Monitoring of Internal Moisture Loads in Residential Buildings—Research Findings in Three Different Climate Zones

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ABSTRACT

This study was conducted to collect moisture load data to support research to better understand the impact of moisture on the thermal performance and durability of homes. Information on the interior hygrothermal loading of residential homes as a function of climates in the USA is limited. This research project has collected one full year of indoor temperature and humidity data for a sample of sixty homes across three different climate regions—the hot, humid southeast (zone 2), the cold northeast (zone 5), and the marine northwest (zone 4).

This research is in direct support to ANSI/ASHRAE Standard 160, Criteria for Moisture-Control Design Analysis in Buildings *(ASHRAE 2009). Understanding the interior loads is critical to the moisture design of building envelope components. With assistance from Oak Ridge National Laboratory as a subcontractor and members of Standard Project Committee 160 in an advisory role, a research methodology was developed. The monitoring protocol involved three site visits to the homes to perform such tasks as collecting basic house and equipment characteristics, installing data loggers, performing testing to quantify envelope leakage and duct leakage, and collection of data recorded by the data loggers. Data compiled in the field tests was analyzed to identify the potential relationships between certain household characteristics and the measured internal humidity levels.*

In this paper, the authors present significant findings from this study. Correlations between indoor moisture levels and climate, occupants, and house characteristics are the focus of the presentation. Conclusions and recommendations for indoor moisture management or future research needs are also discussed.

INTRODUCTION

A complete understanding of the influences certain factors have on a home's overall moisture content and moisture performance is not available. For example, which is more harmful to a home: showering without the fan on or installing metal frame windows? The purpose of this research project was to measure interior relative humidity in low-rise, detached residential buildings. Research was conducted to identify and quantify moisture loads in a home. Three different regions in the United States were targeted—the hot, humid southeast (zone 2), the cold northeast (zone 5), and the marine Pacific Northwest (zone 4). During the initial visits to each home, an engineer collected house and household characteristic data, including occupancy levels, insulation levels, equipment efficiencies, envelope leakages, and duct leakages. 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 year-long exterior and interior moisture load data for the test homes, an analysis of the influence of various components of the homes as well as occupant-related stimuli was conducted. Data compiled in the field tests was analyzed with the intention of identifying relationships between the various household characteristics and the internal humidity levels.

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RESEARCH DESIGN

Objectives

There were three major objectives for conducting this study.

1. **Support Research.** As noted in a paper from the Performance of Exterior Envelopes of Whole Buildings VIII conference (TenWolde and Walker 2001), "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" (p. 1). One intention of this project is to provide the research community with critically important field data for defining boundary conditions for use in moisture models and, through that effort, help them better understand the impact of moisture on the durability of homes.
2. **Support Development of Design Criteria.** ASHRAE Standing Standard Project Committee (SSPC) 160 continues to maintain the relatively new *Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings*. This committee has formulated "performance-based design criteria for predicting, mitigating, or reducing moisture damage to the building envelope, materials, components, systems, and furnishings" (ASHRAE 2009, p. 2). This moisture design standard will help make homes more moisture resistant and thus more durable. Data collected during this project will provide documented support for the interior design loads adopted by the SSPC 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 behavior
    - age of the home

    While 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 interior moisture levels in typical single-family detached homes.

Goals

This project attempts to address a combination of two recommended research projects that each received a "very high" priority ranking in the U.S. Department of Housing and Urban Development (HUD) publication "Building Moisture and Durability: Past, Present, and Future Work" (HUD 2004):

- characterize the moisture performance of existing homes through a field testing protocol, and
- develop statistically validated procedures to assess internal moisture loads for use in hygrothermal analyses and related engineering studies.

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

REVIEW OF EXISTING RESEARCH

The test protocol was developed with the help of an advisory panel. The panel was made up of experts from different segments of the building industry, most of whom are members of SSPC 160.

In addition to the input from this committee, this study is supported by Oak Ridge National Laboratory (ORNL), which has been directly funded by the U.S. Department of Energy (DOE) to support ASHRAE Standard 160. In an effort to determine the most critical information, subcontractor ORNL reviewed ten hygrothermal models. During the last 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 their use as forensic tools in the investigation of building failures, these computer models are increasingly used to make recommendations for building design in various climates. Although SSPC 160 realized that requiring multidimensional models was inconsistent with its goal of having a standard that could be easily used by the design community, they nevertheless listed in Section 5 of the standard a series of criteria that any computer tool needed to satisfy (ASHRAE 2009). Ten hygrothermal models met these requirements; the input variables and data format requirements of these models were examined to ensure that the data generated by this 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 significantly 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. SSPC 160 correctly realized that a consistent approach to moisture design demands a consistent framework for design assumptions or assumed loads.

ASHRAE Standard 160 (ASHRAE 2009) describes three options for estimating the interior conditions. These options contain varying amounts of input data to calculate. However, what is missing is a database of typical temperature and humidity loads that the user of the standard can apply to compare to his or her estimations. While great strides have been made to quantify and standardize meteorological data such as wind-driven rain, little data exist on what are typical indoor conditions. The purpose of this project was to generate some of this data.

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

CLIMATES EVALUATED

Emphasis was placed on three climatic regions of the United States 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 allow us to develop maximum, minimum, and average profiles for modeling and design studies. The three important climatic regions are, for different reasons, the hot, humid southeast (zone 2), the cold northeast (zone 5), and the marine Pacific Northwest (zone 4).

The *International Energy Conservation Code* climate map depicting the eight distinct climate zones is shown in Figure 1 (ICC 2006). This map highlights the three climate zones of this study, with 20 homes measured in each zone:

Zone 2: hot, humid southeast—Florida
Zone 5: cold northeast—New York
Zone 4: marine northwest—Oregon and Washington

These climates have very distinct hygrothermal behaviors and were chosen to provide a large variation of hygric loading.

Moisture issues in the hot and humid southeast climate are influenced more by ambient humidity levels than building conditions or occupant behavior, but the extent that 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 impact the indoor humidity conditions significantly. Rudd and Henderson (2007) conducted relevant monitoring studies and research in this climate region. This research was thoroughly reviewed and served as guidance for the test protocol in this project.

