration and the number of occupants.
- Measurement of exhaust fan airflows.
- Presence of mold and moisture sources.

Researchers transferred all results collected during the evaluation of the home characteristics into a database for subsequent analysis.

Long-Term Data Collection

When evaluating the tools available for the long-term monitoring, researchers considered the following issues:

- Available memory.
- Logging frequency.
- Durability.
- Accuracy.
- Intrusiveness.
- Cost.

Engineers conducted preliminary research on wireless loggers, but they found that the wireless versions were too expensive for this HUD project. They found that the independent (HOBO) data loggers from Onset Computer had a lower cost, were nonintrusive, and were relatively simple to use; so they selected the HOBO.

Subsequent to the short-term assessment, engineers installed the HOBOs for long-term monitoring of temperature and relative humidity. The data loggers collected the following data:

- Outdoor temperature and relative humidity.
- Primary living space (family and great room) temperature and relative humidity.
- Master bedroom temperature and relative humidity (to observe diurnal variations, which could be significant and of interest).
- Primary bathroom (where most showers were taken) temperature and relative humidity (could represent a severe humidity-load condition that could influence the entire home).
- Basement or crawlspace temperature and relative humidity (if present, could be a high moisture-load region of the home).
- Attic temperature and relative humidity where a slab foundation was present (could represent significant diurnal moisture loading).

Engineers set up each data logger to record temperature and relative humidity data every 15 minutes during a 12-month period. (These data have been averaged during post-processing to provide hourly data for model input.)

Final Monitoring Protocol

Using information obtained during the review of existing relevant research projects and moisture-prediction models, and in combination with the goals of the SSPC 160 committee, engineers developed the final monitoring protocol. The following items are the major components of the final monitoring protocol.

Prescreening Telephone Call

Engineers informed the potential participants of the requirements of the study when they asked them to participate, unless the participants were a last minute addition to the study. The engineers used a prescreening questionnaire in a telephone call to confirm that the home was, in fact, a good candidate and to ensure that the occupants understood the reason for the study, what was involved if they participated, and the length of time their home would be monitored. (See the prescreening questionnaire in appendix A.)

Site Visits

To gather the data, the engineers made three site visits to each home. In addition to making the initial visit to collect house characteristics on the Field Data Collection Form and install the HOBOs and the final visit to collect the data loggers, the engineers made an interim site visit because the data loggers were capable of storing only about 200 days worth of data at 15-minute intervals.

Before scheduling the initial field visits, the engineers conducted a trial run on one home in the cold Northeast. They conducted a trial run for several reasons. First, they wanted to confirm the time needed to gather information during the first site visit so that they could efficiently schedule appointments. Also, they needed to work out the best locations for the HOBOs and the best methods for installing them. The engineers had two concerns at this point. First, they wanted to keep the data loggers out of the reach of children and in locations where they would be least likely to get moved or harmed. Second, they wanted to make sure that the HOBOs were attached in a manner that could not damage the participants' property.

A second major reason for the trial run was that the procedure for measuring duct leakage, known as the DeltaQ method, was relatively new and uncommon. This method entails using the blower door to pressurize and depressurize the home with the air-handler fan running and with it off. Using a software program developed by the Energy Conservatory and Lawrence Berkeley National Laboratory (LBNL), the pressures recorded during those tests are analyzed and the duct leakage to the exterior is calculated. This method was selected to minimize the time needed to conduct the initial site visit. Conducting duct blaster tests on existing homes can take a significant amount of time if furnishings need to be moved, and it increases the possibility of damage to the occupants' personal property. During this trial run, engineers worked out problems and questions about the proper procedure for conducting a DeltaQ test.

Third, and finally, the test run could determine if the field checklist needed any last minute additions or deletions before printing them in bulk.

The final preparation for the initial visit included calibrating the sensors. Each sensor was started and allowed to log data for a minimum of 24 hours. The engineers then analyzed the results for accuracy, according to the manufacturer's specifications. The test showed that all data loggers appeared to be operating within the tolerances allowed.

Initial Site Visit (about 2 to 3 hours). During the initial visit, the engineers recorded the basic house and equipment characteristics, made air-leakage and duct-leakage measurements, and installed the data loggers (three inside, one outside, and one in the attic, basement, or crawlspace). They also conducted an interview with the occupant to confirm occupancy schedules, comfort problems, and any upgrades they may have made. (See appendix B for a more detailed explanation of the information collected.)

Interim Site Visit (1 hour). The engineers collected the first 6 months of data recorded during the interim site visit. They also used this visit was to check on the condition and location of the data loggers and to talk with the occupants about any changes that may have occurred during the past 6 months. In addition, they collected any house information that had been missed during the initial visit.

Final Site Visit (1 hour). The final site visit was much the same as the interim visit, with the additional task of removing the data loggers.

Participation Agreement and Compensation

The engineers executed a written agreement with the test home occupants. This agreement established the expectations and responsibilities of all parties involved. This written agreement achieved a secure commitment of cooperation by the occupants. In exchange for volunteering to participate in the study, the occupants received an audit that explained the efficiency levels found in their home and compared those values with the study averages for their region and with the ENERGY STAR values for a new home built in their area. Basic recommendations for moisture-barrier improvements were made if applicable. (See this agreement in appendix C.)

Results and Discussion

This study generated four data sets of internal temperature and relative humidity for each home. Thus, for each climate region with 20 homes, the engineers had 80 data sets for analyzing interior relative humidity and temperature. In addition, they had 15 to 20 data sets per region from exterior sensors that had measured temperature and relative humidity.

Engineers analyzed the data to identify the potential relationships between certain household characteristic data and the measured internal humidity levels.

They performed an evaluation of the data to ensure that all data were collected for each sensor and that the data appeared to be valid. This review indicates that less than 2 percent of data were lost overall; 1.3 percent of the total lost data was in the marine climate. Of the 285 data loggers installed, only 1 was not retrieved, and approximately 10 different data loggers stopped collecting at some point during one of the 6-month periods, between visits. Only two data loggers were determined to have obviously bad data.

The engineers first analyzed the data by region. They calculated averages of interior relative humidity and temperature and compared them with the average outdoor values collected during the same period. Because relative humidity is a function of temperature, they converted this value to humidity ratio (lb_w/lb_{da}) to determine the actual amount of water in the air. Tables 1 through 3 show the average interior values from the collected data for each region compared with the ambient conditions.

Table 1. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Data: Zone 2, Hot-Humid Southeast

Zone 2	Indoor			Outdoor		
Month	**Temperature [°F]**	**Humidity Ratio [lb_w/lb_{da}]**	**Relative Humidity**	**Temperature [°F]**	**Humidity Ratio [lb_w/lb_{da}]**	**Relative Humidity**
January	72.8	0.00907	52.58	59.0	0.00766	69.02
February	72.3	0.00837	49.32	60.1	0.00730	64.42
March	74.5	0.00945	51.71	67.4	0.00958	66.88
April	75.8	0.01002	52.45	71.9	0.01075	65.51
May	77.8	0.00976	47.79	79.2	0.01324	64.04
June	78.4	0.01004	47.92	81.5	0.01631	72.58
July	78.1	0.01013	48.82	81.5	0.01743	76.54
August	77.9	0.01044	50.72	81.9	0.01790	77.54
September	77.9	0.01026	49.90	81.2	0.01691	74.69
October	76.4	0.00999	50.99	73.4	0.01278	71.08
November	73.8	0.00951	53.13	63.3	0.00913	70.88
December	73.8	0.01018	56.92	64.1	0.00962	73.58
Annual	**75.80**	**0.00977**	**51.02**	**72.03**	**0.01238**	**70.56**

Table 2. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Data: Zone 5, Cold Northeast

Zone 5	**Indoor**			**Outdoor**		
Month	**Temperature [°F]**	**Humidity Ratio [lb_w/lb_{da}]**	**Relative Humidit y**	**Temperature [°F]**	**Humidity Ratio [lb_w/lb_{da}]**	**Relative Humidity**
January	64.8	0.00475	36.1	20.9	0.00188	74.10
February	65.5	0.00494	36.7	28.6	0.00258	71.63
March	65.7	0.00522	38.3	37.0	0.00315	63.17
April	67.8	0.00635	42.9	49.7	0.00466	60.65
May	70.0	0.00766	48.2	59.5	0.00689	62.83
June	73.9	0.00951	52.1	68.3	0.01023	67.76
July	75.8	0.01087	56.1	73.0	0.01240	71.22
August	74.1	0.01057	57.7	68.6	0.01100	73.63
September	72.0	0.00988	57.9	64.1	0.00981	75.20
October	67.0	0.00803	56.2	49.5	0.00570	73.75
November	65.9	0.00683	49.8	39.7	0.00433	77.53
December	65.3	0.00558	41.8	30.2	0.00284	74.67
Annual	**68.98**	**0.00752**	**47.81**	**49.09**	**0.00629**	**70.51**

Table 3. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Data: Zone 4, Marine Northwest

Zone 4	Indoor			Outdoor		
Month	Temperature [°F]	Humidity Ratio [lb_w/lb_{da}]	Relative Humidity	Temperature [°F]	Humidity Ratio [lb_w/lb_{da}]	Relative Humidity
January	63.50	0.00622	50.08	39.50	0.00445	84.63
February	63.70	0.00609	48.70	41.76	0.00436	78.30
March	64.30	0.00634	49.53	44.05	0.00460	75.10
April	66.00	0.00688	50.50	51.41	0.00526	67.55
May	68.45	0.00769	51.93	58.76	0.00648	63.97
June	71.06	0.00880	54.11	64.67	0.00815	64.13
July	72.28	0.00864	51.10	66.89	0.00815	60.08
August	73.21	0.00960	54.76	67.23	0.00938	67.45
September	70.21	0.00862	54.78	62.49	0.00794	68.31
October	65.67	0.00795	58.81	52.53	0.00660	77.99
November	64.37	0.00784	60.62	49.09	0.00641	85.21
December	62.95	0.00627	51.32	37.67	0.00431	85.52
Annual	**67.14**	**0.00758**	**53.02**	**53.00**	**0.00634**	**73.19**

Figures 2 through 4 are graphical representations of the temperature and relative humidity data presented in tables 1 through 3.

