Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness

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ABSTRACT

As part of the HUD Healthy Homes Initiative, a campaign was initiated to monitor the temperature and humidity of 76 buildings in Providence, RI, with a goal of quantifying the "wetness" of buildings. This effort was part of a larger study involving lead remediation and other Healthy Homes treatments. Hourly values of temperature and humidity were recorded for units in the buildings, typically in the family room and bedroom. Sensors were also placed in basements of the buildings, and several buildings were equipped with outdoor sensors. The values reported here are for one five-month wintertime period for 15 buildings (31 dwelling units).

The approach in this paper is the moisture balance approach. Values of temperature and relative humidity were recorded for indoor and outdoor air. These values were used to compute the vapor pressure for both indoor and outdoor conditions. The difference between these two values is defined as the moisture balance. This analysis is predicated on the assumption that indoor vapor pressure in many living spaces closely tracks the outdoor vapor pressure, with a slight increment of indoor vapor pressure over outdoor. The increment is one characterization of indoor "wetness."

This paper presents the moisture balance method and describes potential applications of the technique. There is also a discussion of the findings from the Providence homes, including: 1) relation between sensor location within a building and moisture balance value, 2) influence of the duration of the measurement period, 3) impact of the addition of ventilation fans, and 4) buffering effects.

BACKGROUND

The concern for healthy indoor environments has sparked an increased concern for finding effective methods for determining the wetness or dryness of indoor environments. *Clearing the Air: Asthma and Indoor Air Exposures* (IOM 2000) finds that "damp conditions are associated with the existence of doctor-diagnosed asthma and with the presence of symptoms considered to reflect asthma." The means of determining dampness in dwellings, to date, has been by inspection and questionnaire. A fuller description of moisture investigations in residences is given in Tsongas (1994), which is referenced in *Clearing the Air.* Both of these means of characterizing indoor humidity involve subjectivity—greater subjectivity in the case of questionnaires of occupants, lower subjectivity in the case of inspections. *Clearing the Air*, chapter 8, "Indoor Dampness and Asthma," states the need to

1. develop accurate standardized protocols for assessing moisture problems in buildings and
2. develop and document the effectiveness of specific measures for dampness reduction in existing buildings.

This paper was prepared in response to those research needs. The aim of this study was to implement and review one approach of providing objective assessments of the dampness of dwellings. For the purposes of this paper, the approach may be called the "moisture balance" approach.

Consider two different types of moisture problems. The first type consists of local unwanted water entry or accumulation, the kind that might occur from leaking pipes, roof,

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windows, or flashing. These are common problems, solved by investigation, diagnosis, and local repair. In this type of problem, the site of water entry and the site of water damage are usually the same. The second type of water damage may occur where a source of unwanted water leads to elevated indoor humidity, which may lead to moisture damage at some at-risk location distant from the water source (Brown 1933). Those who advise homeowners to reduce unwanted sources of moisture or advise them to use exhaust fans for dilution ventilation are implicitly adopting this second view of moisture problems in buildings. The approach in this paper focuses on the second type. However, this focus should not be interpreted as a way of elevating the importance of the second type of problem in contrast with the first. Indeed, most moisture problems are probably of the first type.

Indoor humidity can be measured with confidence. All air samples contain a small fraction of water vapor. The concentration of water vapor in air may be represented as:

- *Water vapor pressure* (p_w), which is the contribution by water molecules in the air to the barometric pressure (p). The ratio of the vapor pressure to the total barometric pressure equals the mole fraction of water vapor in the air. Vapor pressure was calculated from temperature and relative humidity using the formula given in *ASHRAE Handbook* (ASHRAE 2001).
- *Humidity ratio* (W), which is the ratio of the mass of water to the mass of dry air. This ratio typically varies between 0.001 and 0.02 for common outdoor air samples. For convenience, some choose to represent these values as a mixing ratio, multiplying the humidity ratio by 1000, or as grams of air per kilogram of water. The resulting mixing ratio values would be between 1 and 20. Humidity ratio is derived from vapor pressure by

$$W = 0.62198 p_w / (p - p_w) .$$

- *Absolute humidity* (d_v), which is the ratio of mass of water to the volume of dry air. It is calculated from psychrometric relations (ASHRAE 2001):

$$d_v = 0.62198 p_w / (R_{da} T) ,$$

where R_{da} is the gas constant for dry air (53.352 ft·lbf/lbm·°R or 287.055 J/kg·K) and T is absolute temperature (°R or K).

