Monitoring of Internal Moisture Loads in Residential Buildings - Research Design and Early Findings

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ABSTRACT

The U.S. Department of Housing and Urban Development had funded Steven Winter Associates, Inc. (SWA) to collect moisture load data that will support research to better understand the impact of moisture on the durability of homes. Little to no 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 one full year of indoor temperature and humidity data for a sample of sixty homes across three different climate regions – the hot/humid southeast, cold northeast and marine northwest.

This research is in direct support to the American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. (ASHRAE) Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*. With assistance from Oak Ridge National Laboratory (ORNL) as a subcontractor and members of Standards Project Committee 160 in an advisory role, a research methodology was developed. The monitoring protocol involved three site visits to each home to perform such tasks as collecting basic house and equipment characteristics, installing loggers, performing testing to quantify envelope leakage and duct leakage and collection of data recorded by the loggers.

The project deliverable is a data base of test house characteristics with an overview summary of the test sample characteristics. Data compiled in the field tests has been analyzed to identify the potential relationships between certain household characteristics and the measured internal humidity levels. Potential relationships were also studied more closely for those homes noted as having moisture problems as compared to those that did not.

In this paper, the authors propose to discuss the research design for this project including problems encountered and lessons learned. Specific topics will include candidate requirements, critical parameters measured/recorded and data manipulation and analysis. Samples of the data collected with some discussion of preliminary findings will also be presented.

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INTRODUCTION

While mold is a serious problem for homebuilders, it is generally agreed that mold is the result of excessive moisture. Moisture can find its way into homes in at least four principal ways: 1) through rain penetration of the exterior walls and roofs; 2) through rain or ground water entering foundation systems; 3) through moist air being transmitted through/into the building envelope via air leakage; and 4) through occupant related generation (i.e. cooking, showering, and clothes drying). Moisture can promote corrosion, insect habitation, mold, and rot when present. By controlling exposure to moisture, many other durability problems are also solved.

However, there is not a complete understanding of the influences certain factors have on a homes' overall moisture content and moisture performance. 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 relative humidity. Research was conducted to identify and quantify moisture loads on a home. Three different regions in the United States were targeted – the hot, humid Southeast, the cold Northeast and the Pacific Northwest. House and household characteristic data were collected by an engineer during the initial site visit including occupancy levels, insulation levels, equipment efficiencies, envelope leakage and duct leakage. This information will aid researchers and engineers to develop 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 home as well as occupant related stimulus will be conducted. This analytical activity should provide all the inputs required for the analysis. Data compiled in the field tests will be analyzed with the intention of identifying relationships between the various household characteristics and the internal humidity levels.

RESEARCH DESIGN

1 OBJECTIVES

There were three major objectives for conducting this study.

1. **Research Support**: As noted in a Buildings VIII paper (TenWolde/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." One intention of this 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 them better understand the impact of moisture on the durability of homes.

2. **Support for Development of Design Criteria**: ASHRAE Standing Standard Project Committee 160 continues to maintain the relatively new standard 160-2009 "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 Standard 160-2009). This moisture design standard is intended to 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 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:
    - 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;
    - moisture capacitance of furnishings;
    - age of 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 moisture levels in typical single family detached homes.

2 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" (2004):

- Characterize the moisture performance of existing homes through a field testing protocol;
- 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 has provided is a sound test protocol and an excellent start at developing a critically important data base of information for moisture modeling and standards development.

3 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 and most of them are members of Standing Standard Project Committee (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 DOE to support the ASHRAE 160 process. In an effort to determine what information was most critical, subcontractor ORNL reviewed copies of 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. The last major survey of models was performed in 1996 and reported in the International Energy Agency Annex 24 (Hens, 1996).

The committee responsible for ASHRAE Standard 160 on "Criteria for Moisture Control Design Analysis in Buildings" realized that the operation of multidimensional models was inconsistent with its goal of having a standard that could be easily used by the design community. However, the committee listed, in Section 5 of the standard, a series of criteria that any computer tool needed to satisfy. These requirements include:

(a) Energy transport, including temperature effects of phase change;
(b) Material properties as a function of moisture content;
(c) Water (liquid and vapor) transport, including capillary transport, moisture deposition on surfaces, storage in materials, vapor diffusion, and water leakage.