Figure 2. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Values for Zone 2, Hot- Humid Southeast, From Study Data

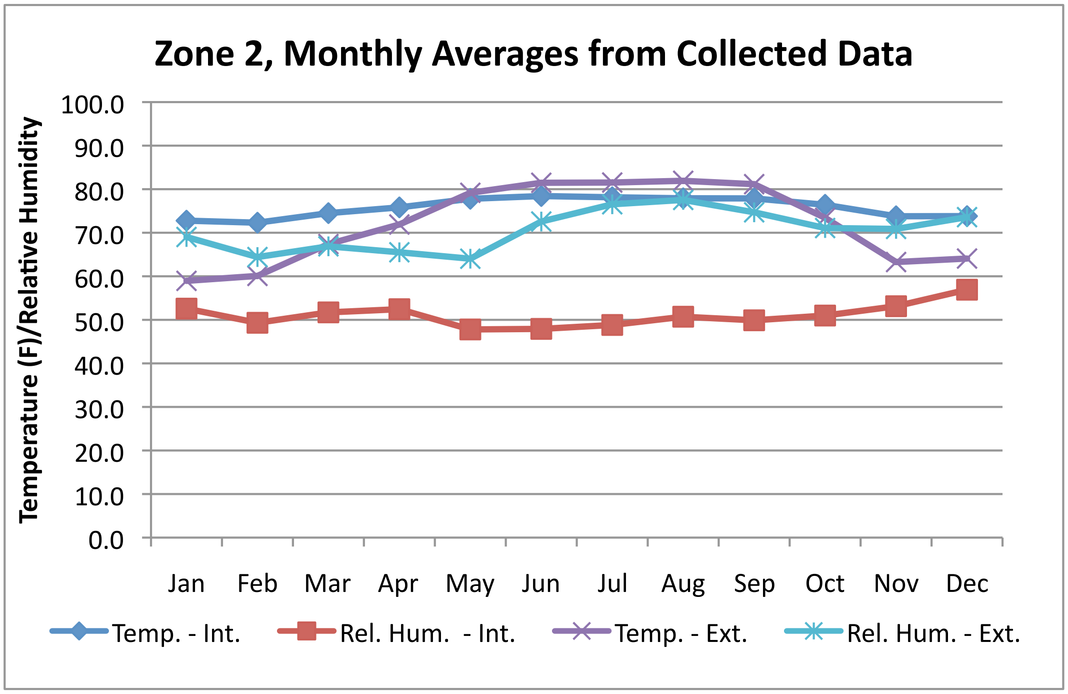


Figure 3. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Values for Zone 5, Cold Northeast, From Study Data

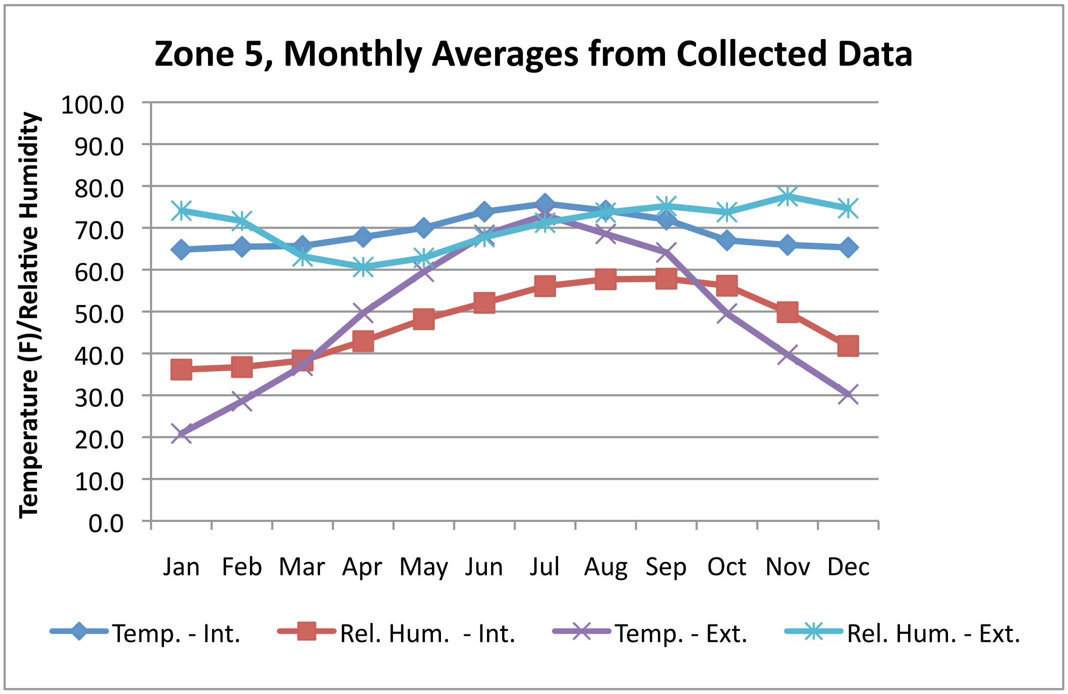
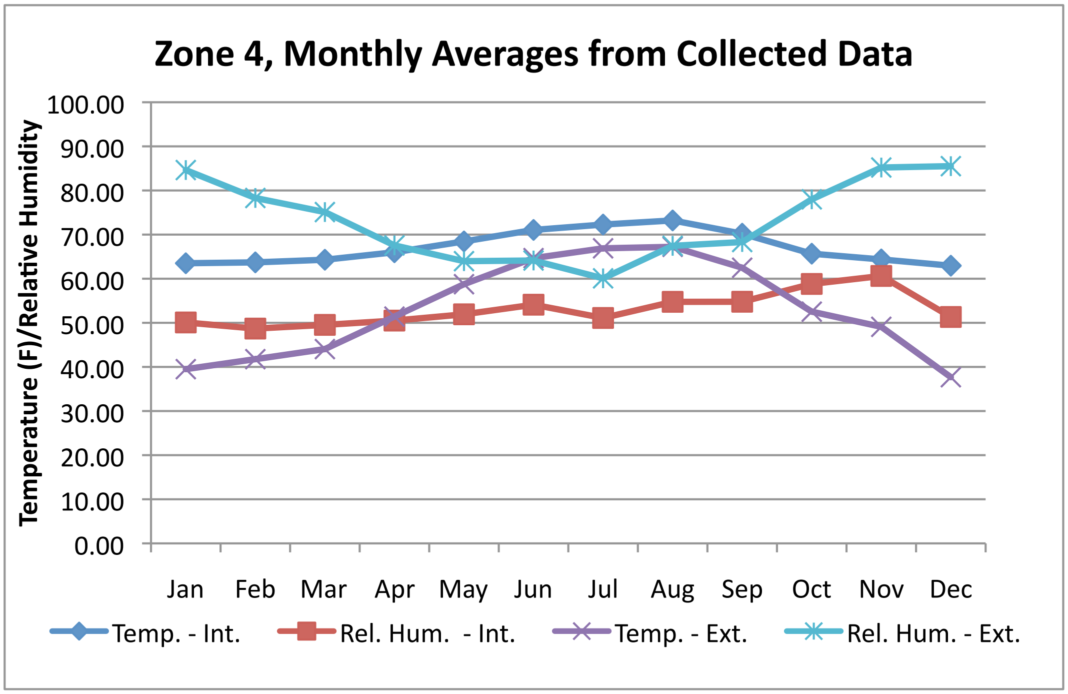


Figure 4. Monthly Averages of Interior and Exterior Temperature and Relative Humidity Values for Zone 4 From Study Data



Next, the engineers compared the average building component characteristics in each region with each individual participant's values. They used these comparisons in audit reports sent to each participant in exchange for their agreement to participate in this study. Table 4 shows the average building age, size, foundation type, and building component efficiencies for each of the three regions.

Table 4. Average House Characteristics by Region

Component	Zone 2, Hot-Humid Southeast	Zone 5, Cold Northeast	Zone 4, Marine Northwest
Year built	1998	1966	1947
Size (conditioned square feet)	1,989	3,118	2,059
# of occupants	3.45	3.10	3.1
Air leakage (ACH50)	6.0	6.1	11.1
Attic R-value (h•ft^2•°F/Btu)	22	36	24
Wall R-value (h•ft^2•°F/Btu)	12	12	7
Dominant foundation type	Slab	Partially finished basement	Basement and crawlspace
Duct leakage (cfm/100ft^2 of conditioned space)	5.6	4.7	13.9
Dominant heating type	AS heat pump	Furnace	Furnace
Cooling efficiency (SEER)	11.54	10.22	14.00
Dominant domestic hot water fuel	Electric	Gas	Gas
Homes with mechanical ventilation (%)	0%	25%	30%
Homes with cooling (%)	100%	75%	20%
Average interior relative humidity (%)	51.7%	47.9%	53.1%
Homes with moisture problems (%)	35%	50%	35%

Note: ACH50 Hourly air change rate at a pressure difference of 50 Pascals between inside and outside.

Table 4 shows that the highest occurrences of moisture problems were noted in homes in Zone 5, the cold Northeast data set. In this report, “moisture problems” refer to any mold or moisture damage or intrusion that engineers noted during the initial site inspection. These moisture problems were a combination of moisture in the basements (which was typically in the spring or fall), mold on the window casings, and musty smells. On average, indoor relative humidity values are highest in the marine climate, with average monthly values above 50 percent during most of the year. The marine climate had the fewest homes with central air-conditioning and the most homes with crawlspaces.

Table 5 summarizes the house characteristics for the homes with moisture problems compared with those homes without moisture problems for each region. What is interesting when looking at this table is that the trends that seem plausible in the cold and marine climates, do not apply to the hot and humid climate. For instance, there seems to be a distinct difference in air changes at 50 Pascals (ACH50) for homes with and without moisture problems in the marine and cold climates, but not in the hot and humid zone. This table implies that blanket recommendations for humidity control cannot be made based on most of the characteristics evaluated during this study, at least not without further research. Too many variables are in play to draw significant conclusions from these data. Each climate has specific characteristics, which are influencing interior moisture levels. More research is needed to determine if the trends suggested in this research are statistically significant.

Table 5. Summary of House Characteristics for Homes With Moisture Problems Versus Homes Without Moisture Problems for Each Climate Zone Region

House Characteristic	Zone 2, Hot-Humid Southeast		Zone 5, Cold Northeast		Zone 4, Marine Northwest	
	Moisture Problems	No Moisture Problems	Moisture Problems	No Moisture Problems	Moisture Problems	No Moisture Problems
House size (conditioned square feet)	1,860	2,059	2,819	3,416	1,701	2,251
Year built	2002	1995	1956	1976	1939	1952
Interior temperature (°F)	75.7	75.8	68.2	69.8	67.2	67.1
Dehumidifier (% of homes)	0	0	80	90	0.00	31
Primary foundation	Slab	Slab	Partially finished basement	Partially finished basement	Crawl-space and partial crawlspace	Mixed
Air leakage (ACH@50)	5.29	6.38	7.50	4.80	15.4	7.7
Occupant density (#/ft^2)	0.00194	0.00175	0.00103	0.00105	0.00227	0.00144
Bath fans (% of homes)	86%	92%	90%	100%	71%	69%
Mechanical ventilation (% of homes)	0.00	0.00	10%	20%	0%	23%
Humidity ratio (lb_w/lb_{da})	0.00971	0.00986	0.00755	0.00751	0.00767	0.00755

A general analysis of the tables and graphs in this section, combined with information gained during the site inspections, suggests the following:

Zone 2, Hot-Humid Southeast. The newer homes in this data set have more moisture problems than the older homes do, although the humidity ratios are not significantly different. The data may suggest a correlation with more efficient, newer homes and the lack of conditioning needed at times than the less efficient older homes would need, or they could suggest a construction failure particular to this community. Several of the newer homes were in the same development. Builders should avoid installing metal windows and other exposed cold surfaces in homes in this region.