Mass concentrations and molar concentrations are independent of temperature, so vapor pressure and humidity ratio are unaffected by changes in temperature. Units adopted here are units of vapor pressure (kPa) in order to ensure that the measures are strictly independent of temperature. Units of humidity ratio could also have been used as they meet this criterion. Values of absolute humidity are not strictly temperature independent—note the temperature term in the denominator above. The self-contained battery-operated datalogging devices used in this project provide absolute humidity as one form of output.

Vapor Pressure and Moisture Balance

Outdoor vapor pressure (p_w) varies with the weather, as shown in Figure 1. For example, one weather pattern may have increasing p_w in outdoor air during a period of high barometric pressure, followed by precipitation with a high spike in p_w, then reduced p_w. Other patterns are common.

In general, indoor p_w tracks outdoor p_w. In a wide-open enclosure of nonporous materials, this tracking might be very close. In a closed building, the response of the interior may be more independent of outdoor humidity. If the interior contains hygroscopic materials, the response of the interior may be buffered. Both of these effects are visible in Figure 1. In general, indoor p_w is higher than outdoor p_w because of generation of indoor moisture from respiration, evaporation, hygiene, cooking, and cleaning. The generated moisture may be diluted through air exchange—infiltration or ventilation. The net of these three effects—outdoor concentration plus generation minus dilution—is called here the moisture balance (MB). It is simply the indoor vapor pressure value ($p_{w\text{-in}}$) minus the outdoor vapor pressure value ($p_{w\text{-out}}$), at any time:

$$MB = p_{w-in} - p_{w-out}$$

At any instant in time, the MB may be positive or negative. On average, the MB tends to be positive in the absence of dehumidification. We would expect damp homes to have higher MB and dry homes to have lower MB.

Characterizing dampness in buildings by finding the moisture balance has been in use for several years. A dampness metric of indoor concentration less outdoor concentration was presented in TenWolde (1987). Since 1993, the *ASHRAE Handbook—Fundamentals* has carried information on indoor

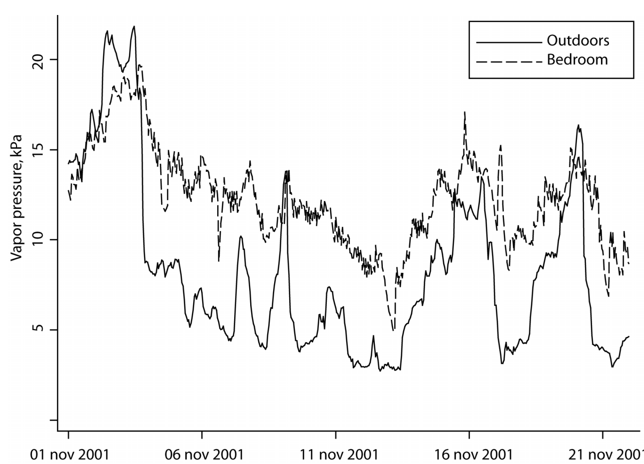

Figure 1 *Vapor pressure—outdoor and indoor—for a three-week period. The moisture balance (MB) is the difference between indoor vapor pressure and outdoor vapor pressure.*

humidity pertinent to the characterization of damp buildings. Chapter 24 (ASHRAE 2001) states:

> A common cause of moisture problems during the heating season is excessive indoor humidity. This is caused by an improper balance between moisture generation and moisture removal. This balance can be changed by reducing the sources of moisture or by increasing the removal rate, usually by ventilation or dehumidification.

Moisture balance, or the difference between indoor and outdoor concentrations, is presented in two papers (Hens 1993; TenWolde 1993) in the 1993 symposium *Bugs, Mold and Rot II*. The 1996 International Energy Agency Annex 24: Heat, Air and Moisture Transfer through New and Retrofitted Insulated Envelope Parts (IEA 1996) showed the vapor pressure difference findings from several studies in European countries with indoor minus outdoor vapor pressure as a wetness characterization of residences. Lawton et al. (1998) made use of moisture balance and expanded on it to estimate moisture generation rate.

A moisture balance assessment of a building or dwelling unit may be expected to provide good quantification of indoor moisture generation during times of the year during which air conditioning does not operate. This was the first concern in this study, so the results are presented for a five-month extended winter season only—November 1 to March 31.

The moisture balance during seasons with air conditioning use is also of interest, as air conditioning would be expected to lower the indoor vapor pressure. However, it would not be possible to assess the indoor generation of moisture in the presence of dehumidification. Once interior moisture generation is established, the moisture balance can be used to assess the ability of the air conditioner to address both outdoor humidity and interior moisture and the success of the dehumidification. This non-winter application of the moisture balance is not considered here.

