Temperature and Humidity Measurements in 71 Homes Participating in an IAQ Improvement Program

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ABSTRACT

A program to improve indoor air quality in Providence, RI, triple-deckers and single-family homes was begun in 2001. Temperature and humidity data logging equipment was placed in playrooms, bedrooms, and basements in 71 dwelling units in 37 buildings from winter 2001 to 2004.

Indoor vapor pressure values were calculated from indoor and outdoor temperature and humidity measurements for each measurement location. The difference between indoor and outdoor vapor pressure—the vapor pressure excess—was the principal tool of analysis. Factors that influence the quality of the results are discussed, including: calibration of the equipment, reliability of outdoor weather measurements and continuity of the indoor measurements. Findings from this study are viewed within the framework of ISO 13788, which permits a vapor pressure excess comparison of these buildings to European residential buildings.

The vapor pressure excess findings from the study are discussed with regard to

- *The effect of humidity in vertically-stacked dwelling units*
- *Wetness and dryness in basements*
- *Conditions in the playroom compared to the bedroom*
- *Assessment of standard means of representation*

This paper provides the analysis of three years of data. An earlier paper presented in Buildings IX provided the results from five months of data. The data are presented here in a format appropriate for comparison to other similar temperature and humidity data.

BACKGROUND

Characterizing Indoor Humidity

Indoor humidity levels result from (1) outdoor humidity, (2) indoor–outdoor air exchange, (3) indoor moisture generation, and (4) indoor moisture removal, with all of these effects buffered by moisture storage in materials. Indoor dampness is associated with certain health effects (Brunekreef et al. 1989; IOM 2004). It is closely associated with occupant comfort. Indoor humidity levels are used as a potential in hygrothermal analysis of building envelope assemblies. For these reasons, among others, it is important to provide accurate characterizations of indoor humidity.

The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS; www.ecbcs.org/annexes) has undertaken efforts to further the study of hygrothermal performance of buildings: Annex 24 addressed building envelopes (Saunders 1996), and Annex 41 addressed whole buildings. One outcome of Annex 41 was the creation of standard indoor climate classes, which took form in *ISO Standard 13788, Hygrothermal Performance of Building Components and Building Elements—Internal Surface Temperature to Avoid Critical Surface Humidity and Intersti-*

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Table 1. ***ISO Standard 13788*** **Indoor Climate Classes**

Indoor Climate Class	Vapor Pressure Excess, Pa	Descriptor in the Standard
1	<270	Storage areas
2	<540	Offices and shops
3	<810	Low-occupancy dwellings
4	<1080	High-occupancy dwellings
5	>1080	High source uses (kitchens)

tial Condensation—Calculation Methods. This European Standard is currently under revision. Table 1 and Figure 1 show the *ISO Standard 13788* characterization of indoor climate classes. The representation of these European climate classes is attributed to Sandberg (1995) by Cornick and Kumaran (2008) and others.

The indoor climate classes in *ISO Standard 13788* classify indoor environments in terms of vapor pressure excess (VPE) versus outdoor temperature. The vapor pressure excess is the difference between indoor and outdoor vapor pressure, which is usually a positive value during heating seasons. Rose and Francisco (2004) and Glass and TenWolde (2009) used the term "moisture balance" to signify the same quantity. *ISO Standard 13788* represents VPE as greater at cold outdoor temperatures, and converging to 0 Pa at 20°C. It also represents VPE as a constant when outdoor temperatures are below zero. Indoor climate classes are not defined for indoor conditions when the outdoor temperature is above 20°C. This is a likely result of the European roots of the standard, and it does not undertake the task of classifying indoor climates where summertime air conditioning may be used.