Zone 5, Cold Northeast. Water seepage into the foundation appears to be a common problem in this data set. Engineers found mold only on the inefficient windows in this group—those having single-pane windows or single-pane windows with storm windows. Air-change rate would appear to be one factor affecting homes with moisture problems in this region. Another factor could be an association with older homes without good foundation moisture control.

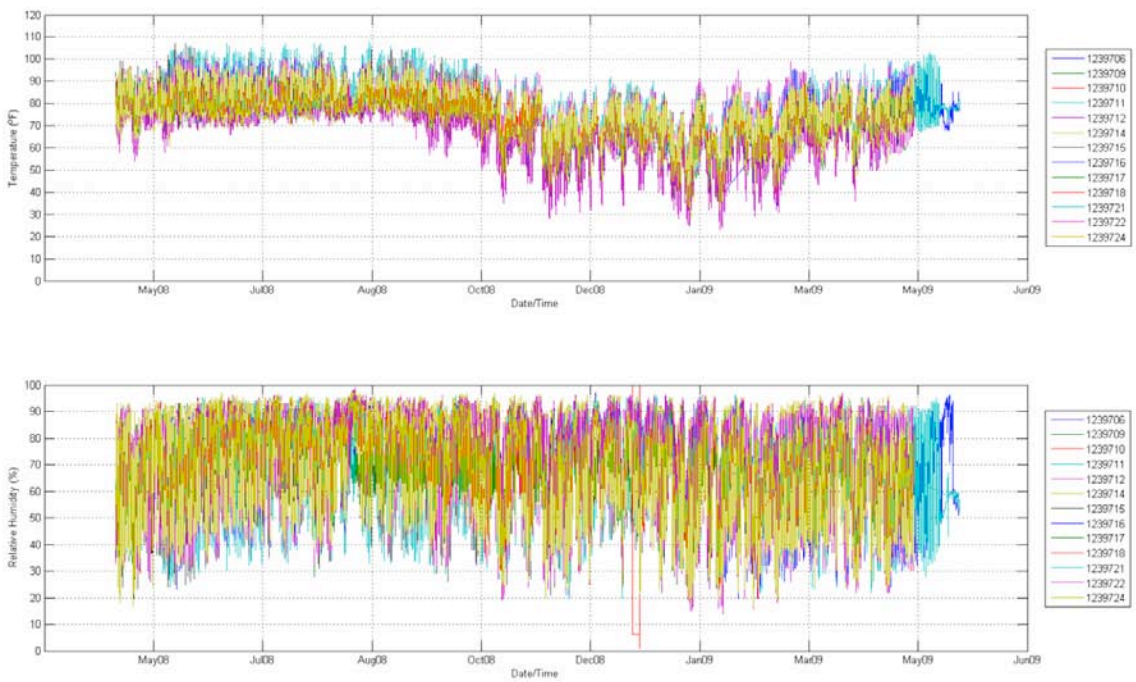
Zone 4, Marine Northwest. The homes with moisture problems in this region all had at least a partial crawlspace foundation with exposed dirt floors. Some of these crawlspaces were vented and some were not, but none had a well-sealed vapor barrier. As in the homes in Zone 5, the air-change rate would appear to be one factor affecting homes with moisture problems, or it could be an association with older homes that coincidentally lack good foundation moisture control. More research is necessary to determine if either of these factors significantly influences interior moisture levels.

PART 2. RESEARCH FINDINGS IN THREE DIFFERENT CLIMATE ZONES

Validation of Data Sets

To identify extreme outliers and potentially bad sensors, the engineers graphed each sensor's raw data against the other sensors in that region for the same location in the home. For example, figure 5 shows the data collected for all the ambient sensors in Florida.

Figure 5. Temperature and Relative Humidity Data From Zone 2, Hot-Humid Southeast, Climate Ambient Sensors



As can be seen in the relative humidity portion of the graph, one sensor recorded values significantly lower than the rest in December. After some investigation, the engineers determined that this sensor simply stopped recording data for a period of 3 days.

The engineers analyzed each set of sensors in the same manner. They determined some other reasons for data anomalies include the following:

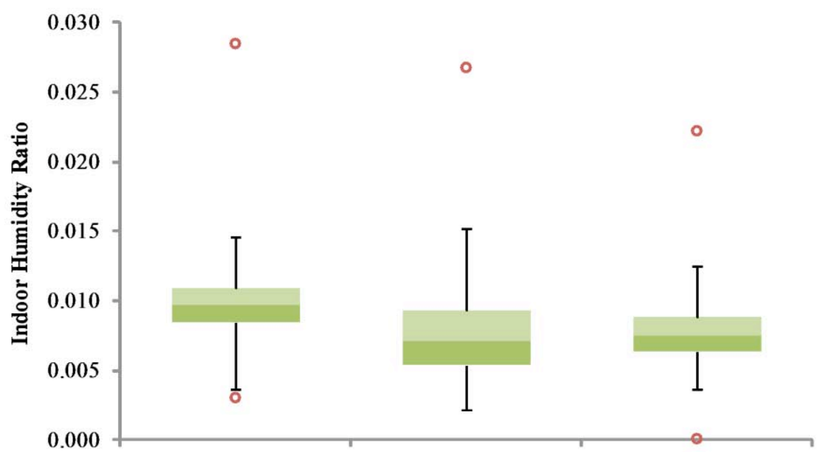
- Placing sensors too near a heating or cooling source, such as a leaky duct or fireplace.
- Occupants with unusual thermostat set points.
- Extended periods when homes were unoccupied.
- Upgrades to homes—a couple of occupants changed windows.
- Unexplained behavior—in one Florida home, all interior temperature sensors read 55 °F in August.

In general, review of the data confirmed that minimal losses of data or bad data occurred during the 12-month collection period. More than 97 percent of the data were successfully collected. Data were not eliminated due to unusual situations such as those listed in the previous list. Data were excluded only if the sensors were thought to be bad—that is, single digits were recorded on only one of the four sensors on the inside of the home, negative numbers were logged, and so on. As explained previously, the engineers calibrated all sensors before installation.

Overview of Results

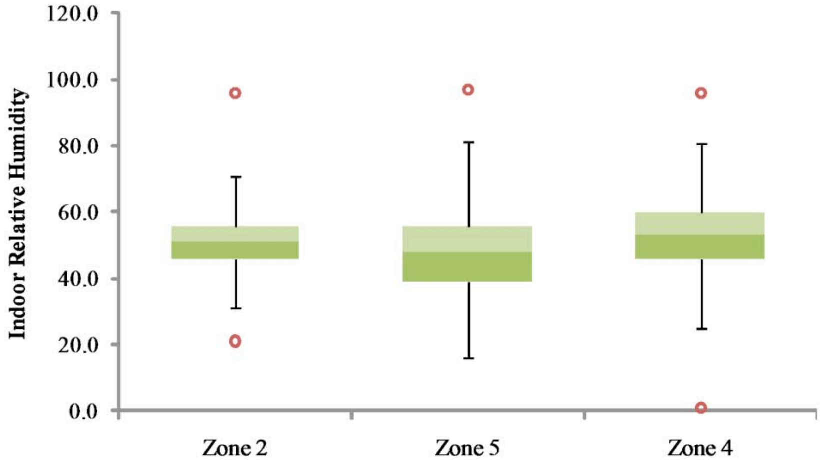
These data are summarized in the box-and-whisker diagrams in figures 6 through 9. Mean values along with minimum, maximum, and median humidity values are listed below each plot. All whiskers represent 1.5 times the interquartile range, or 1.5 times the upper 75th percentile (indicated by the upper edge of the light green box) minus the lower 25th percentile (indicated by the lower edge of the dark green box). The percent outliers describe the percentage of the data collected that lies outside the whiskers. The circles represent the minimum and maximum outliers. All box plots are based on 15-minute-interval data collected during an entire year.

Figure 6. Box Plot for Indoor Humidity Ratio for All Three Climate Zones



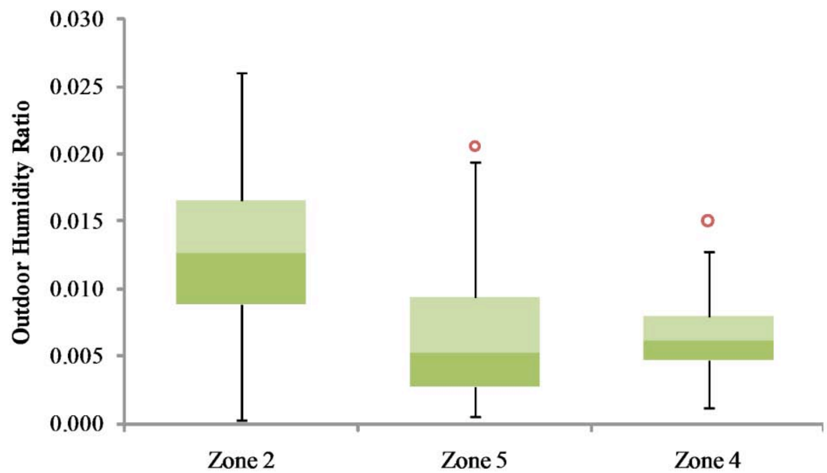
	Zone 2	Zone 5	Zone 4
Min	0.00302	0.002232	0.000117
Max	0.02848	0.261640	0.022210
Mean	0.00978	0.007530	0.007588
Median	0.00965	0.007107	0.007517
% Outliers	2.48%	0.41%	0.63%

Figure 7. Box Plot of Indoor Relative Humidity for All Three Climate Zones



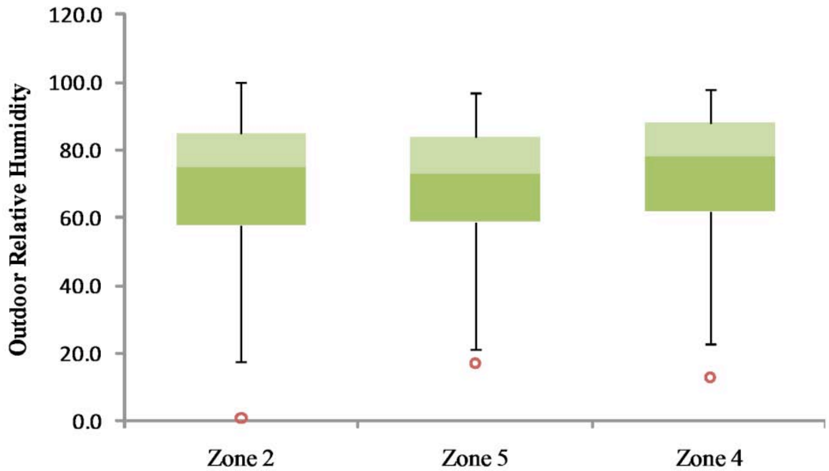
Min	21.0	16.0	1.0
Max	96.0	97.0	96.0
Mean	51.0	47.9	53.1
Median	51.0	48.0	53.0
% Outliers	1.03%	0.24%	0.42%