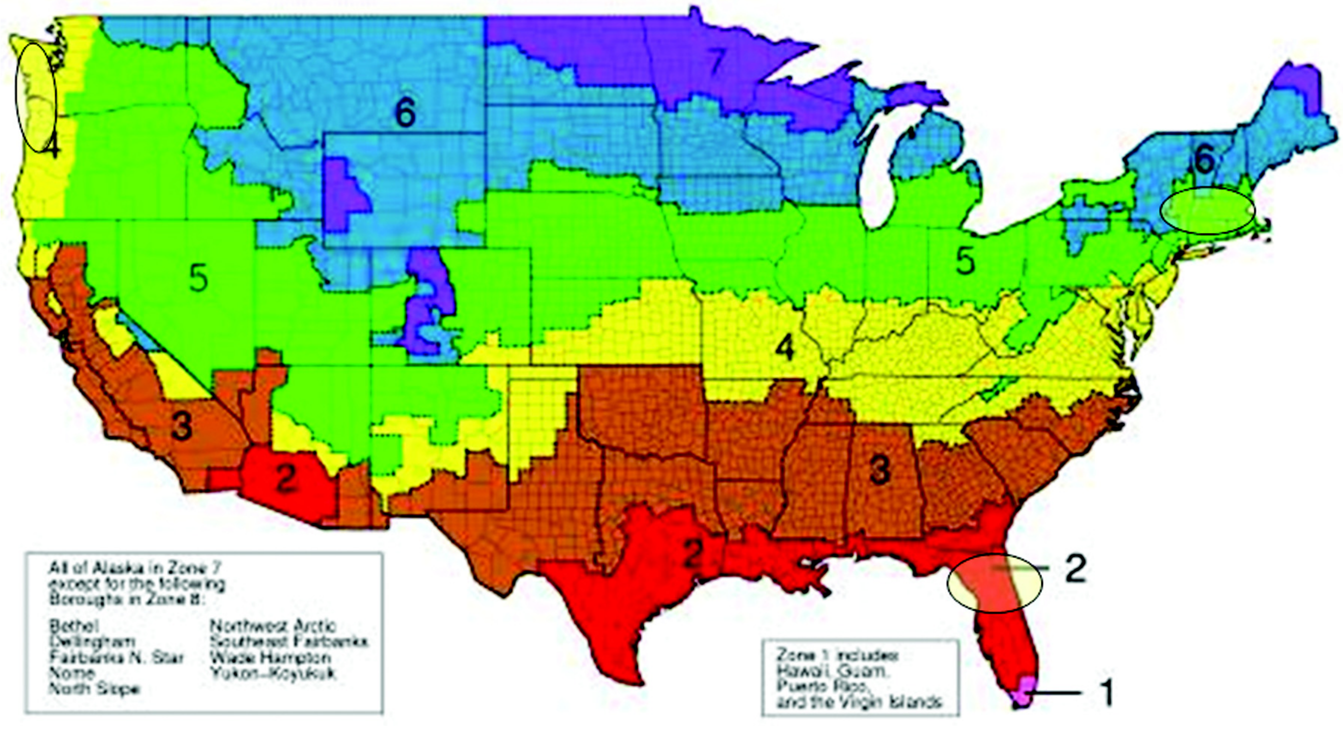


Figure 1 *IECC climate zone map of the United States.*

For residences in cold climates, 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 with subsequent condensation on cold surfaces. TenWolde (2000) documents this problem well and describes how design criteria such as that developed by SSPC 160 would have alerted builders to the potential problem.

The Pacific 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 upon very limited data.

DESIRED HOUSE CHARACTERISTICS

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

- Single-family homes (preferably detached)
- More than one year old
- Less than 3000 ft^2
- 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

A range of characteristics and occupant densities was desired within a focused area.

The identification and selection of test homes for this project was a critically important task. Simply put, without the homes, there would be no data. Care was applied to ensure that the recruitment process avoided selective biases that might occur. For instance, homeowners having problems with or concerns about moisture and humidity issues in their homes may have been more inclined to participate.

Test homes were found through the following sources:

- Building America builder partners
- Local agencies and institutes such the Florida Energy Extension Service
- Employees' relatives and friends
- Study participants

CRITICAL PARAMETERS MEASURED/RECORDED

In addition to determining the number of climate zones and the types of homes to be monitored, there were two key elements of the test protocol:

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

Short-Term Data Collection

As noted previously, the internal moisture load can be dependent upon 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 of the critical tasks during the development of the test protocol was to determine which house characteristics were vital to the assessment of internal moisture loads. The result of that analysis was translated into the Field Data Collection Form, a copy of which is located in Appendix A. This form was developed to ensure consistency and completeness in the data collection process and was completed for each home during its initial site visit.

Short-term testing and data collection was conducted at the time of monitoring equipment installation. This testing and data collection 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, etc.;
- a description of the HVAC equipment, including the type, capacity, and presence and description of humidifiers, dehumidifiers, and mechanical ventilation systems;
- documentation of the house size and configuration and number of occupants;
- measurement of exhaust fan airflows; and
- presence of mold and/or moisture sources.

All results collected during evaluation of the home characteristics were transferred into a database for subsequent analyses.

Long-Term Data Collection

When evaluating the choices available for the long-term monitoring, the following issues were considered:

- available memory,
- logging frequency,
- durability,
- accuracy,
- intrusiveness, and
- cost.

Preliminary research was conducted on wireless data loggers, but these were found to be too expensive for this project. The independent data loggers used were low-cost, nonintrusive, and relatively simple to use.

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

- outdoor temperature and relative humidity,
- primary living space (family/great room) temperature and relative humidity,

- master bedroom temperature and relative humidity (diurnal variations can be significant and of interest),
- primary bathroom (bathroom where most showers occur) temperature and relative humidity (often represents a severe humidity load condition that can influence the entire home),
- basement or crawlspace temperature and relative humidity (if present, can be a high moisture load region of the home), and
- attic temperature and relative humidity where a slab foundation was present (significant diurnal moisture loading has been observed).

Each data logger was set up to record temperature and relative humidity data every 15 minutes over a 12-month period. These data were averaged during post-processing to provide hourly data for model input.