If the design includes a ventilated cavity, the analysis shall include the effects of such cavity.

Additionally, the analytic procedure shall provide the following output:

(a) Temperature and surface relative humidity at each surface and interface of the material layers;
(b) Average temperature for each material layer; and
(c) Average moisture content for each material layer.

For those models that met the requirements, the input variables and data format requirements 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 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 committee responsible for ASHRAE Standard 160 correctly realized that a consistent approach to moisture design demands a consistent framework for design assumptions or assumed "loads."

One load which has been overlooked by most researchers is that of the indoor conditions. While great strides have been made to quantify and standardize meteorological data such as wind driven rain, little data exists on what are typical indoor conditions. The ASHRAE Standard 160 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 estimations. The purpose of this project was to generate some of this data.

We conducted a review of data from other research studies similar in nature to this one, but vital information was missing from each in one form or another, and therefore could not be used to supplement the dataset from this study. For instance, one study produced numerous data points on relative humidity and temperature, but had not collected detailed information about the house characteristics (Piggs, 2003).

4 CLIMATES EVALUATED

Emphasis was placed on three climatic 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 allow us to develop max, min, and average profiles for modeling and design studies. The three important climatic regions are, for different reasons, the Pacific Northwest (Zone 4), the cold Northeast (Zone 5), and the hot/humid Southeast (Zone 2).

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.

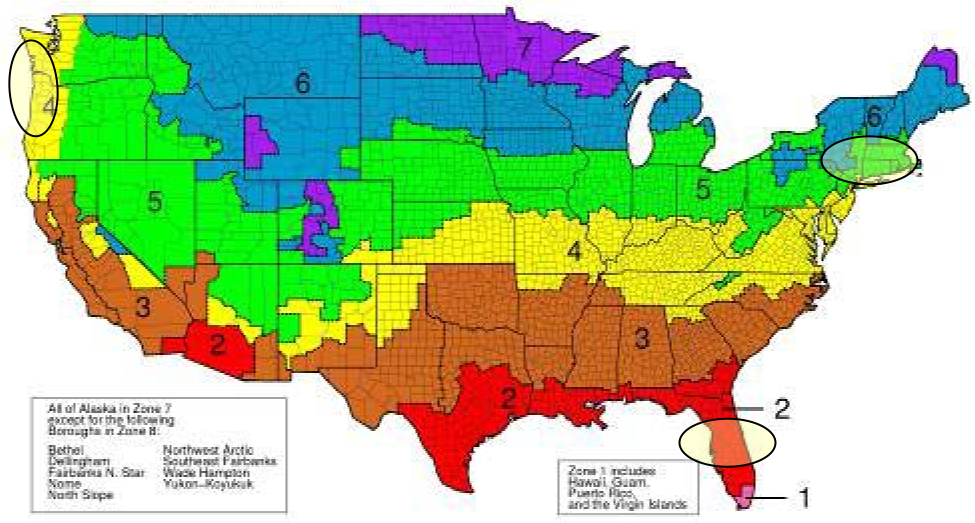

Figure 1 IECC Climate Zone Map of the United States

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 ASHRAE SPC 160 would have alerted builders to the potential problem.

Moisture issues in the hot and humid Southeast climate are influenced more by ambient humidity levels, 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 have conducted relevant monitoring studies and research in this climate region (Rudd, 2007). This research was thoroughly reviewed and served as guidance for the Test Protocol.

5 DESIRED HOUSE CHARACTERISTICS

After evaluating existing research and discussing goals with the committee, 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 with 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 that are having problems or concerns about moisture and humidity problems 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;
- SWA employees' relatives and friends;
- Study participants' relatives and friends.

6 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 to the test protocol:

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

6.1 Short Term Data Collection

As noted earlier, 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 to the Field Data Collection Form, a copy of which is located in the appendix. This form was developed to ensure consistency and completeness in the data collection process and was completed for each home during the Initial Site Visit.

Short-term testing and data collection was conducted at the time of monitoring equipment installation. This testing and data collection included:

- 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 the 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 air flows; and
- presence of mold &/or moisture sources.