Figure 8. Box Plot of Outdoor Humidity Ratio for All Three Climate Zones



Min	0.00021	0.000591	0.001174
Max	0.02604	0.020187	0.015050
Mean	0.01246	0.006309	0.006358
Median	0.01263	0.005197	0.006163
% Outliers	0.00%	0.003%	0.14%

Figure 9. Box Plot of Outdoor Relative Humidity for All Three Climate Zones

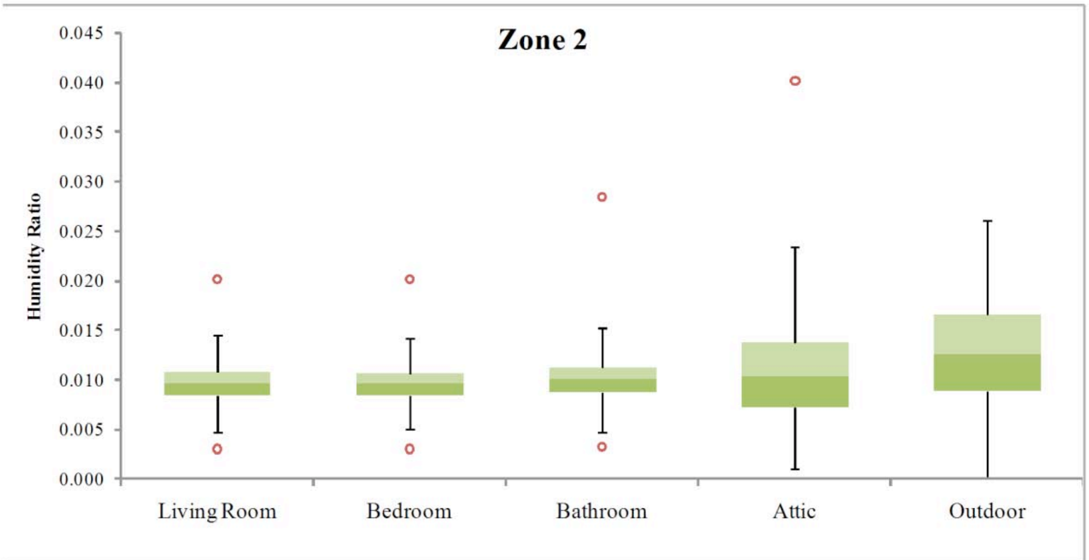


	Zone 2	Zone 5	Zone 4
Min	1.0	17.0	13.0
Max	100.0	97.0	98.0
Mean	70.8	70.5	73.5
Median	75.0	73.0	78.0
% Outliers	0.09%	0.072%	0.16%

Statistical Breakdown of Data

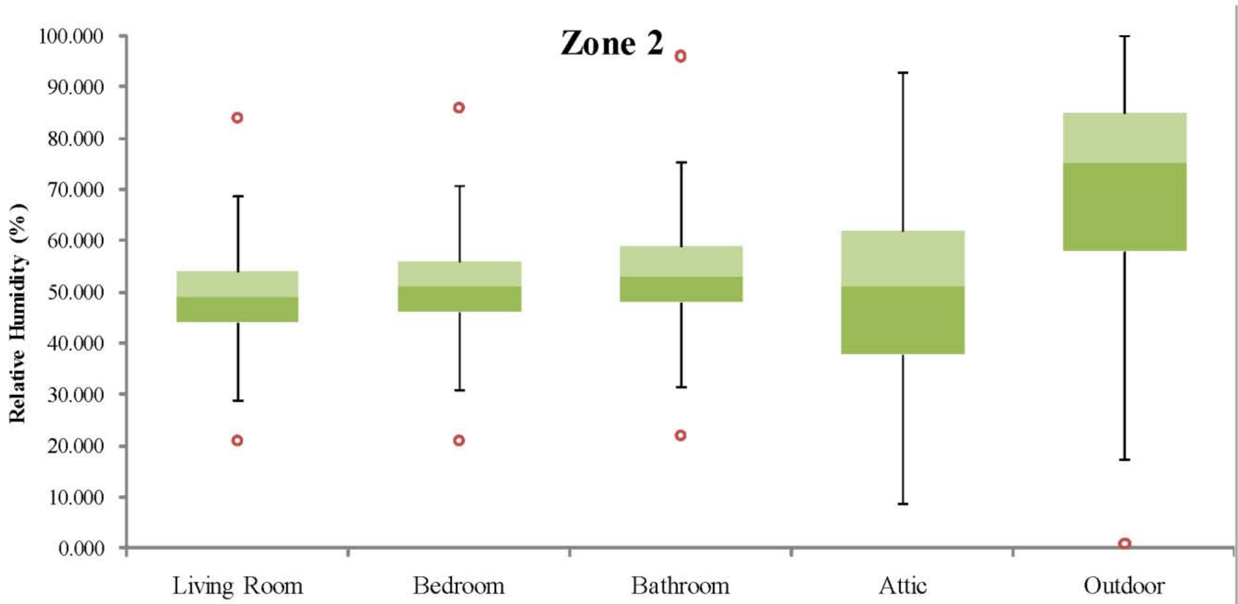
Figures 10 through 15 show box plots of the average humidity ratios and relative humidity for each sensor location, for each region. For each of the three climate zones, the humidity ratios and relative humidity are quite uniform for all the interior sensors, with the bathroom sensor consistently showing slightly higher values.

Figure 10. Humidity Ratio Box Plots for Zone 2, Hot-Humid Southeast Climate for Each Sensor Location



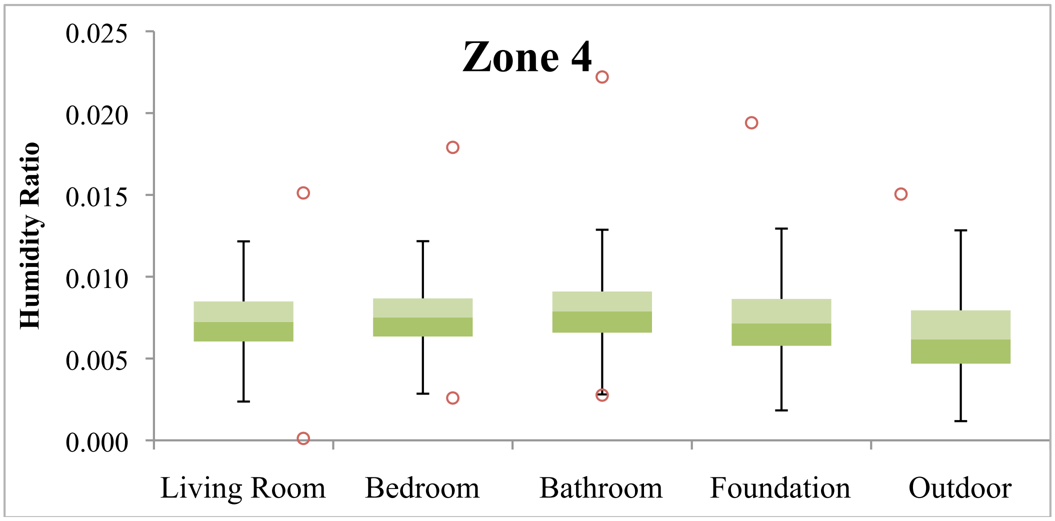
	Living Room	Bedroom	Bathroom	Attic	Outdoor
Min	0.00305	0.003020	0.003262	0.001073	0.000208
Max	0.02848	0.020165	0.028477	0.040180	0.026040
Mean	0.00978	0.009692	0.010168	0.010820	0.012460
Median	0.00965	0.009596	0.010011	0.010390	0.012630
% Outliers	2.57%	2.64%	2.75%	1.07%	0.00%

Figure 11. Relative Humidity Box Plots for Zone 2, Hot-Humid Southeast Climate for Each Sensor Location



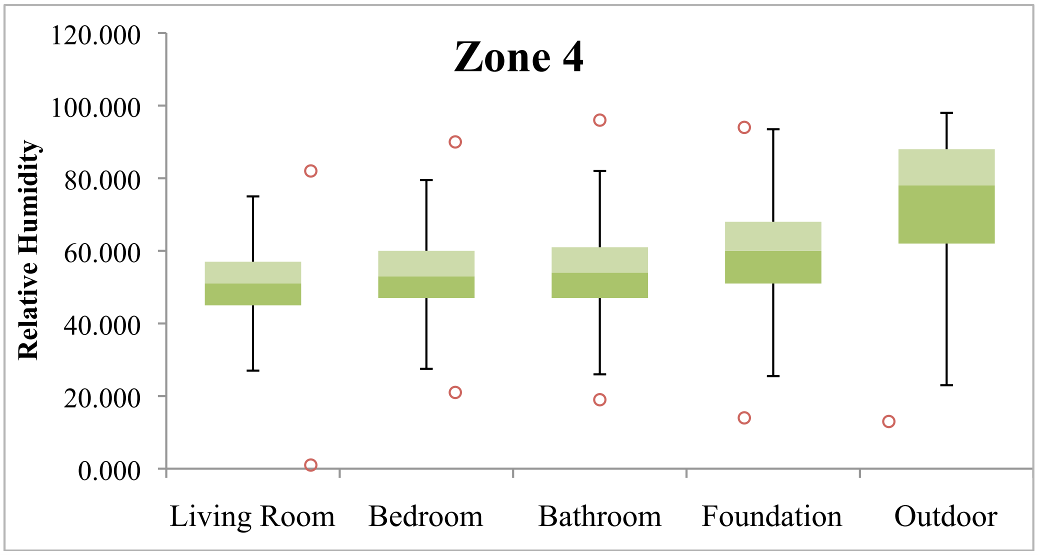
	Living Room	Bedroom	Bathroom	Attic	Outdoor
Min	21.0	21.0	22.0	9.0	1.0
Max	84.0	86.0	96.0	93.0	100.0
Mean	49.0	51.2	53.2	49.9	70.8
Median	49.0	51.0	53.0	51.0	75.0
% Outliers	0.51%	2.64%	1.43%	0.00%	0.09%

Figure 12. Humidity Ratio Box Plots for Zone 4, Marine Northwest Climate for Each Sensor Location