Another promising application of the moisture balance approach is to determine whether certain areas of a building are providing more moisture than others, such as basements, bedrooms, etc. In this case, the method could be slightly modified to preclude the need for an outdoor sensor, since what is important is the difference between rooms, not the difference between indoors and outdoors.

STUDY DESIGN

The moisture balance measurements were originally intended to help determine the relative impact of adding bathroom exhaust fans in homes compared to homes in which no ventilation was added.

The number of homes in the Providence, RI, study was 76. Installation of sensors began in early 2001. It had been part of the original plan to measure temperature and humidity for one full season (summer or winter) prior to intervention and the same full season following intervention. However, there was significant pressure to begin and complete the interventions, and few pre-intervention data were obtained.

By November 1, 2001, a total of 15 buildings had been instrumented (and which met the criterion of continued sensor operation through the study period). The 15 buildings contained a total of 31 dwelling units. Eleven of these buildings were multi-story, multi-unit buildings. Some were "triple-deckers"—a traditional New England house type with a basement and three individual floors, with individual dwelling units on each floor. The remaining four buildings were single-family residences.

Instruments were placed in the following locations:

1. Bedroom, high on the wall, away from exterior walls to reduce the impact of outdoor temperatures
2. Family room, with the same directions for placement as in the bedroom
3. Basement, away from outside walls and away from the floor
4. Outdoors, shielded from sun and rain—usually applied to a porch ceiling or inside a garage

Table 1 lists the number of sensors installed in the 15 buildings (31 dwelling units) in this study.

For the purposes of this paper, results are reported from the bedroom sensors. Family room sensors provided output roughly similar to that from the bedroom sensors, and family room sensor output was not available for all units. Bedroom MB values appeared to be, on average, about 15% wetter (15% higher MB) compared to family room MB values.

Three of the basement sensors from these units failed during the course of the study period. Five of the six instruments originally installed to measure outdoor conditions failed before the end of the study period. However, these failures went unnoticed because of long periods of time between downloading data and in reviewing data. New outdoor sensors have been installed in the ongoing project, but a clear lesson

Table 1. Sensor Count of Each Type

	Number of Sensors Installed	Number of Sensors that Remained in Operation: November 1 2001-March 31, 2002
Bedroom	31	31
Family room	31	28
Basement	15	12
Outdoors	6	1

from the study is the lack of robustness of the sensor when subject to outdoor conditions. Data from the single operational outdoor sensor were compared to weather data from the Providence, RI, airport. Airport vapor pressure mean value for the January through March 2002 period was higher than the local outdoor sensor vapor pressure by only 6 Pa. Using airport data adds an uncertainty of about 2 Pa expressed as a 95% confidence interval. Data from the one outdoor sensor in operation began to fail in May 2002.

Sensors

The temperature and humidity sensor devices used in this study were self-contained, battery-operated 12 bit devices. The instruments were checked for calibration both before installation and upon removal from service. The 95% confidence interval of the variability among sensors was 4 Pa, measured after the sensors had been removed from the field. The confidence interval is the size of the range within which the mean is included with 95% confidence. Such a small error indicates that if the instruments remain in operation, even for a period as long as three years, they hold calibration quite well.

The data sampling interval for the study was one hour. Moisture balance for all units was calculated by subtracting the vapor pressure of the single operational outdoor sensor, in units of kPa, from the vapor pressure of the indoor sensor. There were 3624 hourly readings in the November 1-March 31 data collection period.

FINDINGS

The overall findings are shown in Figure 2. The moisture balance (MB) represented here is the average difference between indoor and outdoor vapor pressure (kPa). The average is taken for hourly values during November 2001 through March 2002. The error bars represent the 95% confidence interval of the mean. The moisture balance values fall roughly into a normal distribution, so the 95% confidence interval of the mean is calculated as

$$1.96\sigma/\sqrt{n} \, ,$$

where σ is the standard deviation and n is the number of hourly observations. Note that the error bands do **not** represent the range where 95% of the observation values fall but rather the range where, with 95% confidence, the mean of those values is expected to fall. Because the number of observations is high, the 95% confidence of the mean is small.

Figure 2 shows that the moisture balance tends to be higher at the upper stories in the multi-family buildings. This is consistent with wintertime airflow due to stack effect. In the heating season, outdoor air enters buildings low and exits high. This causes some moisture from lower stories to be carried to upper stories, where it is added to the moisture generated in the upper story units. Previous research using multiple tracer gases has shown that there can be a significant connection between lower and upper story units. One study of three multi-story apartment buildings in the Pacific Northwest found that 15% to 36% of air in upper units came from lower units (Palmiter et al. 1996). Those cases where the moisture balance is higher in lower units likely reflect significantly greater moisture generation rates in these lower units.