All results collected during evaluation of the home characteristics were transferred into an ACCESS data base for subsequent analyses.

6.2 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,
- cost.

Preliminary research was conducted on wireless loggers such as those available from Omega, but these were found to be too expensive for this project. The independent HOBO data loggers from Onset Computer are low cost, nonintrusive, and relatively simple to use.

Subsequent to the short-term assessment, SWA 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 (where most showers were taken) 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);
- attic temperature and relative humidity where a slab foundation was present (significant diurnal moisture loading has been observed).

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

7 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 ASHRAE 160 committee, the final monitoring protocol was developed. Following are the major components of the final protocol.

7.1 Pre-Screening Telephone Call

Unless they were a last minute addition to the study, the potential candidates were informed of the requirements of the study when they were asked to participate. The pre-screening telephone call was used to confirm that the home was in fact a good candidate and to ensure that the homeowner understood the reason for the study, what was involved if they participated and the length of time their home would be monitored. A copy of the Pre-Screening Questionnaire is included in APPENDIX A – PRE-SCREENING QUESTIONNAIRE

7.2 Site Visits

Three site visits to each home were required to gather the data. Besides the initial visit to collect house characteristics and install the HOBO's and the final visit to collect the loggers, an interim site visit was necessary because the data loggers were only capable of storing about 200 days worth of data at 15 minute intervals.

Before the initial field visits were scheduled, a trial run was conducted on one home in the cold climate. This was done for several reasons. First, it was done to confirm the time needed to gather information during the first site visit so we could efficiently schedule appointments.

Also, we wanted to work out the best locations for the HOBO's and the best methods for installing them. There were two concerns here. First, we 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, we wanted to avoid attaching them in any way that would damage the candidates' property.

Another major reason for the test run was that we were using a relatively new and uncommon procedure for measuring duct leakage known as the DeltaQ method. 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 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 increases the possibility of damage to the occupants' personal property. Problems and questions about the proper procedure for conducting a DeltaQ test were worked out during this trial run.

Lastly, we wanted to see if the field checklist needed any last minute additions or deletions before we printed them off in bulk.

The final preparation for the initial visit included calibration of the sensors. Each sensor was started and allowed to log data for a minimum of 24 hours. The results were then analyzed for accuracy according to the manufacturer's specifications. All loggers appeared to be operating within the tolerances allowed.

7.2.1 **Initial Site Visit (approx. 2-3 hours).** During the initial visit the basic house and equipment characteristics were recorded, air leakage and duct leakage measurements were made and the data loggers were installed (3 inside, 1 outside, and 1 in the attic or basement/crawlspace). An interview with the occupant was also conducted to confirm occupancy schedules, comfort problems and any upgrades they may have made. A more detailed explanation of the information collected can be found in section 6.1 Short Term Data Collection.

7.2.2 **Interim Site Visit (1 hour).** The first six months of data recorded was collected during this time. This visit was also used to check on the condition and location of the data loggers and talk to the occupants about any changes that may have occurred over the last 6 months. Any house information missed during the initial visit was also collected at this time.

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

7.3 Participation Agreement and Compensation

SWA has learned through experience that it is important to have a written agreement established with the test home occupants. This agreement establishes the expectations and responsibilities of all parties involved. SWA has found that this written agreement achieves a more secure commitment of cooperation by the occupants. In exchange for volunteering to participate in this study, the occupants were given an audit which explained the efficiency levels found in their home and compared those values to the study averages for their region as well as to the Energy Star values for a new home built in their area. Basic recommendations for improvements were made if applicable. A copy of this agreement can be found 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, 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.

SWA transferred all data collected – house characteristics and data from the loggers - into Microsoft ACCESS. Analysis has been conducted using Microsoft ACCESS and The MathWorks™' MATLAB utility which is better suited for large amounts of data. Data has been analyzed to identify the potential relationships between certain household characteristic data and the measured internal humidity levels. These regressions, which may not all be statistically significant, are expected to be useful to the research community and the ASHRAE Standard 160 committee.