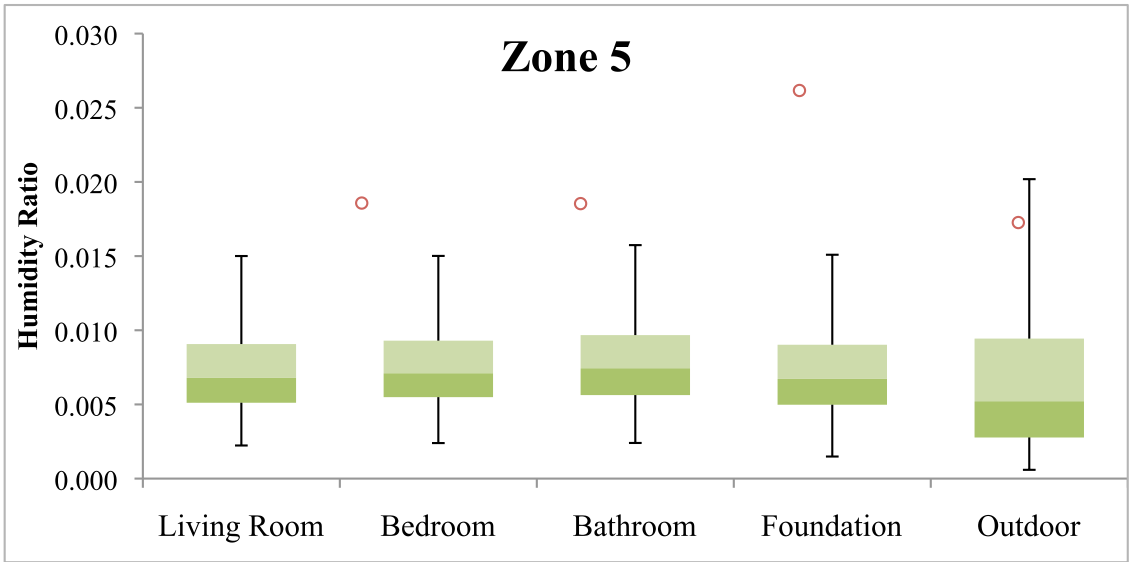
Min	0.00012	0.002588	0.002764	0.001830	0.001174
Max	0.01512	0.179050	0.022207	0.019410	0.015050
Mean	0.00730	0.007544	0.007915	0.007245	0.006358
Median	0.00725	0.007506	0.007874	0.007140	0.006163
% Outliers	0.29%	0.49%	1.08%	0.28%	0.14%

Figure 13. Relative Humidity Box Plots for Zone 4, Marine Northwest Climate for Each Sensor Location



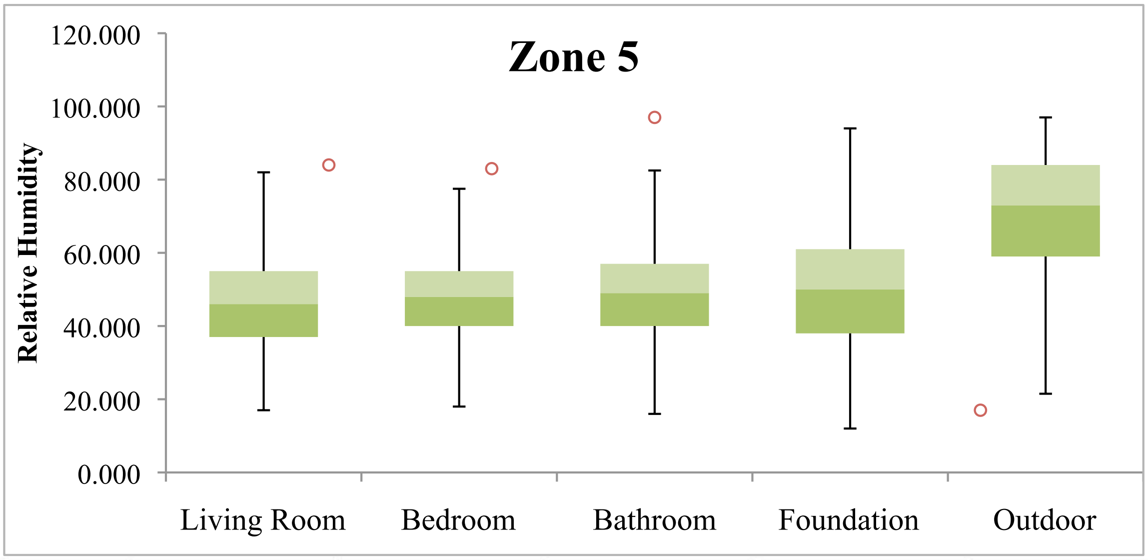
Min	1.0	21.0	19.0	14.0	13.0
Max	81.0	90.0	96.0	94.0	98.0
Mean	51.2	53.7	54.2	59.2	73.5
Median	51.0	53.0	54.0	60.0	78.0
% Outliers	0.61%	0.49%	0.92%	0.46%	0.16%

Figure 14. Humidity Ratio Box Plots for Zone 5, Cold Northeast Climate for Each Sensor Location



Min	0.00223	0.002395	0.002402	0.001488	0.000591
Max	0.01858	0.018538	0.026164	0.016901	0.020187
Mean	0.00725	0.007520	0.007823	0.007135	0.006309
Median	0.00679	0.007100	0.007427	0.006727	0.005197
% Outliers	0.38%	0.28%	0.56%	0.08%	0.00%

Figure 15. Relative Humidity Box Plots for Zone 5, Cold Northeast Climate for Each Sensor Location



Min	17.0	18.0	16.0	12.0	17.0
Max	84.0	83.0	97.0	94.0	97.0
Mean	46.7	47.7	49.2	49.6	70.5
Median	46.0	48.0	49.0	50.0	73.0
% Outliers	0.00%	0.28%	0.65%	0.00%	0.07%

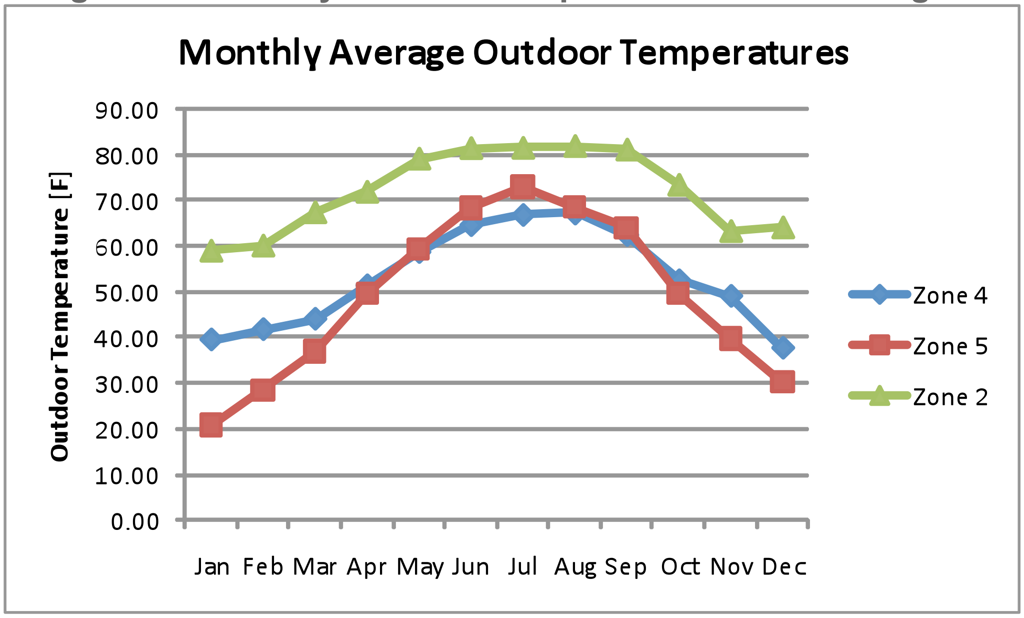
Regional Analysis

As noted previously in Part 1, Results and Discussion, the highest occurrences of moisture problems were noted in the Zone 5, cold Northeast housing data set, and the highest interior relative humidity of the three zones was in the Zone 5, marine Northwest housing data set, which also had a higher humidity ratio than housing in the cold Northeast data set. Several of the moisture problems in the cold Northeast were associated with water leakage into the basement.

The marine Northwest data set had the fewest homes with central air-conditioning and the most homes with crawlspaces. These basic results suggest possible correlations among indoor relative humidity and cooling-system use and operation, heating-system use and type, foundation type, and climate.

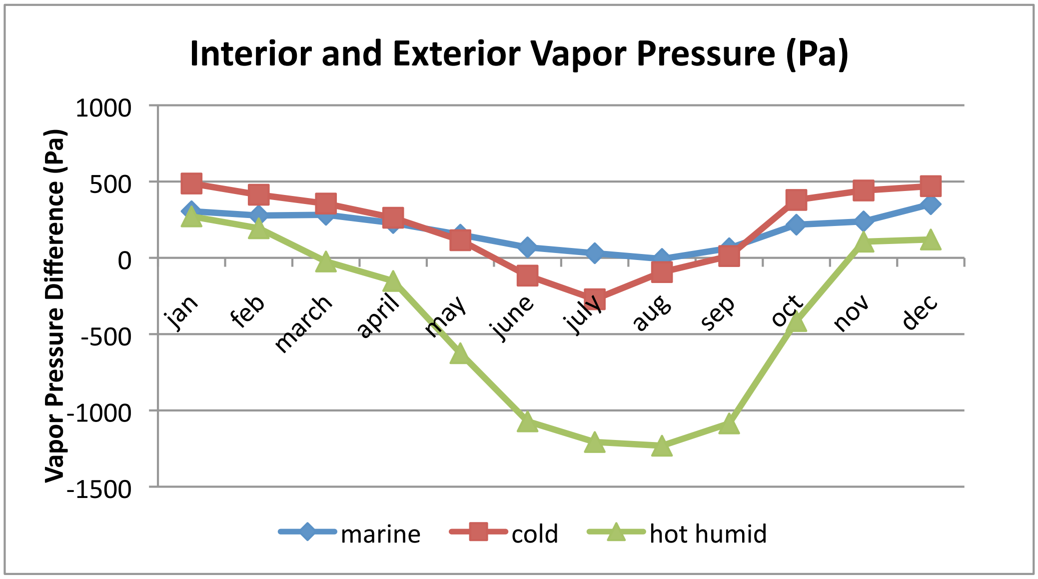
Although humidity ratios are not that different for the cold and marine climates, the marine climate is milder, as figure 16 shows. These milder conditions result in less of a need for space conditioning and, thus, dehumidification.

Figure 16. Monthly Outdoor Temperatures for Each Region



A vapor-pressure analysis of the monitored homes revealed that the average annual interior vapor pressure was approximately 1,550 Pascals for Zone 2, 1,213 Pascals for Zone 4, and 1,192 Pascals for Zone 5. Looking at the monthly differences between interior and exterior vapor pressure as shown in figure 17 gives a good indication of the direction of the flow of moisture in each climate. The very large negative difference between interior and exterior vapor pressure indicates that the flow of moisture is likely to be from outside to inside for at least 6 months of the year in Zone 2. The results for the cold climate suggest a change in the direction of the moisture flow, but the primary direction appears to be from inside to outside during at least 6 to 7 months of the year. Zone 4 shows a consistent positive vapor pressure difference for the entire year.