Figure 2 also shows that basements in the multi-unit buildings tend to be quite dry relative to the living space in those buildings. Results from the basements of single-family dwellings were not so strongly indicative—two of the four basements were wetter than the bedroom in the floor above, with another nearly identical to the bedroom. It is likely that the basements in the multi-unit buildings are more isolated from the dwelling spaces than in the single-family homes. In multi-unit buildings the doors to the basements often open from outside the building, whereas in single-family buildings the doors often open from the living space. Perhaps also the greater height of multi-unit buildings caused greater buoyancy-induced air exchange in these units. In addition, doors between outdoors and the basements in multi-unit buildings may be left open or be poorly fitting, further increasing the connection to outdoors and limiting any moisture buildup.

Moisture Balance Uniformity with Time

The sampling period represented here is a five-month winter season. It is worthwhile to inquire whether significant results can be found using a shorter sampling period. To address this, three buildings were evaluated in greater detail. Data from three units were broken into five one-month periods, and the moisture balances were summarized for each period.

One of the buildings evaluated in this way was a single-family home (building 12), while the other two were multi-

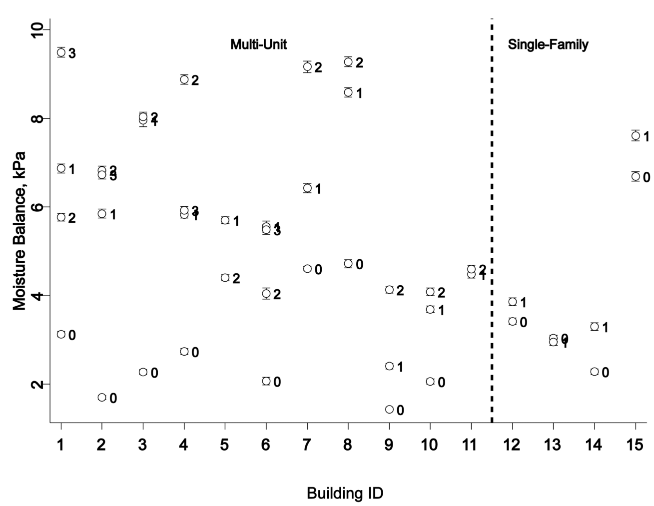

Figure 2 *Mean values of moisture balance (MB) for 15 buildings (31 dwelling units) with error bars representing the error of the mean value. Numbers represent the floor, with basements indicated by 0.*

unit buildings. The three units were selected to represent a range of moisture balance levels. The results are displayed in Figure 3, which shows the 95% confidence interval on the monthly mean for each month at each unit.

This figure shows that there is significant fluctuation from month to month. The moisture balance is affected by outdoor vapor pressure: if the indoor conditions are stable or buffered compared to outdoor conditions, then a low outdoor vapor pressure (dry outdoor conditions) results in a high value for the moisture balance. In the case above, December was a cold, dry month. Occupant behavior may also have an impact, such as having visitors or going on vacation during holidays. Changes in occupancy were not recorded, and the relative impact of occupant behavior is not addressed here.

Despite the lack of consistency within a unit on a month-to-month basis, the rank order among units remains consistent. This suggests that, in cases where there is concern about moisture problems, a shorter monitoring period may be possible to isolate the source of the higher moisture within a building.

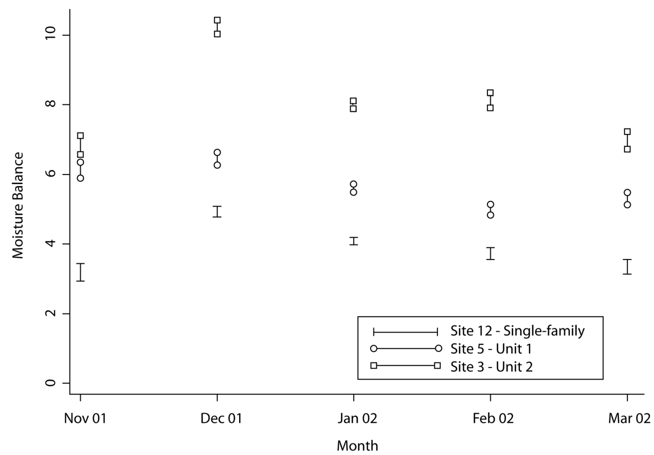

Figure 3 *Monthly values of moisture balance for three units. The bands represent the 95% confidence interval of the mean monthly value.*