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, 80 data sets were generated for analysis for interior relative humidity and temperature. Fifteen to twenty sets of data were generated per region from exterior sensors also measuring temperature and relative humidity.

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

Validation of Data Sets

Initial evaluation of the data was performed to ensure all data were collected for each sensor and that the data were valid. This initial review indicated that there was less than a 2% loss in data overall; 1.3% of the total loss was in zone 4, 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.

To identify extreme outliers and potentially bad sensors, each sensor's raw data was graphed against the other sensors in that region for the same location in the home. For example, Figure 2 shows the data collected for all the ambient sensors in Florida.

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

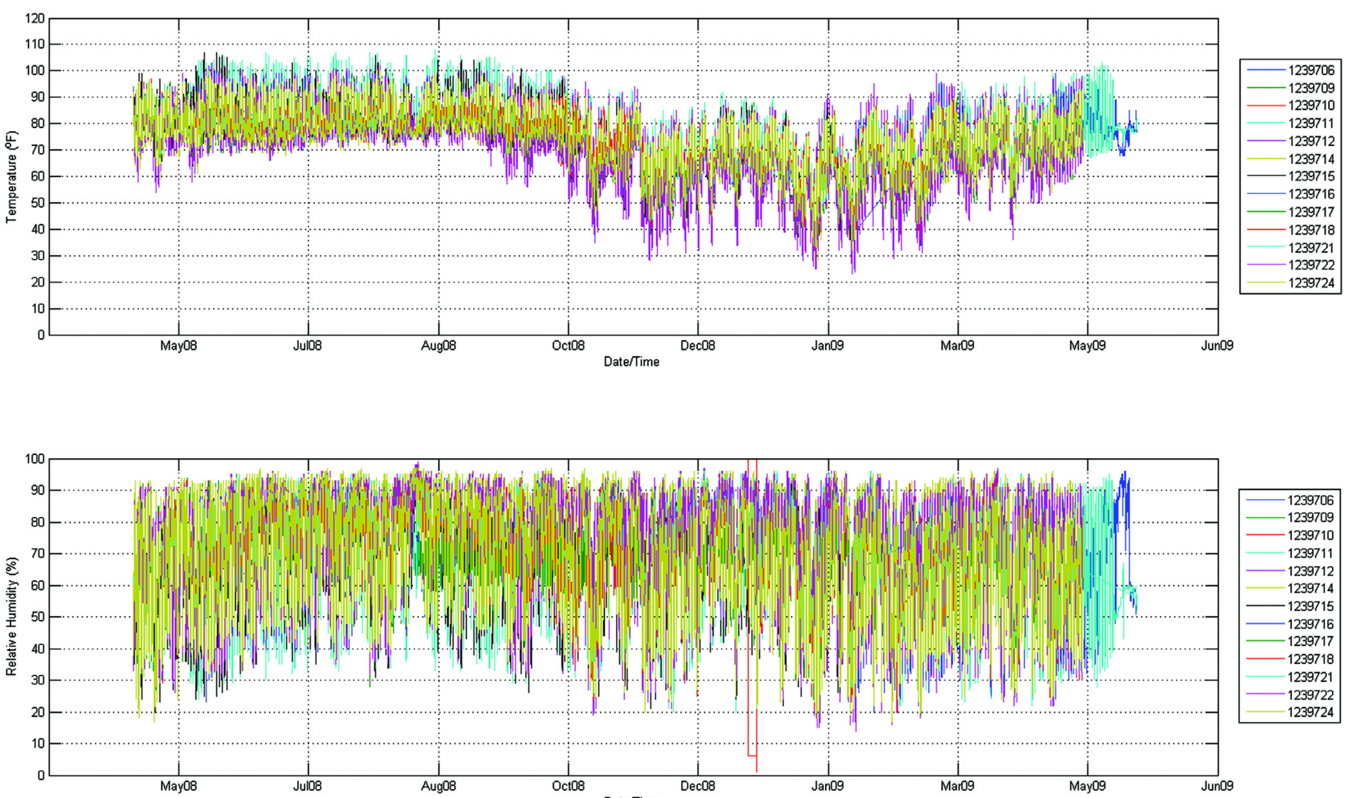


Figure 2 *Temperature and relative humidity data from climate zone 2, hot humid: ambient sensors.*

Each set of sensors was analyzed in the same manner. Some other reasons for data anomalies include:

- placement of sensors too near a heating/cooling source such as a leaky duct or fireplace,
- occupants with unusual setpoints,
- extended periods when homes were unoccupied,
- upgrades to homes (a couple of occupants changed windows), and
- unexplained behavior (in one Florida home, all the interior temperature sensors were reading 55°F in August).

In general, review of the data confirmed that there was minimal lost or bad data during the 12-month collection period. More than 97% of the data was successfully collected. Data was not eliminated due to unusual situations like those listed above; data was only excluded if the sensors were thought to be bad—i.e., if single digits were recorded on only one of the four sensors inside the home, negative numbers were logged, etc. All sensors were calibrated prior to installation.

Overview of Results

Following validation, extensive calculations were performed on the data sets. Because relative humidity is a function of temperature, this value was converted to humidity ratio to determine the actual amount of water in the air. This also allows a more direct comparison of moisture levels across regions. Once these calculations were performed on the raw data, average annual and average monthly relative humidities, humidity ratios, and temperatures were calculated for:

- the exterior sensors,
- the basement/crawlspace (or attic) sensors,
- the three interior sensors combined, and
- the three interior sensors individually.

Tables 1, 2, and 3 show the average interior values for each region compared to the ambient conditions.

On average, indoor relative humidity values are highest in zone 4, the marine climate, with average monthly values over 50% during most of the year, although humidity ratios are highest in climate zone 2 (hot, humid).

This data is summarized in the box plots in Figures 3 through 6. Average values along with maximum, minimum, and median values are also 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). "% Outliers" describes 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 data collected over an entire year.

Statistical Breakdown of Data

Box plots of the average humidity ratios and relative humidities for each sensor location for each region are shown in Figures 7 through 12. For each of the three climate zones, the humidity ratios and relative humidities are quite uniform for all the interior sensors, with the bathroom sensors consistently showing slightly higher values.