Oak Ridge National Lab has conducted analysis on the dataset from this study. HAM model-compatible data files for each climate were developed. ORNL exercised two of the three embedded methods for computing the internal moisture loads within ASHRAE 160 for each climate region for which field data was collected. The data was processed such that the accuracy of the two calculation methods could be compared to the data and recommendations for improvements to these methods has been offered.

Evaluation of the data was performed to ensure all data were collected for each sensor and that the data looked valid. This review indicates that there was less than a 2% loss in data overall, 1.3% of the total lost was in the Marine climate. Of the 285 data loggers installed, only 1 was not retrieved, and approximately 10 different loggers stopped collecting at some point during one of the 6 month periods between visits. Only 2 loggers were determined to have obviously bad data.

The data was first analyzed by region. Averages of interior RH and temperature were calculated and compared to the average outdoor values collected during the same time period. Because relative humidity is a function of temperature, this value has been converted to humidity ratio (lb_w/lb_{da}) to get a better sense of the actual amount of water in the air. The following tables show the average interior values from the collected data for each region compared to the ambient conditions.

Table 1 Monthly Averages of Temperature and Relative Humidity Data: Zone 2, Hot/Humid

Zone 2	**Indoor**			**Outdoor**		
Month	Temperature [^{0}F]	Humidity Ratio	Relative Humidity	Temperature [^{0}F]	Humidity Ratio	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 Temperature and Relative Humidity Data: Zone 5, Cold

Zone 5	**Indoor**			**Outdoor**		
Month	Temperature [^{0}F]	Humidity Ratio	Relative Humidity	Temperature [^{0}F]	Humidity Ratio	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 Temperature and Relative Humidity Data: Zone 4, Marine

Zone 4	Indoor			Outdoor		
Month	Temperature [^{0}F]	Humidity Ratio	Relative Humidity	Temperature [^{0}F]	Humidity Ratio	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**

Figure 2 through Figure 4 are graphical representations of the temperature and relative humidity information in the above tables.

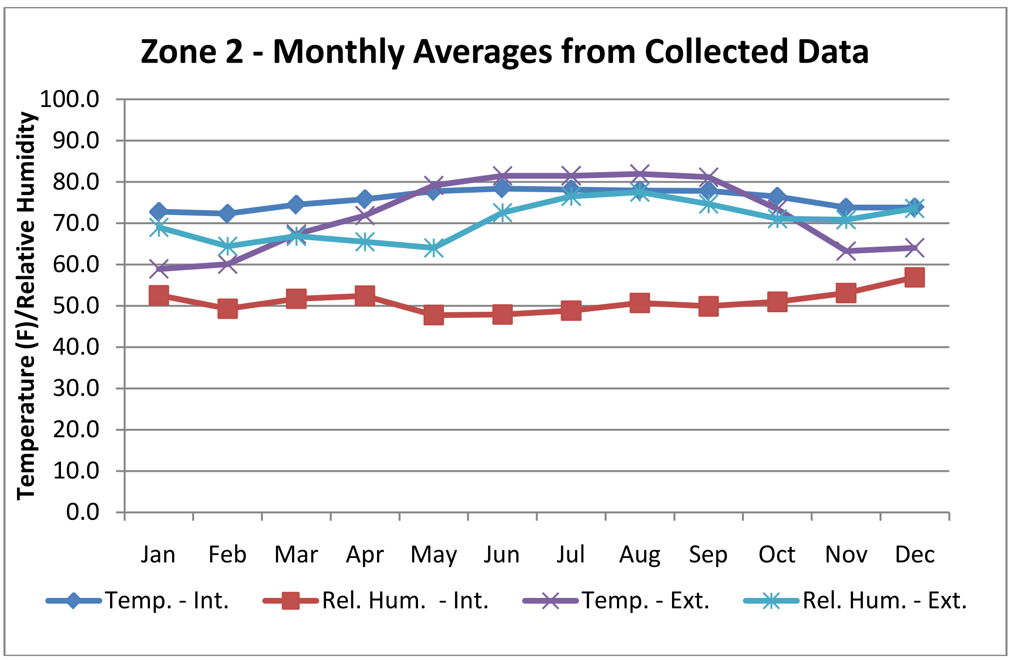

Figure 2 Monthly Averaged Temperature and Relative Humidity Values for Zone 2 from Study Data