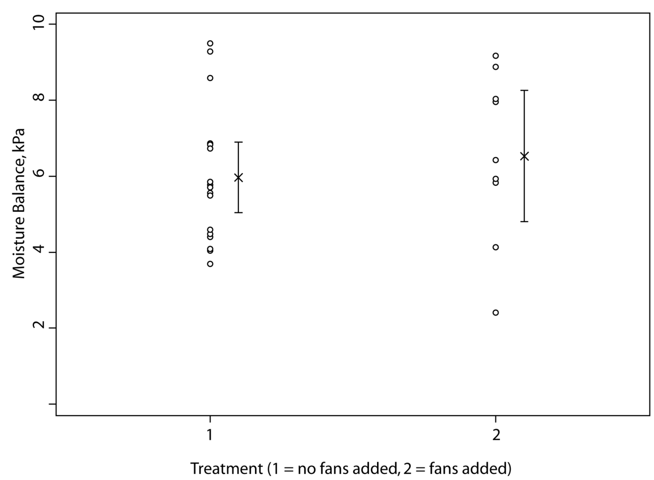

Figure 4 *Comparison of moisture balance in units that received bathroom fans and units with no bathroom fans added. The error bars represent the 95% confidence interval of the group mean.*

Impacts of Ventilation Fans

Each unit received some level of remediation. Remediation at some units was limited to addressing lead paint issues, while others additionally had ventilation fans installed. In order to assess the impact of ventilation fans, it had been hoped that data would be available to do an analysis of the moisture contents in both types of units before and after remediation was done.

Unfortunately, the scheduling was such that there was insufficient data prior to remediation to make this possible. As a result, the best that can be done is to use homes without ventilation fans as a control group against which to compare the homes with fans. This is problematic because of the small sample size and because usage patterns are unknown. Considering only the multi-unit buildings, there are 7 that did not receive added ventilation fans (total of 17 units) and 4 that did (total of 9 units).

Figure 4 shows the results of this evaluation. The circles indicate the bedroom moisture balance for the individual units, and the spikes indicate the mean and 95% confidence interval of the mean for each treatment group.

The average moisture balance for the 17 units without added fans is 0.337 kPa, while the average moisture balance for the 9 units with added fans is 0.359 kPa. Since the confidence intervals overlap, no overall conclusion can be made as to whether the fans had a positive impact on the moisture balances.

CONCLUSIONS

The moisture balance approach is a promising means of quantifying the wetness of a residence. Despite the small values being estimated, the approach routinely provides results that are both reasonable and have the expected sign. Further, there are systematic trends that are supported by known phenomena. For example, there is a tendency for upper units to have higher moisture balances than lower units, which is consistent with heating season stack effect.

There are some obvious cautions or limitations to the method. One is the need to use robust outdoor sensors. All but one of the sensors placed for obtaining outdoor humidity measurements failed early in the study. It remains to be seen whether more careful placement of these sensors to provide shielding from precipitation will reduce the failure rate.

The utility of the method in assessing how wet a building can get may be limited to the heating season. In the summer, the use of dehumidification will often confound efforts to estimate how much moisture is generated within the building. The method could be used in the summer to assess the effectiveness of dehumidification once the moisture generation has been determined.

Another limitation is the amount of time required for obtaining an estimate of the moisture balance. Since the indoors acts as a buffer, there will be times when the moisture balance will be negative, such as when it is raining outdoors. Therefore, monitoring must be done over long enough periods of time to account for these events. There can be significant variation from one month to another, and it is up to the user to decide whether the variations are acceptable. Over a five-month period within the heating season, the average moisture balances within a unit are determined with much more confidence.

One potential use for the moisture balance method that does not require as long a monitoring period is for determining where in a building the primary source of moisture is located. This only requires comparison between portions of a building, so the buffering of humidity levels by building materials relative to outdoor changes is not important.

One possibility that will require further study to evaluate is the extent to which monthly differences can be explained by behavioral changes by the occupants. It is possible that some of these differences can result from vacations, holidays, etc., but without documentation of occupant activities it is not currently possible to assess this possibility.

Due to the small sample size, it was not possible to determine any statistical difference between moisture balances in homes that had fans added compared to those without new fans. Determining this would require either much larger samples of both the control and action groups or testing both before and after fans are installed.

An interesting finding in this study was that, for the multi-story residences monitored, basements were dry. In all of the multi-unit buildings, the basements were the driest areas in the building, at least for the period of study. In multi-unit buildings the basements are often accessed through loosely fitting doors from outside, whereas basements in single-family homes are largely isolated from outdoors.

ACKNOWLEDGMENTS

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