Table 1. Monthly Averages of Temperature and Relative Humidity Data: Hot, Humid Southeast Region (Climate Zone 2)

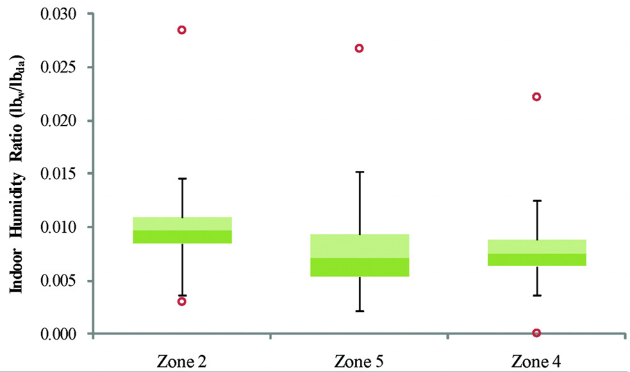
Zone 2	Indoor			Outdoor		
Month	Temperature, °F	Humidity Ratio, lb_w/lb_{da}	Relative Humidity	Temperature, °F	Humidity Ratio, lb_w/lb_{da}	Relative Humidity
Jan	72.8	0.00907	52.6	59.0	0.00766	69.0
Feb	72.3	0.00837	49.3	60.1	0.00730	64.4
Mar	74.5	0.00945	51.7	67.4	0.00958	66.9
Apr	75.8	0.01002	52.4	71.9	0.01075	65.5
May	77.8	0.00976	47.8	79.2	0.01324	64.0
Jun	78.4	0.01004	47.9	81.5	0.01631	72.6
Jul	78.1	0.01013	48.8	81.5	0.01743	76.5
Aug	77.9	0.01044	50.7	81.9	0.01790	77.5
Sep	77.9	0.01026	49.9	81.2	0.01691	74.7
Oct	76.4	0.00999	51.0	73.4	0.01278	71.1
Nov	73.8	0.00951	53.1	63.3	0.00913	70.9
Dec	73.8	0.01018	56.9	64.1	0.00962	73.6
Annual	75.8	0.00977	51.0	72.0	0.01238	70.6

Table 2. Monthly Averages of Temperature and Relative Humidity Data: Cold Northeast Region (Climate Zone 5)

Zone 5	Indoor			Outdoor		
Month	**Temperature, °F**	**Humidity Ratio, lb_w/lb_{da}**	**Relative Humidity**	**Temperature, °F**	**Humidity Ratio, lb_w/lb_{da}**	**Relative Humidity**
Jan	64.8	0.00475	36.1	20.9	0.00188	74.1
Feb	65.5	0.00494	36.7	28.6	0.00258	71.6
Mar	65.7	0.00522	38.3	37.0	0.00315	63.2
Apr	67.8	0.00635	42.9	49.7	0.00466	60.6
May	70.0	0.00766	48.2	59.5	0.00689	62.8
Jun	73.9	0.00951	52.1	68.3	0.01023	67.8
Jul	75.8	0.01087	56.1	73.0	0.01240	71.2
Aug	74.1	0.01057	57.7	68.6	0.01100	73.6
Sep	72.0	0.00988	57.9	64.1	0.00981	75.2
Oct	67.0	0.00803	56.2	49.5	0.00570	73.7
Nov	65.9	0.00683	49.8	39.7	0.00433	77.5
Dec	65.3	0.00558	41.8	30.2	0.00284	74.7
Annual	69.0	0.00752	47.8	49.1	0.00629	70.5

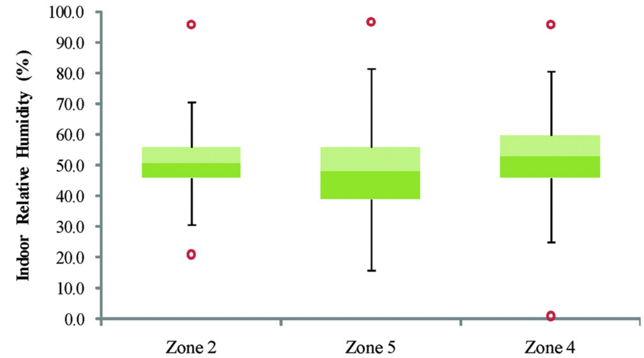
Table 3. Monthly Averages of Temperature and Relative Humidity Data: Marine Northwest Region (Climate Zone 4)

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**
Jan	63.5	0.00622	50.1	39.5	0.00445	84.6
Feb	63.7	0.00609	48.7	41.8	0.00436	78.3
Mar	64.3	0.00634	49.5	44.0	0.00460	75.1
Apr	66.0	0.00688	50.5	51.4	0.00526	67.6
May	68.5	0.00769	51.9	58.8	0.00648	64.0
Jun	71.1	0.00880	54.1	64.7	0.00815	64.1
Jul	72.3	0.00864	51.1	66.9	0.00815	60.1
Aug	73.2	0.00960	54.8	67.2	0.00938	67.4
Sep	70.2	0.00862	54.8	62.5	0.00794	68.3
Oct	65.7	0.00795	58.8	52.5	0.00660	78.0
Nov	64.4	0.00784	60.6	49.1	0.00641	85.2
Dec	62.9	0.00627	51.3	37.7	0.00431	85.5
Annual	67.1	0.00758	53.0	53.0	0.00634	73.2



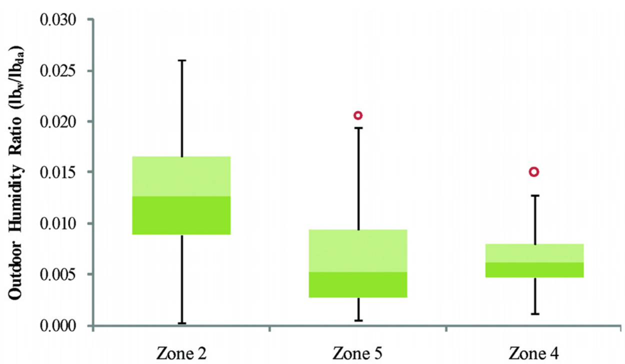
	Zone 2	Zone 5	Zone 4
Min	0.00302	0.00223	0.00012
Max	0.02848	0.26164	0.02221
Mean	0.00978	0.00753	0.00759
Median	0.00965	0.00711	0.00752
% Outliers	2.48%	0.41%	0.63%