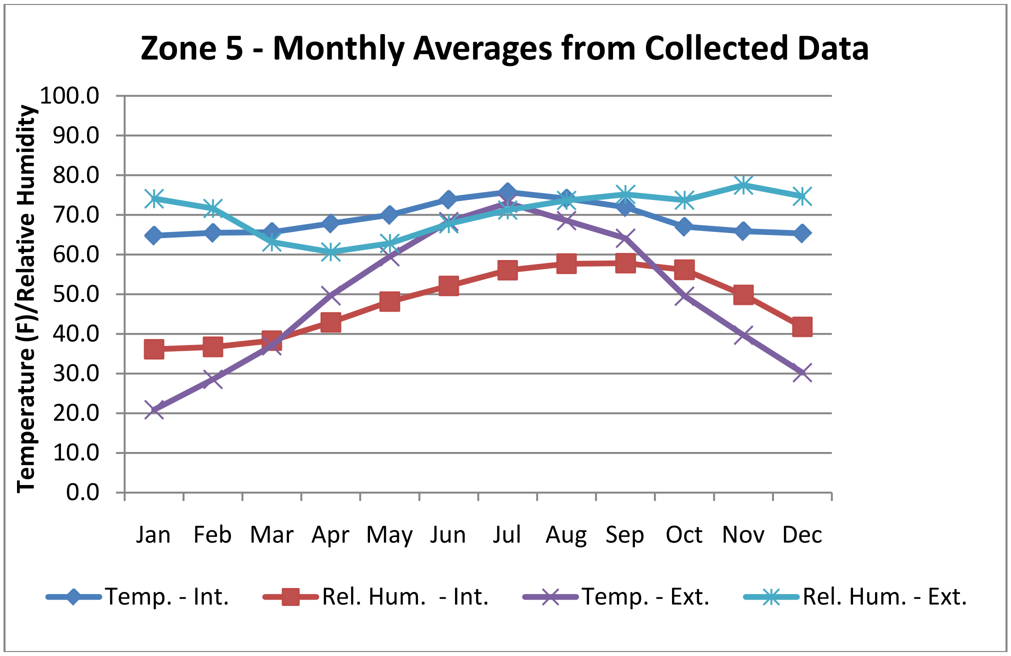

Figure 3 Monthly Averaged Temperature and Relative Humidity Values for Zone 5 from Study Data