The reporting method used in this paper is based on the *ISO Standard 13788* approach, but aims at greater specificity than is offered by the distinction into 5 climate classes. Any set of temperature and humidity data can be plotted as vapor pressure excess against outdoor temperature. A linear regression of those data can be constrained to pass through the value of 0 Pa, 20°C. The vapor pressure excess value reported for the data in this paper represents the intersection of the regression line with 0°C (see Figures 4 and 5 for examples of this representation). Using this method, a regression line that intersects 0°C at values between 0 Pa and 270 Pa is in climate class 1, a regression line that intersects 0°C at values between 270 Pa and 540 Pa is in climate class 2, and so on.

Vapor pressure excess is expressed in units of pascals (Pa) of vapor pressure (difference). Since the pascal pressure unit is gaining wider acceptance among building researchers, and since temperatures in Celsius and Fahrenheit are readily converted by most users, I-P units are not presented in this paper.

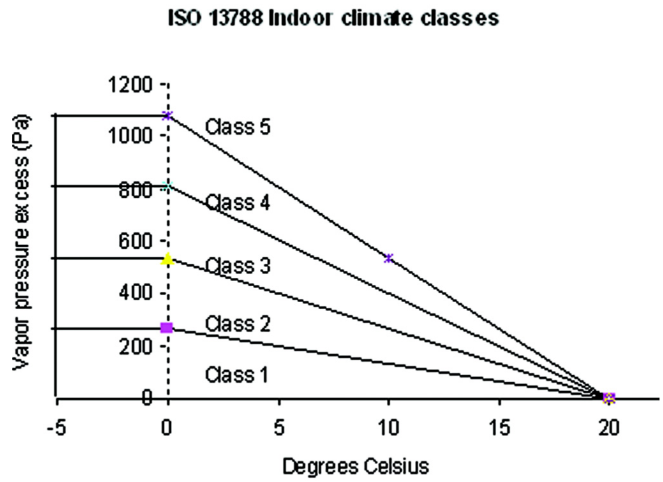

Figure 1 *Graphic representation of* ISO Standard 13788 *climate classes.*

Providence Study

In 2000, an indoor air quality study was undertaken by the University of Illinois at Urbana–Champaign Building Research Council (BRC) and the National Center for Healthy Housing (NCHH) in cooperation with the City of Providence Rhode Island's Healthy Homes Program. The results of the first winter of study regarding this comparison were reported in Rose and Francisco (2004).

Data loggers that record hourly temperature and humidity were placed in residences in Providence, RI, from winter 2001 to spring 2003. The equipment was placed in 37 different buildings, 10 of which were single-family dwellings and 27 were multifamily. Many of the multifamily buildings were triple-deckers, with three dwelling units stacked vertically. Most of the buildings were on basements, and measurements were taken in 30 basements.

A total of 71 dwelling units were monitored in these 37 buildings. Of these dwelling units, 35 were first-floor (including single-family homes), 22 were second-floor, and 14 were third-floor units. Monitoring equipment was intended to be installed in the playrooms and bedrooms of each dwelling unit. Occasional equipment malfunction led to some dwelling unit results that were limited to one rather than two monitoring instruments. Outdoor temperature and humidity data are taken from Providence, RI, airport data. Data loggers recorded temperature and relative humidity hourly at each location. The vapor pressure value was calculated from the hourly temperature and relative humidity values. There was no averaging in these hourly calculations of vapor pressure.

FINDINGS

The general findings are presented in Table 2. Recall that the 0°C intersection represents the vapor pressure excess, and determines the indoor climate class to which the subject data would belong. Buildings with "SF" following the ID are single-family homes.