Figure 3 *Box plot for indoor humidity ratios for all three climate zones.*



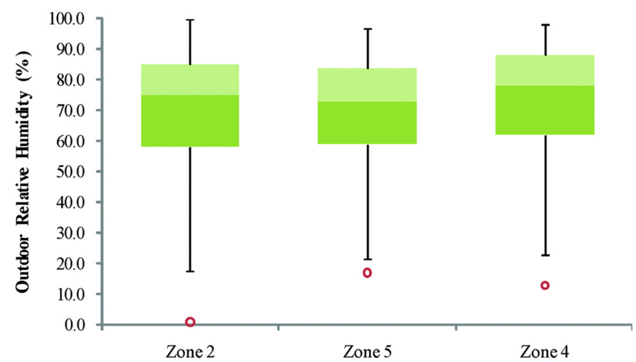
	Zone 2	Zone 5	Zone 4
Min	21.0	16.0	1.0
Max	96.0	97.0	96.0
Mean	51.0	47.9	53.1
Median	51.0	48.0	53.0
% Outliers	1.03%	0.24%	0.42%

Figure 4 *Box plot of indoor relative humidities for all three climate zones.*



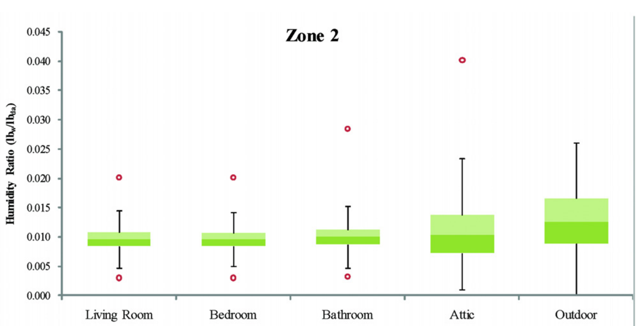
	Zone 2	Zone 5	Zone 4
Min	0.00021	0.00059	0.00117
Max	0.02604	0.02019	0.01505
Mean	0.01246	0.00631	0.00636
Median	0.01263	0.00520	0.00616
% Outliers	0.00%	0.003%	0.14%

Figure 5 *Box plot of outdoor humidity ratios for all three climate zones.*



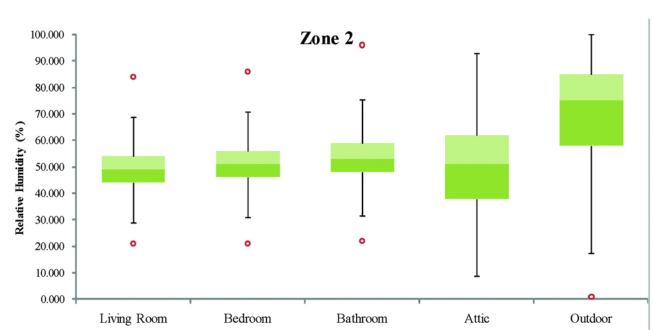
	Zone 2	Zone 5	Zone 4
Min	1.0	17.0	13.0
Max	100.0	97.0	98.0
Mean	70.8	70.5	73.5
Median	75.0	73.0	78.0
% Outliers	0.09%	0.072%	0.16%

Figure 6 *Box plot of outdoor relative humidities for all three climate zones.*



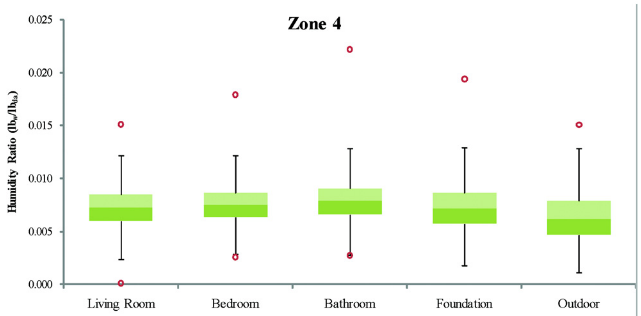
	Living Room	Bedroom	Bathroom	Attic	Outdoor
Min	0.00305	0.003020	0.003262	0.001073	0.000208
Max	0.02848	0.020165	0.028477	0.040180	0.026040
Mean	0.00978	0.009692	0.010168	0.010820	0.012460
Median	0.00965	0.009596	0.010011	0.010390	0.012630
% Outliers	2.57%	2.64%	2.75%	1.07%	0.00%

Figure 7 *Humidity ratio box plots for zone 2, hot and humid climate, for each sensor location.*



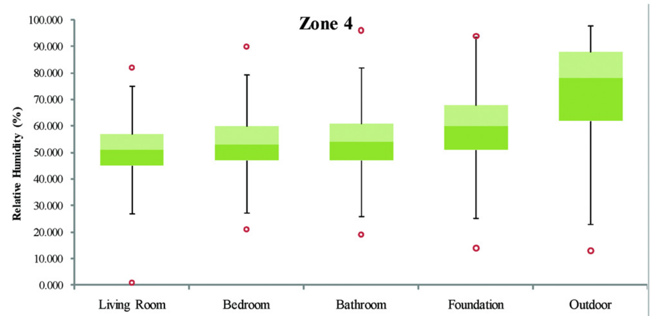
	Living Room	Bedroom	Bathroom	Attic	Outdoor
Min	21.0	21.0	22.0	9.0	1.0
Max	84.0	86.0	96.0	93.0	100.0
Mean	49.0	51.2	53.2	49.9	70.8
Median	49.0	51.0	53.0	51.0	75.0
% Outliers	0.51%	2.64%	1.43%	0.00%	0.09%

Figure 8 *Relative humidity box plots for zone 2, hot and humid climate, for each sensor location.*