Figure 17. Difference Between Interior and Exterior Vapor Pressure (Pascals) for the Three Climate Zones



Correlations between house characteristics and internal moisture loads were investigated within each region for—

- Number of occupants.
- Occupant density.
- House size.
- Foundation type.
- Air leakage.
- Mechanical ventilation.

The most consistent trends appear to be between indoor humidity and (1) occupant density, although even that is questionable with coefficients of determination (R^2) not much higher than 0.2 (see figures 18 and 19), and (2) the presence of a foundation with exposed dirt floors.

Further research is needed to determine if significant correlations exist between these two housing characteristics.

Figure 18. Humidity Ratio versus Occupant Density for all Climate Zones

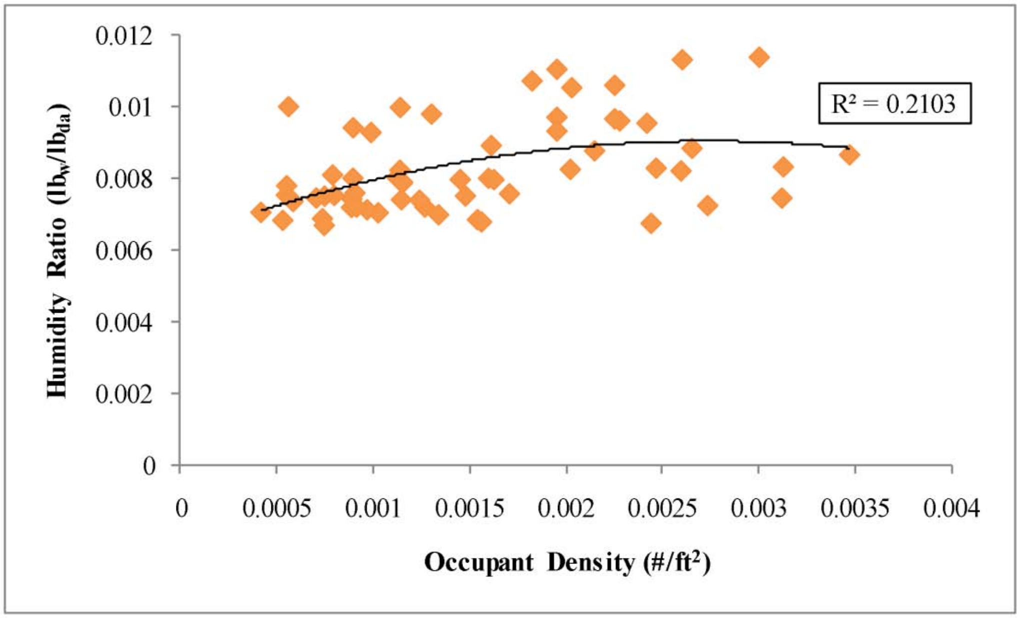
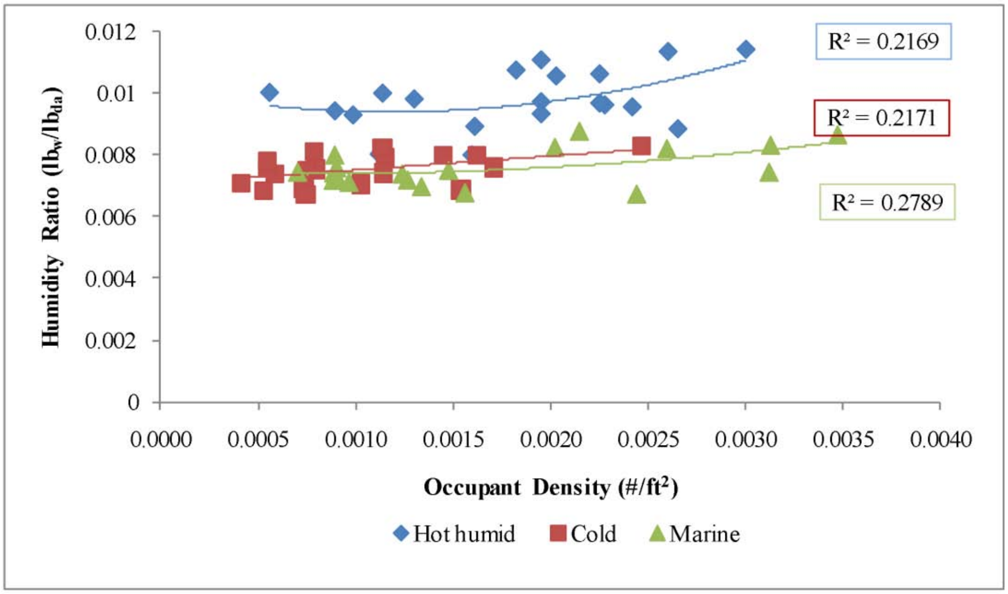


Figure 19. Humidity Ratio versus Occupant Density for Each Climate Zone



Analysis of Homes With Moisture Problems

The engineers conducted all site inspections between late May and mid-July. They questioned all occupants about the presence of mold or moisture problems in their homes during the course of the entire year and verified all reported concerns during the site visits.

In all three regions, the highest occurrence of mold or moisture damage observed during the initial site visits was on or around the windows and in the bathrooms. In the hot and humid climate, mold was visible on several air handlers around the cooling coil, usually on air handlers located outside the conditioned space, such as in a garage. Also, several incidents of moldy caulk were found on the new homes in Gainesville, FL. This issue was specific to this housing development, which may mean that the caulk used during construction was not mold resistant and is not an indication of a typical problem in this region.

In the cold climate, moisture problems included musty smells within the conditioned space that were reported by the occupants and confirmed on site. Several homes had moisture leaks in the basements for part of the year. In more than one instance musty smells were noted on the upper floors of the home as opposed to the basements. Table 6 summarizes the moisture problems noted during the site inspections.

Table 6. Summary of Moisture Problems in Study Homes

House #	Moisture Problem	Potential Moisture Source
Climate: Hot-Humid		
4	Mold on ceiling and windows in baths and on air handler in garage	No bath fans
6	Mold on windows on 2nd floor bath; water stain in toilet closet on 1st floor	No bath fan in bath; possible water leakage
10	Window sills on west side of house showing mold and moisture damage on drywall around frames and interior sill; occupants reported condensation during early winter months	Nothing out of the ordinary
13	Mold on caulk around most windows; occupants reported condensation during early winter months	Small fountain in living room
14	Mold on caulk around windows; moisture stains on drywall around frames; occupants reported condensation on windows during early winter months; mold on caulk in bathrooms and on exterior siding	Nothing out of the ordinary
17	Mold, window sills and air handler; mostly on north side of house	Unknown
20	Wet plywood under air handler	Condensation on air-conditioning drain line
Climate: Cold		
21	Damp basement	Occasional water leakage
22	Mold on storm windows; some condensation on sills; mold in shower (bath fan present)	Unknown
27	Damp basement	Occasional water leakage
29	Condensation on basement walls	Lots of water seepage into space; crawlspaces with dirt floors
30	Musty smells, 2nd floor; insulated behind built-ins; smell gone	Unknown
32	Mold in upstairs bathroom (fan present)	Unfinished basement with stone foundation open to house
35	Musty smell upstairs	Moisture in basement
36	Water in basement	Occasional water leakage
38	Some mold in mechanical room on drywall near floor; occupants were remodeling and fixing air leaks and replacing windows	Previous plumbing leakage into basement ceiling; was being repaired
39	Mold in bathrooms	Very low bath-fan flows; two dogs and a fish tank
Climate: Marine		
44	Mold on windows (all single-pane windows)	Partial dirt crawlspace; vapor barrier not well installed
45	Mold on ceiling and windows in bathroom	Partial dirt crawlspace; no bath fan
46	Mold on bathroom ceiling (fans present)	Fireplace: gas insert; no damper in flue per code; no doors
49	Mold on windows (single-pane windows) and bath ceiling (fan present—timer on 10 minutes)	Two fish tanks, four rabbits, and two dogs; some foundation leakage during heavy rain
56	Windows: mold where glass meets sash (dble-pane, low-e, vinyl)	Vented crawlspace
57	Mold in upstairs bath and on windows (single-pane windows)	No bath fans
61	Mold in 2nd floor bath	Bath fans present but do not work

The engineers analyzed these data sets more closely to determine if their humidity ratios were notably different from the other homes in their region. Again, correlations between indoor humidity and the following characteristics were examined:

- Number of occupants.
- Occupant density.
- Foundation type.
- Air leakage.
- Mechanical ventilation.
- Presence of bath fans.

First, the engineers compared the average monthly interior humidity ratios for the homes with moisture problems with the homes without moisture problems. The results for Zone 2 show increased humidity levels from October through April for the homes with moisture problems. In Zone 4, the interior humidity levels were slightly higher for the homes with problems and the foundation humidity levels were significantly higher. Zone 5 showed significantly higher levels in both the interior and the foundation humidity levels compared with those homes without reported moisture problems. Figures 20 through 22 display the monthly average humidity ratios for the homes with reported moisture problems and for those without moisture problems for each zone. The graphs for Zones 4 and 5 show the foundation humidity ratios compared with the interior humidity ratios for both cases.