Table 2. Vapor Pressure Excess and *ISO Standard 13788* Indoor Climate Classes for Sample of Homes

	ISO Standard 13788 0°C Intersection (Pa)				*ISO Standard 13788* Indoor Climate Class			
Building ID	**Basement**	**1st Floor**	**2nd Floor**	**3rd Floor**	**Basement**	**1st Floor**	**2nd Floor**	**3rd Floor**
3	229	487	410	750	1	2	2	3
4	41	362	401	492	1	2	2	2
6	194	616	647		1	3	3	
7SF	295	218			2	1		
8	165	266	612	390	1	1	3	2
9		412	258	281[2]		2	1	2
10	130	365	312	342	1	2	2	2
11SF	165	32			1	1		
12	233	504	417		1	2	2	
13SF	175	154			1	1		
14	306	684	812		2	3	4	
15	133	478		348	1	2		2
18	205	268	222	278	1	1	1	2
19	30	150	360		1	1	2	
20SF	129	232			1	1		
21SF	512	511			2	2		
22	113	252	282		1	1	2	
23	184	236	349[1]	438	1	1	2	2
24		298	235			2	1	
25	140	326	210		1	2	1	
26			224[1]	231			1	1
30	137	210	256	354	1	1	1	2
32	148	278[1]	610		1	2	3	
33	237	282	509[2]	377	1	2	2	2
36		211				1		
41	280	298[1]	450		2	2	2	
42		203				1		
43	209	202[1]	609	619[1]	1	1	3	3
45SF	266	158[1]			1	1		
46SF	182	856			1	4		
49	207	396	819		1	2	4	
50SF		754				3		
52				850				4
54SF	338	436			2	2		
55	311	720[2]	527[2]		2	3	2	
56		176				1		
146SF	425	370			2	2		
Average	211	354	433	442	1	2	2	2