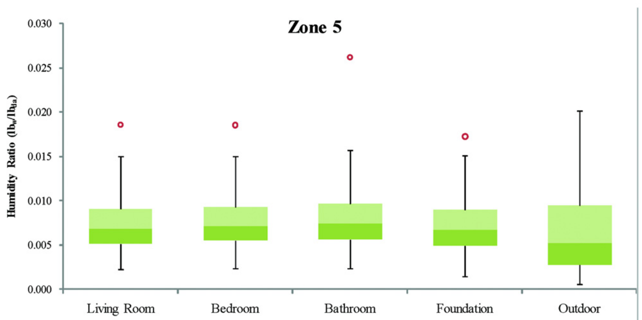
	Living Room	Bedroom	Bathroom	Foundation	Outdoor
Min	0.00012	0.00259	0.00276	0.00183	0.00117
Max	0.01512	0.17905	0.02221	0.01941	0.01505
Mean	0.00730	0.00754	0.00791	0.00725	0.00636
Median	0.00725	0.00751	0.00787	0.00714	0.00616
% Outliers	0.29%	0.49%	1.08%	0.28%	0.14%

Figure 9 *Humidity ratio box plots for zone 4, marine climate, for each sensor location.*



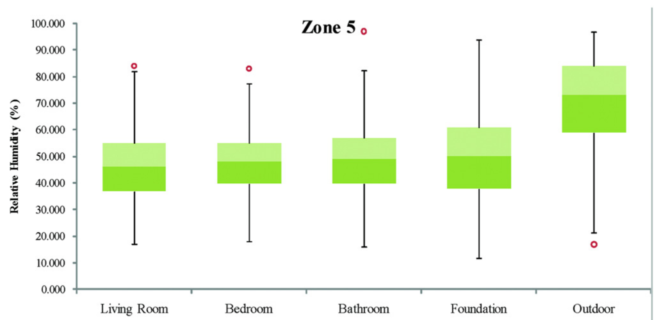
	Living Room	Bedroom	Bathroom	Foundation	Outdoor
Min	1.0	21.0	19.0	14.0	13.0
Max	81.0	90.0	96.0	94.0	98.0
Mean	51.2	53.7	54.2	59.2	73.5
Median	51.0	53.0	54.0	60.0	78.0
% Outliers	0.61%	0.49%	0.92%	0.46%	0.16%

Figure 10 *Relative humidity box plots for zone 4, marine climate, for each sensor location.*



	Living Room	Bedroom	Bathroom	Foundation	Outdoor
Min	0.00223	0.00240	0.00240	0.00149	0.00059
Max	0.01858	0.01854	0.02616	0.01690	0.02019
Mean	0.00725	0.00752	0.00782	0.00713	0.00631
Median	0.00679	0.00710	0.00743	0.00673	0.00520
% Outliers	0.38%	0.28%	0.56%	0.08%	0.00%

Figure 11 *Humidity ratio box plots for zone 5, cold climate, for each sensor location.*



	Living Room	Bedroom	Bathroom	Foundation	Outdoor
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%

Figure 12 *Relative humidity box plots for zone 5, cold climate, for each sensor location.*

Regional Analysis

Regional trends in the data were investigated first. Average building component efficiencies in each region were calculated. The average building age, size, foundation type, and building component efficiencies for each of the three regions are displayed in Table 4.

The last row of Table 4 lists the percentage of homes in each climate that experience moisture problems. For the purpose of this study, "moisture problems" refers to the presence of mold, musty smells, and/or water penetration through the building shell from the exterior. This table shows that the highest occurrences of moisture problems were noted in zone 5, the cold housing set, while zone 4, the marine climate, saw the highest interior relative humidity of the three zones as well as a higher humidity ratio than the cold climate. Several of the moisture problems in the cold climate were associated with water seepage into the basement.

The marine climate had the fewest homes with central air conditioning and the most homes with crawlspaces. In addition to these conditions, the marine climate is milder year round, as can be seen in Figure 13. These milder conditions result in less need for space conditioning and thus dehumidification. These basic results suggest possible correlations between indoor relative humidity and cooling system use and operation, heating system use and type, and foundation type and climate.

A vapor pressure analysis of the monitored homes revealed the average annual interior vapor pressure to be approximately 1550 Pa for zone 2, 1213 Pa for zone 4, and 1192 Pa for zone 5. Looking at the monthly differences between interior and exterior vapor pressures, as shown in Figure 14, 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 pressures indicates that the flow of moisture is likely to be from outside to inside for at least six months of the year in zone 2. The results for the cold climate, zone 5, suggest a change in the direction of the moisture flow, but the primary direction appears to be from inside to outside during at least six to seven months of the year.

Table 1. Average House Characteristics by Region

Component	Humid	Cold	Marine
Year built	1998	1966	1947
Size (conditioned ft^2)	1989	3118	2059
Number of occupants	3.45	3.10	3.1
Air leakage (ach@50)	6.0	6.1	11.1
Attic R-value ($h \cdot ft^2 \cdot °F/Btu$)	22	36	24
Wall R-value ($h \cdot ft^2 \cdot °F/Btu$)	12	12	7
Dominant foundation type	slab	partially finished basement	basement/crawlspace
Duct leakage (cfm/100 ft^2 of conditioned space)	5.6	4.7	13.9
Dominant heating type	air-source 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%