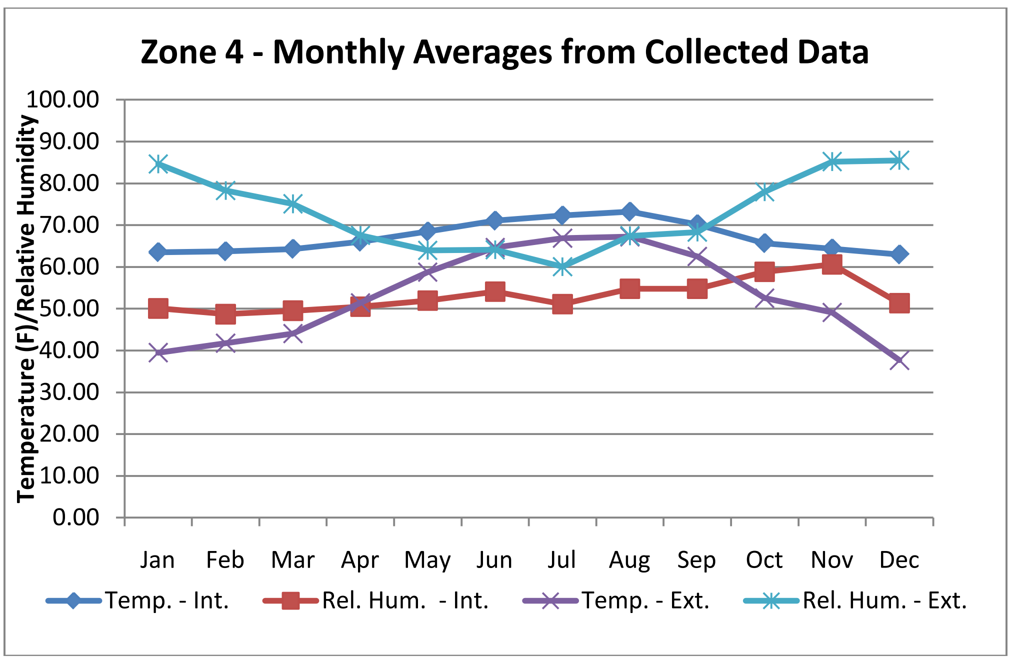

Figure 4 Monthly Averaged Temperature and Relative Humidity Values for Zone 4 from Study Data

Next, a comparison was made between the average building component characteristics in each region and each individual candidate's values. These comparisons were used in audit reports sent to each participant in exchange for their cooperation with this study. The average building age, size, foundation type and building component efficiencies for each of the three regions are displayed in Table 4.

Table 4 Average House Characteristics by Region

Component	Humid	Cold	Marine
Age (years)	11.5	45	61.7
Size (square feet)	1989	3118	2059
# of Occupants	3.45	3.10	3.1
Occupant density (ft^2/occupant)	576.5	1005.8	664.2
Air Leakage (ACH@50)	6.0	6.1	11.1
Attic R-value	22	36	24
Wall R-value	12	12	7
Dominant Foundation Type	slab	partially finished bsmt	basement/crawl
Duct leakage (cfm/100ft^2 of conditioned floor area)	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 w/ Moisture Problems (%)	35%	50%	35%
Homes w/ Mechanical Ventilation (%)	0%	25%	30%
Homes w/ Cooling (%)	100%	75%	20%
Average Interior Relative Humidity (%)	51.7%	47.9%	53.1%
Average Interior Humidity Ratio (lb_w/lb_{da})	0.00978	0.00753	0.007588

This table shows that the highest occurrences of moisture problems were noted in Zone 5, the cold housing set. For the sake of this paper, "moisture problems" refer to any mold or moisture damage or intrusion that was 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 windows and musty smells. On average though, indoor relative humidity values are highest in the marine climate with average monthly values above 50% during most of the year. The marine climate had the fewest homes with central air conditioning and the most homes with crawlspaces.

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 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. There were also several incidents of moldy caulk on the new homes in Gainesville, FL. This 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 a couple of instances musty smells were noted on the upper floors of the home as opposed to the basements. The data sets for homes with moisture problems were analyzed more closely to determine if their humidity ratios were notably different from the other homes in their region.

Table 5 is a summary of the house characteristics for the homes with moisture problems compared to those without problems for each zone. 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/humid climate. For instance, there seems to be a distinct difference in air changes at 50 Pascals for homes with and without moisture problems in the marine and cold climates, but not in the hot/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 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 w/ Moisture Problems vs. Homes without Problems for Each Climate Zone

House Characteristic	Zone 2 Moisture Problems	Zone 2 No Moisture Problems	Zone 5 Moisture Problems	Zone 5 No Moisture Problems	Zone 4 Moisture Problems	Zone 4 No Moisture Problems
House Size (ft^2)	1860	2059	2819	3416	1701	2251
Year Built	2002	1995	1956	1976	1939	1952
Interior Temp (^0F)	75.7	75.8	68.2	69.8	67.2	67.1
Dehumidifier (% of homes)	0	0	0.80	0.90	0.00	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)	0.00	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:

1. Zone 2 (Hot/Humid): The newer homes in this sample set are having more moisture problems than the older, although the humidity ratios are not significantly different. There may be a correlation with more efficient homes and the lack of conditioning needed at times that less efficient homes would need it, or this could be a construction failure particular to this community. Several of the newer homes were in the same development. Metal windows and other cold surfaces should be avoided in this region.
2. Zone 5 (Cold): Water seepage into the foundation appears to be a common problem in

this subset. Mold was only found on the inefficient windows in this group – those having single pane or single pane windows with storms. Air change rate would appear to be one of the factors that is affecting homes with moisture problems, or it could just be an association with older homes without good foundation moisture control.