[1] Based on playroom only. [2] Based on bedroom only

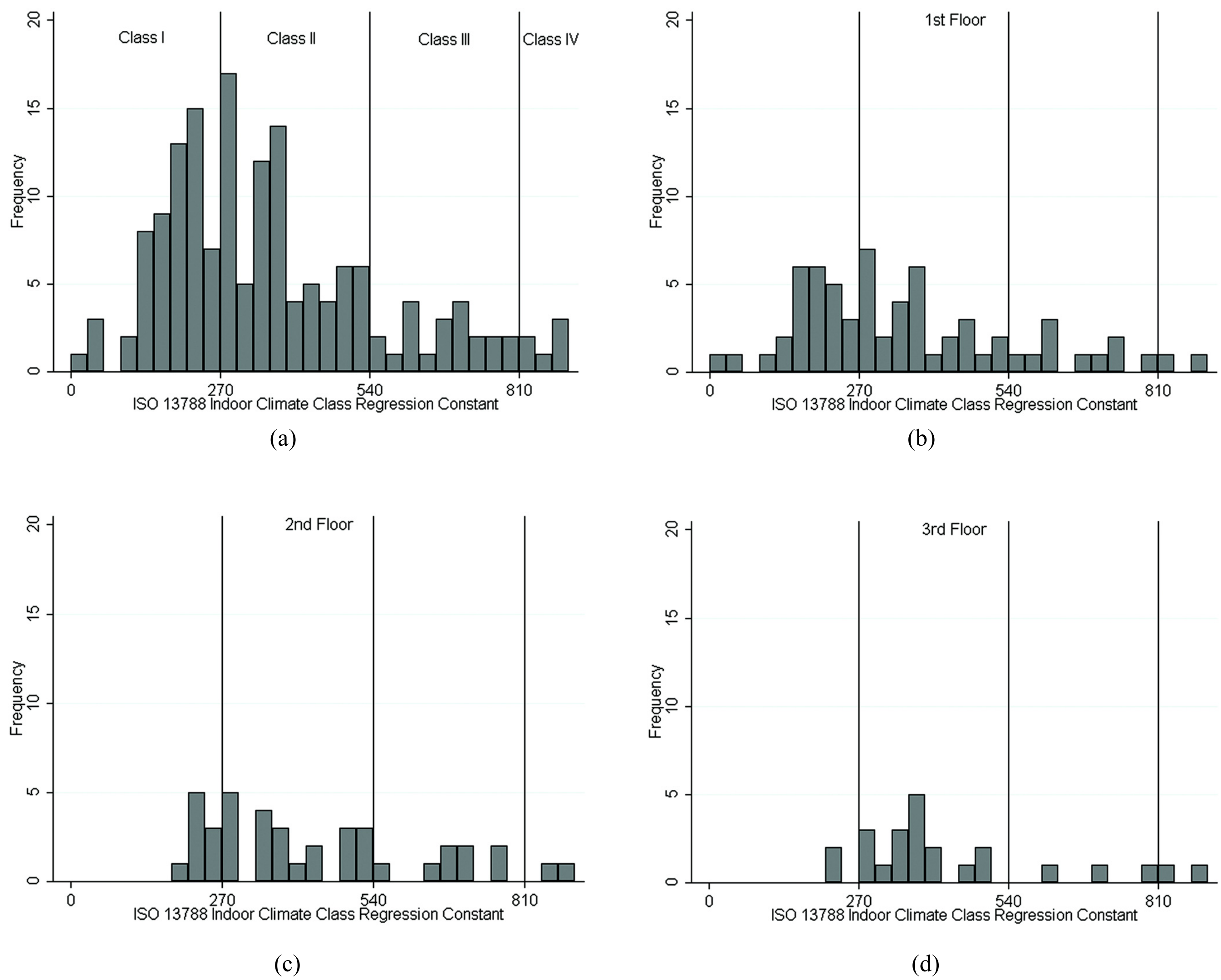

Figure 2 *Graph (a) summarizes the indoor climate class findings for all dwelling units; (b), (c), and (d) show the distributions of indoor climate classes by floor of the building.*

The number of units falling into individual classes is seen in Figure 2a, using data taken from Table 2. The findings here argue that the buildings of this study have lower VPE values than European buildings that form the basis of the *ISO Standard 13788* classification. This may indicate greater air exchange, though other possible explanations such as moisture storage should not be excluded.

Six of the triple-decker buildings have data for all sensors, for basement and three floors. These allow a review of the vertical distribution of humidity in a triple-decker, which is shown in Figure 3. In these buildings, the basement has a low VPE, and increasing humidity appears in the upper two floors. This makes sense, given the general heating-dominated climate, which leads to thermal buoyancy and upward flow of air in the building. This image also suggests that occupant use provides most of the generated moisture, while the basement provides little.

Table 3 summarizes the vapor pressure excess results for those dwelling units for which both bedroom and playroom data are available, for both multifamily and single-family dwellings.

On average, bedrooms were about 11% wetter than playrooms, based on the regression constant. This is consistent with the findings of Rose and Francisco (2004), who determined bedrooms to be about 10% wetter for one season of data. A paired t-test showed that the difference is statistically significant, with $t = 3.7694$ at $\alpha = 0.05$.