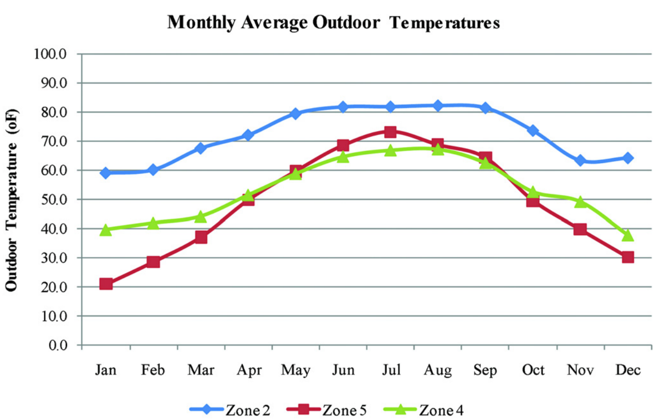


Figure 13 *Monthly outdoor temperatures for each region.*

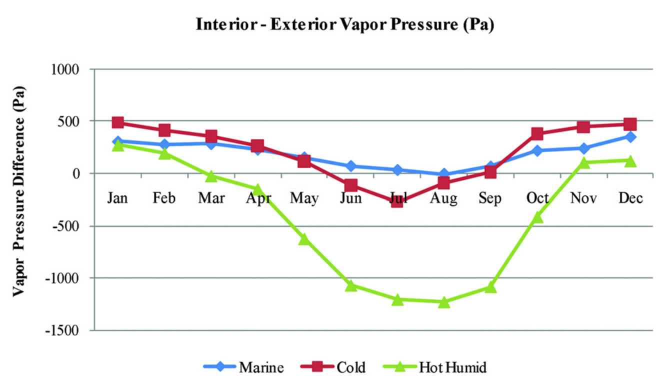


Figure 14 *Difference between interior and exterior vapor pressures (Pa) for each of the three climate zones.*

Zone 4 shows a consistent positive vapor pressure difference for the entire year.

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, and
- 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 15 and 16) and 2) the presence of foundations with exposed dirt floors.

Further research is needed to determine if there are significant correlations with these two house characteristics.

Analysis of Homes with Moisture Problems

All site inspections were conducted between late May and mid-July. All occupants were questioned about the presence of mold or moisture problems in their homes over the course of the entire year. All reported concerns were verified 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, humid

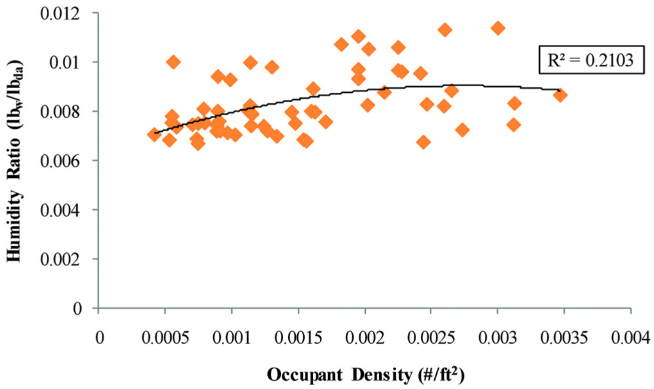


Figure 15 *Humidity ratio vs. occupant density for all climate zones.*

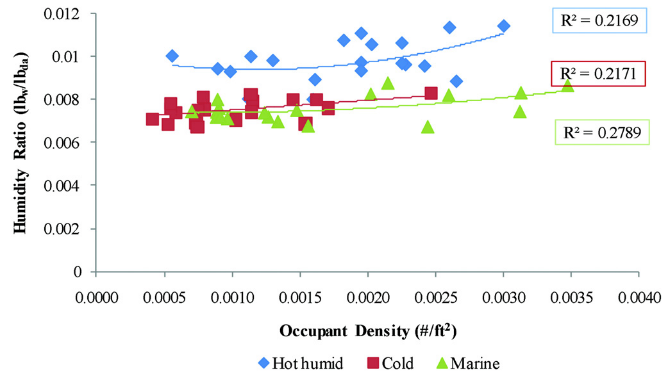


Figure 16 *Humidity ratio vs. occupant density for each climate zone.*

climate, zone 2, mold was visible on several air handlers around the cooling coils, usually on air handlers located outside the conditioned space, such as in a garage. There were also several incidents of moldy caulk on the new homes in Gainesville, Florida. This was specific to this housing development, which may mean that the caulk used during construction was not mold resistant and that this is not an indication of a typical problem in this region.

In the cold climate, zone 5, 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. A summary of the moisture problems noted during the site inspections is provided in Table 5.

These data sets were analyzed more closely to determine if their humidity ratios were notably different from the other homes in the region. Correlations between indoor humidity and the following characteristics were examined:

- number of occupants,
- occupant density,
- foundation type,
- air leakage,
- mechanical ventilation, and
- presence of bath fans.

First, the average monthly interior humidity ratios for the homes with moisture problems were compared to the homes without problems. The results for zone 2 (illustrated in Figure 17) show increased humidity levels from October through April for the homes with moisture problems. Figure 18 displays the monthly average humidity ratios for the homes in zone 4 and shows that the interior humidity levels were slightly higher for the homes with problems and that the foundation humidity levels were significantly higher. Zone 5 showed significantly higher levels in both the interior and the foundation humidity levels as compared to those homes without reported problems (Figure 19).

Next, correlations between the homes with moisture problems and house characteristics were investigated. These results are summarized in Table 6.

Statistical significance for each category in Table 6 was evaluated using the chi-square test or T-tests as applicable. Statistical significance was found for the following:

- Zone 5, cold: year built (t = 2.28, df = 18, p < 0.05), interior temperature (t = 3.02, df = 18, p < 0.05), and air leakage (t = 2.16, df = 18, p < 0.05)
- Zone 4, marine: air leakage (t = 3.12, df = 18, p < 0.05) and occupant density (t = 1.97, df = 18, p <0.05).

What is interesting when analyzing differences between the homes with and without moisture problems within each zone is that the trends that seem plausible in the cold (zone 5) and marine (zone 4) climates do not apply to the hot, humid climate (zone 2). For instance, there seems to be a distinct difference in air changes at 50 Pa for homes 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. There are too many variables in play to draw significant conclusions from this data. Each climate has specific characteristics that influence interior moisture levels.

CONCLUSIONS

Of the three climates in the study, the homes in zone 4, the marine climate, appear to consistently have indoor relative humidity levels above 50% for most of the year, 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:

1. **Age.** Homes in zone 4, the marine climate, were much older than those in the other two sets.