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

PROBLEMS ENCOUNTERED/LESSONS LEARNED

This survey was subject to the Paper Work Reduction Act since it was federally funded. A delay occurred because it was decided not to recruit candidate households until Office of Management and Budget (OMB) approval of the survey instrument was granted. This was done to avoid having to reschedule the initial site visits, thereby inconveniencing the candidates. Once the approval was granted, candidate selection and scheduling began.

The biggest difficulty at the beginning of the project was finding participants that would agree to have their homes inspected for several hours for the initial site visit and/or being monitored for a full year. In Florida, finding willing volunteers was so difficult, the size of the homes allowed in the study was increased from 3000 ft^2 to 3500 ft^2, more block homes were used than intended and a couple of candidates homes with only one occupant were allowed. Although it was originally thought that builders who had worked or were currently working with SWA would be good sources of leads for candidates, this didn't turn out to be the case. Most of the builders were concerned that such a study could cause them problems if moisture problems were detected in homes they had constructed.

Overall, there weren't many problems encountered during the data collection period. Three homeowners decided to do some level of remodeling, the affects of which will be investigated. One sensor was lost (most likely to vermin) and a few stopped collecting 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 us recruit others at the beginning of the study.

Interpretation of conditioned building envelope proved 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 won't make sense. For instance, if you consider an unfinished basement as unconditioned, but the homeowners leave the door open most of the time for pets or children, removing that space from the air leakage analysis and conditioned square footage calculation would be wrong. Since these are a couple of the major characteristics being analyzed for their affects on interior humidity levels, proper characterization is important to this study. Years of professional experience combined with occupant interviews were used to determine what spaces should be considered conditioned vs. unconditioned.

The biggest difficulties were in trying to analyze a data file this size (almost ten million records total with 5 data points for each record) and trying to find significant correlations from so few homes across such unique climates. Quickly and efficiently analyzing that amount of data proved challenging for Microsoft ACCESS. Although the initial review was conducted with ACCESS, in the end The MathWorks MATLAB software was decided upon for the more critical work of identifying correlations.

CONCLUSIONS

For a large study, independent loggers proved to be a reliable, cost-effective method for collecting data. Less than a 2% loss of data was realized in 285 separate loggers. Even though 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 man hours necessary to conduct the extra site visit.

Analysis of the data shows that homes in the marine climate consistently see indoor relative humidity levels above 50%. This is not to say that all the homes in that climate are above this level throughout the year, or that homes in the other regions were all below that threshold, but if the data is looked at on an average monthly level for the whole housing set by region, the indoor relative humidity levels in the homes in the marine climate are consistently above 50% for most of the year and are higher than the levels detected in the other regions on an average basis. In all three regions, the highest occurrence of visible mold or moisture damage was on or around the windows and in the bathrooms.

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

- Age – homes in the marine climate were much older than the other two sets;
- 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 hot humid homes were all on slabs and the cold climate homes were primarily built on partially finished basements that were conditioned;
- Cooling equipment – only 20% of the homes in the marine climate had central A/C units whereas 75% of the homes in the cold climate and 100% in the hot humid climate had central air conditioning;
- 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.

An analysis of the homes with and without moisture problems in each climate zone has lead to the following conclusions:

1. Zone 2 (Hot/Humid): 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/early winter in the newer homes which are more efficient and have a lower air change rate. This 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 during those months.

2. Zone 5 (Cold): Many of the homes in this set 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 as opposed to the basements. Homes with moisture problems in this set also have a much higher average air change rate as compared to those without. The impact of foundation moisture on the interior humidity levels should be investigated.
3. Zone 4 (Marine): This housing set was considerably older than the other two climates. There were a significant number of dirt crawls in this set, some vented and some not. The homes with moisture problems all had a crawl or partial crawl and none had a well sealed vapor barrier over the dirt. Other notable differences were the air change rates and the occupant densities. All of these characteristics should be investigated further for their influence on interior moisture levels.
4. In general, no statistically significant correlations across climate zones could be determined. Each region appears to have problems specific to that location that should be addressed. Non blanket recommendations for moisture control should be made across zones.

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APPENDIX A – PRE-SCREENING 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