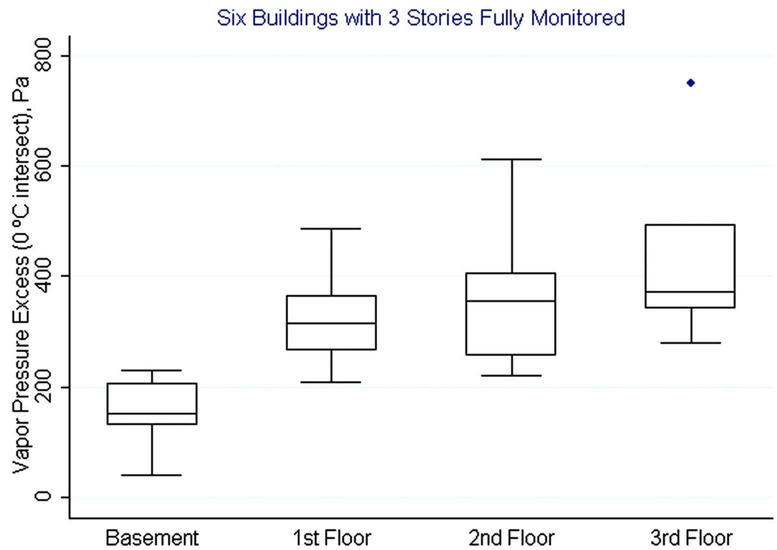

Figure 3 *Box plots of vapor pressure excess in six triple-decker buildings, by floor. The line within each of the boxes indicates the median value. Each box indicates the inter-quartile range (IQR). Lines with end bars indicate the full range of data, where minimum and maximum values are within 1.5 times the IQR of the median value. The outlier value (3rd floor) exceeds the IQR.*

Table 3. Vapor Pressure Excess, 0°C Intersect Values

Multifamily	*n*	Playroom, Pa	Bedroom, Pa	Ratio, Bed/Play
3rd Floor	11	433	449	1.04
2nd Floor	18	411	469	1.14
1st Floor	21	328	356	1.09
		Basement, Pa		
Basement	20	182		
Single-Family	***n***	**Playroom, Pa**	**Bedroom, Pa**	**Ratio, Bed/Play**
1st Floor	9	359	433	1.21
		Basement, Pa		
Basement	9	276		

Single-family (SF) basements, on average, had about higher vapor pressure excess values (by approximately 52%) than multifamily basements. SF basements averaged Class II, with 4 of 9 SF basements being class II. Only 3 of 20 multifamily basements were Class II. Identifications of the buildings are not made, so individual building characteristics cannot be used to determine the reasons for this difference. With greater building height, thermal buoyancy (chimney effect) would be enhanced in a triple-decker, leading to enhanced rates of disposal of basement moisture. Compared to those in multifamily triple-deckers, basements in single-family homes may be more widely used for moisture-generating activities such as laundry. Also, the construction of triple-decker homes typically predated single-family homes, possibly on building sites were drier and better drained. A higher or lower vapor pressure does not necessarily indicate wetness or dryness, since temperature of the space affects the relative humidity. Relative humidity is the largest determinant of the perception of wetness and dryness.

DISCUSSION

Examples

In the examples that follow the data are weekly averages. These averages were used for multiple reasons, including consistency with the *ISO Standard 13788* methodology. Using hourly values would also be too noisy for viewing.

Regressions applied to actual VPE data are shown in Figures 4 and 5. Figure 4 represents basement conditions at site 4. The 0°C intersect is 40 Pa—an indication of low moisture generation. There is wide scatter in the data, which indicates that the regression representation is weak. It also indicates that moisture conditions in the space may be quite independent of outdoor vapor pressure. For several weeks, the