Figure 20. Interior Humidity Ratios for Homes With and Without Moisture Problems in Zone 2

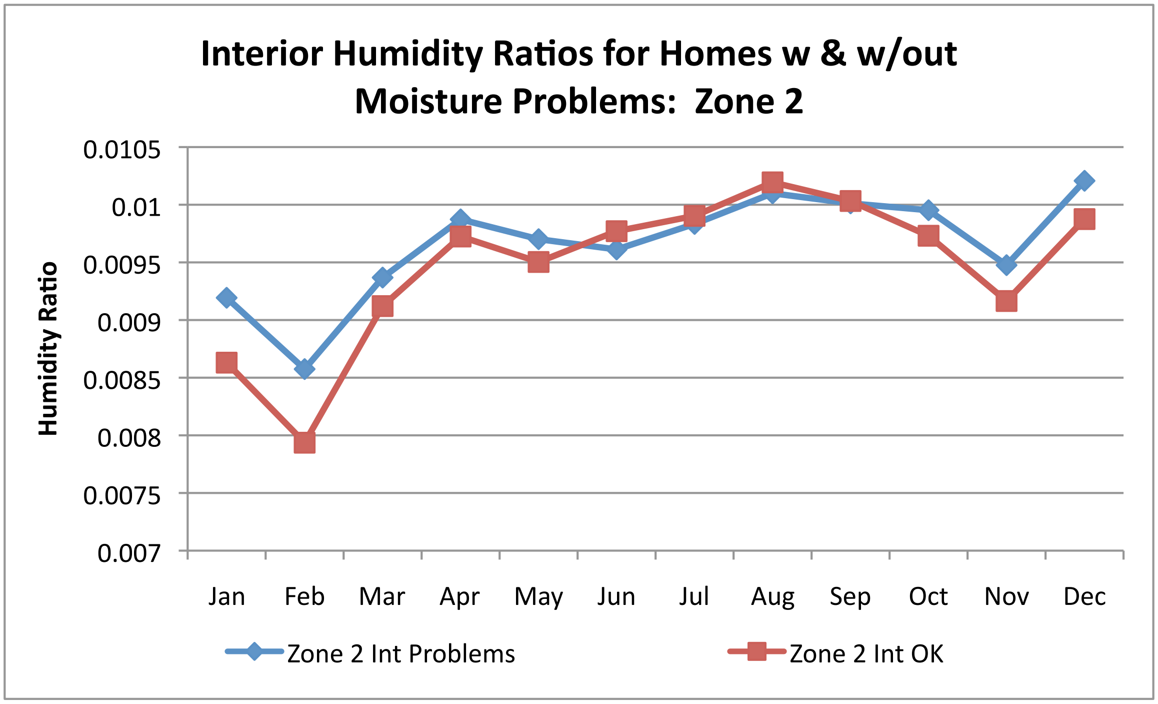


Figure 21. Humidity Ratios for Homes With and Without Moisture Problems in Zone 4

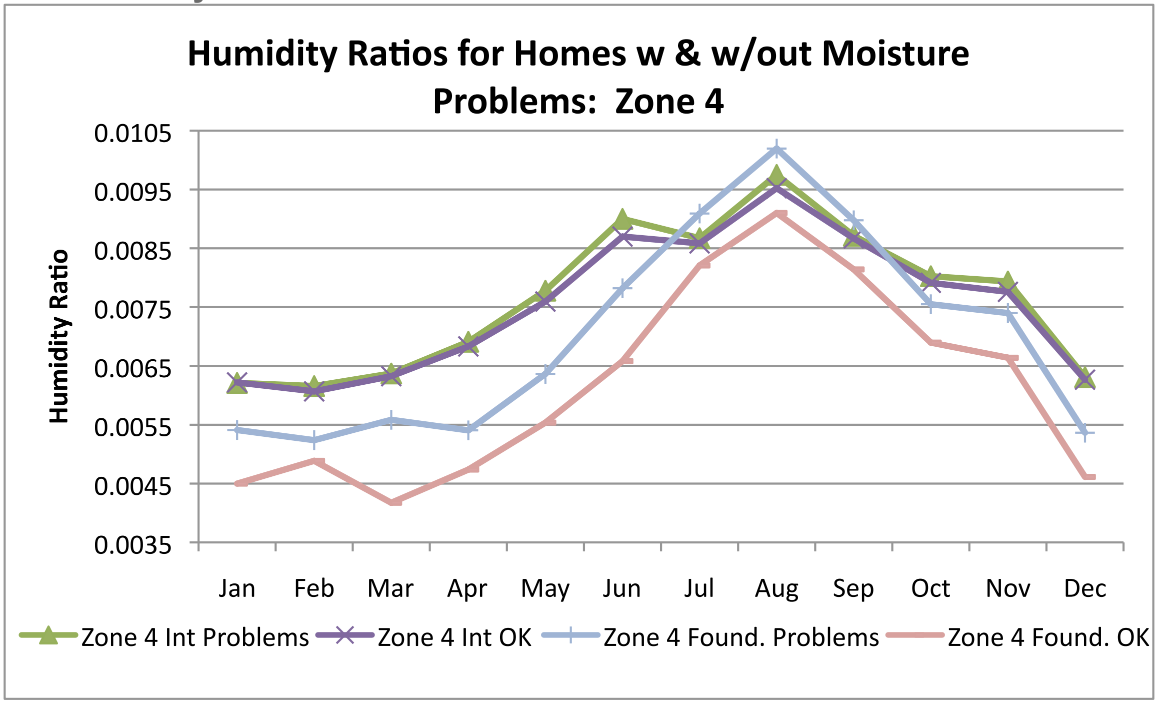
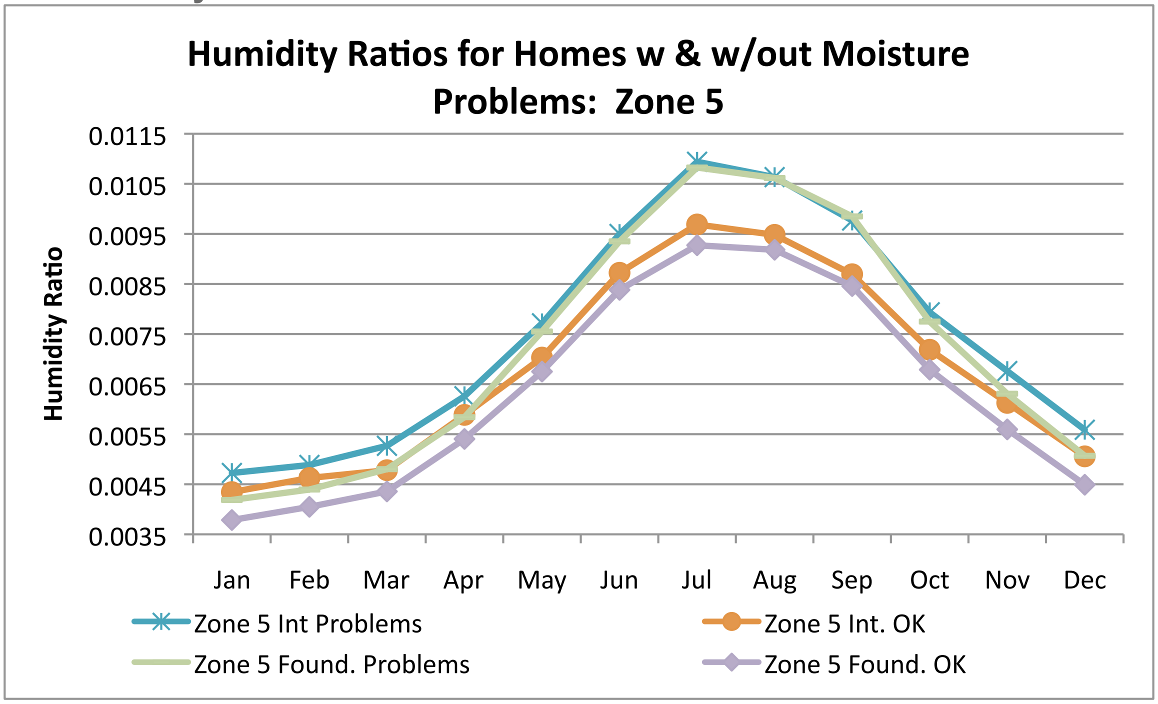


Figure 22. Humidity Ratios for Homes With and Without Moisture Problems in Zone 5



Problems Encountered and Lessons Learned

Because this federally funded survey was subject to the Paperwork Reduction Act, a delay occurred while waiting for the Office of Management and Budget to approve the amount of paper being used in the survey instrument. This delay resulted in a delay in recruiting candidate households, which was done as a courtesy to avoid having to reschedule the initial site visits and thereby inconveniencing the candidates. After the OMB approved the survey instruments, the engineers began selecting candidates and scheduling initial site visits.

At the beginning of the project, the biggest difficulty was finding participants who would agree to have their homes inspected for several hours for the initial site visit and to be monitored for a full year. In Florida, finding willing volunteers was so difficult that the engineers changed the parameters for selecting participants: they increased the size of the homes allowed in the study from 3,000 square feet to 3,500 square feet, used more block homes than was originally intended, and allowed a couple of the participants' homes with only one occupant. Although it was originally thought that builders who had worked or were currently working with the engineers? would be good sources of leads for candidates, this expectation did not turn out to be the case. Most of the builders were concerned that such a study could cause them legal problems if moisture problems were detected in homes they had constructed.

Overall, the engineers did not encounter many problems during the data collection period. Three occupants decided to do some level of remodeling, the effects of which will be investigated. One sensor was lost (most likely to vermin) and a few stopped collecting data along the way. In a couple of instances, the occupants forgot where the sensors were located and moved furniture that had loggers stuck to the back. In general, the participants were very cooperative and many were involved in helping to recruit others at the beginning of the study.

Interpretation of the conditioned building envelope proved to be challenging in some cases simply because of the way the occupants used the home. Unlike performing an energy rating on new construction, existing homes must be evaluated based on how the occupants use and condition the space, or the analysis will not make sense. For instance, if an engineer considers an unfinished basement as unconditioned, but the occupants leave the door open most of the time for pets or children, it would be wrong to remove that space from the air-leakage analysis and conditioned square footage calculation. Because these conditions were some of the major characteristics being analyzed for their effects on interior humidity levels, proper characterization was important to this study. The engineers combined their professional experience with the occupant interviews to determine what spaces they should consider conditioned versus unconditioned.

Among the biggest challenges of this study were (1) analyzing a large data file (almost 10 million records total with five data points for each record) and (2) finding significant correlations from so few homes across such unique climates. Quickly and efficiently analyzing that amount of data proved to be challenging using Microsoft ACCESS. Although the engineers conducted the initial review with ACCESS, they later decided to use MathWorks MATLAB software for the more critical work of identifying correlations.

Conclusions

Of the three climates in the study, the homes in Zone 4, the marine Northwest climate, appear to consistently have indoor relative humidity levels above 50 percent, but the highest level of moisture problems occurred in Zone 5, the cold Northeast climate.

After conducting an initial review of the data, the engineers noted that major differences between the housing sets appear to include the following:

- **Age.** Homes in the marine climate were much older than homes in the other two climates.
- **Air leakage.** The air-leakage rate (ACH50) was almost twice as high in the marine climate than in the other two climates.
- **Foundation type.** Several homes in the marine climate were built on vented crawlspaces with dirt floors. Homes in the hot-humid climate were all built on slabs, and homes in the cold climate were primarily built on partially finished basements that were conditioned.
- **Cooling equipment.** Only 20 percent of the homes in the marine climate had central air-conditioning units, whereas 75 percent of the homes in the cold climate and 100 percent of the homes in the hot-humid climate had central air-conditioning.
- **Heating equipment.** Only about 50 percent of the homes in the marine climate had forced-air heating. The other 50 percent of the homes had a mixture of boilers with baseboard radiators or electric heat.

In all three regions, the highest occurrence of visible mold or moisture damage was on or around windows and in the bathrooms. In the hot-humid climate, mold was visible on several air handlers around the cooling coil, usually on air handlers located outside the conditioned space such as in a garage.

In the cold climate, moisture problems included musty smells within the conditioned space that were reported by the occupants and confirmed on site. Several homes had water leakage problems in the basements. In a couple of instances these smells were noted on the upper floors of the home as opposed to the basements.