Table 5. Summary of Moisture Problems in Study Homes

Climate	House #	Moisture Problem	Potential Moisture Source
Zone 2, Hot, Humid	4	Mold on ceiling and windows in baths, on air handler in garage	No bath fans
	6	Mold on windows in second floor bath, water stain in toilet closet on first floor	No bath fan in bath, possible water leak
	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	Around most of the windows the caulk is moldy, 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 on window sills and on air handler, mostly on north side of house	Unknown
	20	Wet plywood under air handler	Condensation on air-conditioner drain line
Zone 5, 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, crawlspace with dirt floor
	30	Musty smells on second floor, insulated behind some built-ins, smell has gone away	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, were remodeling and fixing air leaks and replacing windows	Previous plumbing leak into basement ceiling, was being repaired
	39	Mold in bathrooms	Very low bath fan flows, two dogs and a fish tank
Zone 4, Marine	44	Mold on windows, all single-pane	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, bath fans present	Gas insert in fireplace, no damper in flue per code, fireplace has no doors
	49	Mold on single-pane windows and bath ceiling, bath fan present—timer on ten minutes	Two fish tanks, four bunnies, two dogs, some foundation leaks during a heavy rain
	56	Mold on double-pane, low-e, vinyl windows where glass meets sash	Vented crawlspace
	57	Mold in upstairs bath and on single-pane windows	No bath fan
	61	Mold in second floor bath	Bath fans present but not working

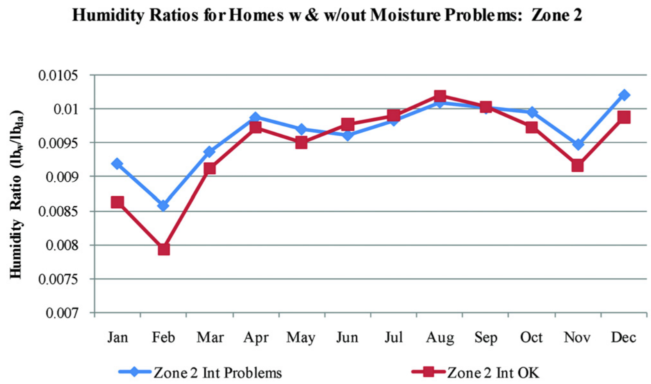


Figure 17 *Monthly average humidity ratios for homes with and without moisture problems in climate zone 2, hot, humid.*

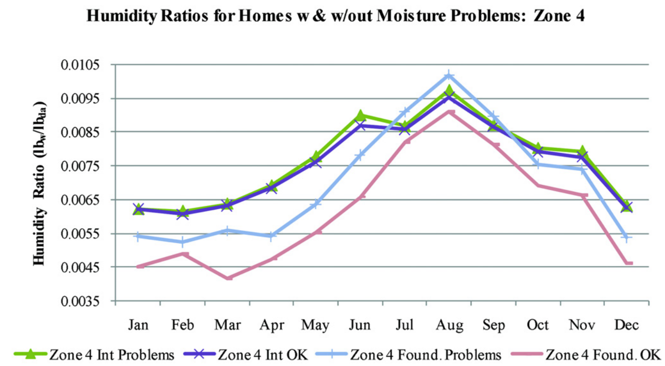


Figure 18 *Monthly average humidity ratios for homes with and without moisture problems in climate zone 4, marine.*

2. **Air Leakage**. The air leakage rate (ach50) was almost twice as high in the marine climate as in the other two climates.
3. **Foundation Type.** Several homes in the marine climate were built on vented crawlspaces with dirt floors. The zone 2 (hot and humid) homes were all on slabs, and the cold climate homes, in zone 5, were primarily built on partially finished basements that were conditioned.
4. **Cooling Equipment.** Only 20% of the homes in the marine climate had central air-conditioning units, whereas 75% of the homes in the cold climate and 100% of the homes in the hot, humid climate had central air conditioning.
5. **Heating Equipment.** Only about 50% of the homes in the marine climate had forced-air heating. The other 50% 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 (zone 2), mold was visible on several air handlers around the cooling coils, 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 more than one instance, 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, across regions, and with respect to those homes that did and did not have moisture problems, correlations that deserve further investigation are increased humidity levels due to

- high air change rates,
- high occupant densities,

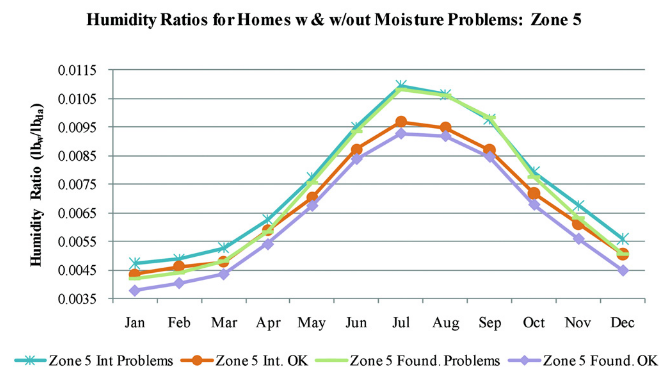


Figure 19 *Monthly average humidity ratios for homes with and without moisture problems in climate zone 5, cold.*

- the presence of unfinished/unconditioned basements and/or crawlspaces, and
- the use of materials with higher condensation and mold resistance potential in climate zone 2, such as vinyl vs. metal windows, wood vs. marble window sills, better caulk, etc.

ACKNOWLEDGMENTS

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Table 6. Summary of House Characteristics for Homes with Moisture Problems vs. Homes without Problems for Each Climate Zone

House Characteristic	Zone 2		Zone 5		Zone 4	
	Moisture Problems	No Moisture Problems	Moisture Problems	No Moisture Problems	Moisture Problems	No Moisture Problems
Size (conditioned ft^2)	1860	2059	2819	3416	1701	2251
Year built	2002	1995	1956	1976	1939	1952
Interior temp (°F)	75.7	75.8	68.2	69.8	67.2	67.1
Dehumidifier (% of homes)	0%	0%	80%	90%	0%	31%
Primary foundation	Slab	Slab	Partially Finished Basement	Partially Finished Basement	Crawl/ Partial Crawl	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%	0%	10%	20%	0%	23%
Humidity ratio (lb_w/lb_{da})	0.00971	0.00986	0.00755	0.00751	0.00767	0.00755

* Includes exhaust only, supply only, or balanced ventilation on timers or continuous. Does not include intermittent bathroom, laundry, or kitchen exhaust.

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APPENDIX A—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

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.?

____

____

____

____

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.