The engineers were not able to establish strong correlations between house characteristics and indoor humidity levels because of the small sample size. After evaluating the data regionally, across regions, and with respect to those homes that did and did not have moisture problems, the engineers determined that trends that deserve further investigation are related to increased humidity levels due to the following:

- High air-change rates.
- High-occupant densities.
- The presence of unfinished and unconditioned basements and crawlspaces.
- The use of materials with higher condensation and mold potential in climate Zone 2, such as metal windows and marble window sills.

For a large study, independent loggers proved to be a reliable, cost-effective method for collecting data. Less than a 2-percent loss of data was realized in 285 separate loggers. Although an interim site visit was required to download data half way through the study, ease of installation, accuracy, and cost of equipment outweighed the costs associated with the travel and hours necessary to conduct the extra site visit.

The engineers' analysis of the homes with and without moisture problems in each climate zone led to the following conclusions.

Zone 2, Hot-Humid Southeast

For homes in this climate, mold was visible on several air handlers around the cooling coil, usually on air handlers located outside the conditioned space, such as in a garage. The humidity ratios are not much different between the homes with moisture problems and the homes without. The moisture problems seem to be occurring during the late fall and early winter in the newer homes that are more efficient and have a lower air-change rate. This result could be due to the fact that these homes are more comfortable and require less heating during those months, allowing the interior relative humidity levels to rise.

Zone 5, Cold Northeast

Many of the homes in this climate with moisture problems had moisture leakage in the basement and all had a portion of the basement that was unfinished. Musty smells within the conditioned space were reported by the occupants and confirmed on site. In a couple of instances these smells were noted on the upper floors of the home rather than in the basements. Homes with moisture problems in this region also have a much higher average air-change rate compared with those homes without moisture problems. The engineers suggest that the effect of foundation moisture on the interior humidity levels should be investigated.

Zone 4, Marine Northwest

The homes in this climate were considerably older than homes in the other two climates. A significant number of homes in this region had dirt crawlspaces, some vented and some not. The homes with moisture problems all had a crawlspace or partial crawlspace and none had a well-sealed vapor barrier over the dirt. Other notable differences were the air-change rates and the occupant densities. The engineers suggest that all these characteristics should be investigated further to determine their influence on interior moisture levels.

The engineers conclude that each region appears to have problems specific to that location that should be addressed. They also suggest not making blanket recommendations for moisture control across zones.

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APPENDIX A. PRESCREENING QUESTIONNAIRE

OMB Control Number: 2528-0252

Moisture Monitoring Participant Recruitment

INITIAL RECRUITMENT CONTACT

Region:______________________ Referred by: ________________________

Name: __________________________________ Phone:_________________

Address: ___________________________ City: _____________ State: ______

1. We are conducting a research study on humidity levels in homes and your home has been identified as a potential candidate for the study. The study involves a researcher coming to your home, conducting some tests to determine the tightness of your home and the performance of your HVAC systems, and installing several non-intrusive sensors that will remain for a year.
   Would you be willing to participate? Yes No
2. This is a year-long monitoring study. Based upon your current circumstances, do you plan to stay in your current home for at least a year? Yes No
3. How many people live in the home? ____________
4. Do you anticipate any significant changes to the home's occupancy during the coming year (e.g., new family members, kids going off to college, etc.)? Yes No
   Comments: ____
5. Do you plan to do any remodeling or additions in the coming year? Yes No
   Comments: ____
6. What year was the home built? __________
7. How big is the home (ft2)? _____________
8. Is the home single- or two-story? ______________
9. Does it have a basement? Yes No Finished? Yes No
10. Verify home's address.
11. Obtain information for contacting again to schedule visit. ___________________
    ____
12. Determine convenient time(s) for 4 hour visit. Certain days of week? Morning vs. afternoon? ____

APPENDIX B. FIELD DATA COLLECTION FORM

Field Visit Date: ____________________ *Site I.D. Number* ___ *OMB Control Number:* 2528-0252
*Expiration Date:*_12/31/2010__

Humidity Monitoring Field Data Form

Home Contact Information

First Name: ________________ Last Name: __________________________

Address: ____

City: ____ State: ______ Zip: _______________

Phone (h): ________________Phone (w): _________________Phone (m): _______________________

Home Characteristics

House Type (ranch, cape, colonial, townhome, etc.): __________________ Year of Construction: _______

Approximate square footage: basement _________ 1st floor ________ 2nd floor _______ other _______

Ceiling heights: basement _________ 1st floor ________ 2nd floor _______ other _______

# of Bedrooms _______ # of Bathrooms _________

Occupancy: # of occupants: ________ # of adults:_________ # of children: _________

# of all-day occupants: _______ # of adults:_________ # of children: _________

Foundation type (basement, finished/unfinished, crawlspace, vented/unvented, etc.):

____

Notable Moisture Sources (i.e., plants, pets, aquariums, etc.): ____________________________________

____

____

Primary floor coverings: ❑ vinyl ❑ wood ❑ carpet ❑ tile ❑ other _____________________________________

Primary Siding Material ❑ wood ❑ metal ❑ vinyl ❑ stucco ❑ brick ❑ other _____________________________

Structure: ❑ 2 x4 wood frame ❑ 2 x 6 wood frame ❑ other _________________________________

Windows: ❑ single-glazed ❑ double-glazed ❑ low-e ❑ other _____________________

Window frames: ❑ wood ❑ vinyl ❑ metal ❑ other

____

Attic insulation type: ❑ blown fiberglass ❑ blown cellulose ❑ fiberglass batt ❑ other

____

Attic insulation depth: _______ inches

Foundation insulation description: ____

____

____

Notes

Steven Winter Associates, Inc. *1*

Field Visit Date: ___________________ *Site I.D. Number* ___ *OMB Control Number:* 2528-0252
Expiration Date: _12/31/2010__

Mechanical Equipment (if multiple systems, complete survey for all systems)

How many air handling units? ___________

Central HVAC System: ❑ heating only ❑ cooling only ❑ heating and cooling

Heating Fuel: ❑ gas ❑ oil ❑ propane ❑ electric ❑ wood/coal ❑ other

Heating Type: ❑ Furnace ❑ Boiler Baseboard ❑ Hydro-air ❑ Elec. Resistance ❑ Heat Pump (AS or GS)

System Location: ______________________ ❑ conditioned ❑ unconditioned

Duct Location: ❑ Attic Only ❑ Basement/Crawlspace Only ❑ Both ❑ All within envelope

Heating Make: ____________Model #: ______________ Input Size (MBtuh): ______ AFUE: _____

Cooling Make: ____________Model: _______________Output Size (MBtuh): ______ SEER: _____

Central dehumidifier (type/location) ______________________________

Central humidifier (type/location) ________________________________

Central mechanical ventilation (type/location) ______________________________________

Domestic Hot Water System Type: ❑ tank ❑ indirect tank ❑ tankless coil ❑ instantaneous
❑ other: ____

Domestic Hot Water Fuel: ❑ gas ❑ oil ❑ propane ❑ electric ❑ wood/coal ❑ other: _______________

Domestic Hot Water Venting Type: ❑ atmospheric ❑ fan-assisted ❑ sealed combustion ❑ N/A

Appliances

Kitchen Stove Fuel: ❑ gas ❑ electric ❑ other

Clothes Dryer Fuel: ❑ gas ❑ electric ❑ other

Fireplace(s) or Stoves: ❑ gas ❑ wood ❑ other _________________________
❑ vented ❑ unvented ❑ other _________________________

Room Air Conditioner(s): How many? _____ Where? ____________________________________

Humidifier(s): How many? _____ Where? ______________________________________

Dehumidifier(s): How many? _____ Where? ______________________________________

Are dryer, bath fans, range hood, etc vented to the outside? ________________________________

Notes

Other Observations:

Is there evidence of potential moisture problems such as mold growth, water damage at window sills, etc.?

____

____

____

____

Field Visit Date: ___________________ *Site I.D. Number* ___ *OMB Control Number:* 2528-0252
*Expiration Date:*_12/31/2010__

Measurements:

BATH EXHAUST FAN AIR FLOWS (WITH LO-FLOW BALOMETER)

Fan location: ______________________ Measured cfm: ___________ Method of Control: ___________

Fan location: ______________________ Measured cfm: ___________ Method of Control: ___________

Fan location: ______________________ Measured cfm: ___________ Method of Control: ___________

Fan location: ______________________ Measured cfm: ___________ Method of Control: ___________

BLOWER DOOR TEST

House Pressure: ____________ Pa Fan Pressure: ____________ Pa Ring: ❑open ❑A ❑B

CFM50: ___________________

Notes:

DUCT SYSTEM AIR LEAKAGE MEASUREMENT (DELTA Q METHOD)

Total Duct Leakage ___________ cfm BD Ring: ❑ open ❑ A ❑ B ❑ C

Supply: _________ Return: _________

Notes:

Data Logger Installation

	Specific Location	I.D. Number
Living Room/Family Rm		
2nd Floor Bedroom or Master Bedroom		
Primary Bathroom		
Basement/crawlspace/attic		
Ambient		

Note: With homeowners' permission, digital photographs will be taken to complement the data collection.

APPENDIX C. MONITORING AGREEMENT

AGREEMENT TO PARTICIPATE IN MONITORING STUDY

_________________________________ ("I/We") agrees to work with Steven Winter Associates, Inc. (SWA) to monitor the indoor conditions (temperature and relative humidity) of my home at ________________________ (the "Home"). Monitoring will involve:

- An initial half-day visit to collect characteristic data on the Home and install data loggers for long-term monitoring.
- Data loggers installed by SWA personnel at several locations in the home will monitor temperature and relative humidity conditions. These loggers may require servicing by SWA personnel. I/We agree, upon reasonable notice provided, to authorize and permit personnel of SWA or its partners with access to the Home during the monitoring period at pre-arranged times to service the loggers.
- Upon completion or termination of the monitoring period, the data loggers will be removed from the home at no expense to me/us by SWA personnel. I/We understand that I/we will not be offered an opportunity to keep the data loggers.
- If, during the period of this monitoring project, I/we decide to sell, move from, or rent out the Home, I/we will exert our best efforts to provide at least thirty (30) days' advance notice to the SWA point of contact listed below so that the data loggers can either be removed or arrangements for continued monitoring can be established directly with the new occupants.
- No personally identifiable information will ever be released in any report produced by SWA as a result of the data collected from the Home, nor will personally identifiable information be shared with parties other than SWA.
- I/We agree to waive all claims against SWA, except for claims caused by the negligent acts of SWA or any of their respective employees, contractors, partners, or agents, during the term of this Agreement.

I/We hereby agree to the provisions set forth above, and agree to work with SWA representatives to facilitate this monitoring work of my/our Home.

____________________ Homeowner Signature	____________________ SWA Contact Signature
____________________ Print Homeowner Name	____________________ Print SWA Contact Name
____________________ Homeowner Telephone number	Steven Winter Associates, Inc 50 Washington Street, Norwalk, CT 06854 Phone: 203-857-0200