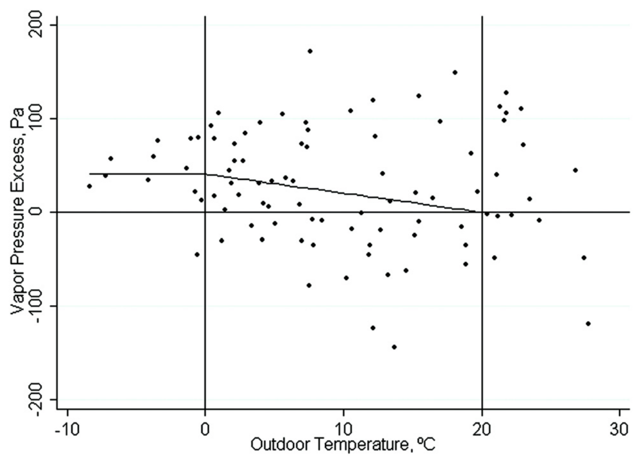

Figure 4 *Site 4 basement data with* ISO Standard 13788 *representation.*

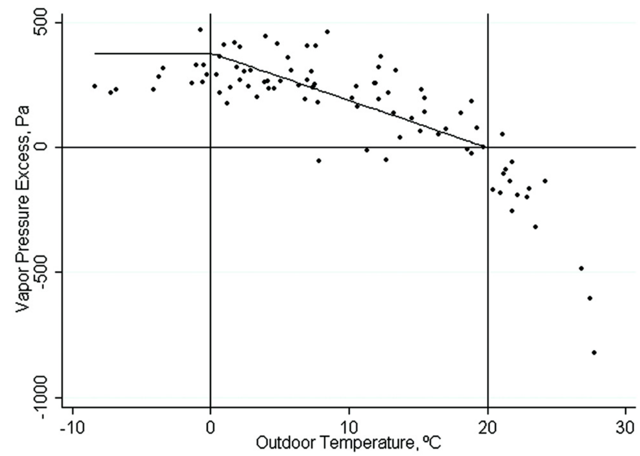

Figure 5 *Site 4 first-floor data with* ISO Standard 13788 *representation.*

basement air had lower vapor pressure than outdoors. This can occur provided there is no substantial moisture source, and provided the space is highly buffered. Temperature may play a role: highly buffered spaces may show higher vapor pressure at higher temperatures as the RH (and material moisture contents) tends toward stability.

Figure 5 shows conditions on the first floor of site 4. The VPE data for this location track outdoor temperature more closely than the basement data. The regression coefficient is higher than the coefficient for the basement. This indicates a moisture source in the living space, stronger than the basement source. This site also shows negative VPE at outdoor temperatures above 20°C. This is evidence of air conditioning or dehumidification, although it could not be verified whether air-conditioning equipment is in place in the building.

The representation of excess vapor pressure in order to define indoor climate classes uses a linear approximation of these conditions, as seen in Figure 1. Several elements in this linear approximation merit discussion:

- When the outdoor temperature is at 20°C, it is expected that windows will be open, so outdoor and indoor vapor pressures should be at the same value. It is reasonable to assign a value of 0 for excess vapor pressure at that outdoor temperature. The standard does not address higher temperatures where windows may be closed and air conditioning may be used. In climates and areas where air conditioning is used, the resulting moisture load may be hard to define. See *ASHRAE Standard 160, Criteria for Moisture-Control Design Analysis in Buildings*, section 4.3.2.2.
- The dog-leg appearance at 0°C is a product of the design of the standard. It represents the change in slope in temperatures below 0°C and between 0°C and 20°C.
- There are few weekly average data points of outdoor temperature lower than 0°C. It is difficult to draw conclusions about this analysis at temperatures in the below-0°C range.

Representing Vapor Pressure Excess

The reason for representing vapor pressure excess (VPE) from measured data is to use those findings in order to estimate appropriate indoor moisture loads for modeling and other purposes. Indoor vapor pressure—a primary potential for estimating moisture flux—is typically higher than outdoor vapor pressure. Figure 6 shows two hypothetical indoor vapor pressure conditions, one constant and one linearly increasing with outdoor temperature. It also shows weekly average outdoor vapor pressure plotted against outdoor temperature from Providence airport data, together with a regression (exponential) of that data. The values for conditions A and B are derived from the average outdoor vapor pressure of 1700 Pa, at average 20°C outdoor temperature. These vapor pressure values are higher than values found in the study. Figure 7 gives the shape of the vapor pressure excess (VPE) curve resulting from these two theoretical conditions. For condition A, the vapor pressure excess is simply the mirror image of the outdoor conditions about the constant value. The excess decreases through the entire temperature range. For condition B, the shape of the excess curve depends on the slope of the indoor vapor pressure. Under the conditions shown, the excess curve may reach a maximum.

The VPE values found in this study fall between these two limiting conditions, A and B. The different curve shapes prompted the question whether the *ISO Standard 13788* representation of VPE (dogleg, with single reported regression coefficient at 0°C) is appropriate for the data in this study. The standard ISO representation was considered appropriate for this study, for several reasons:

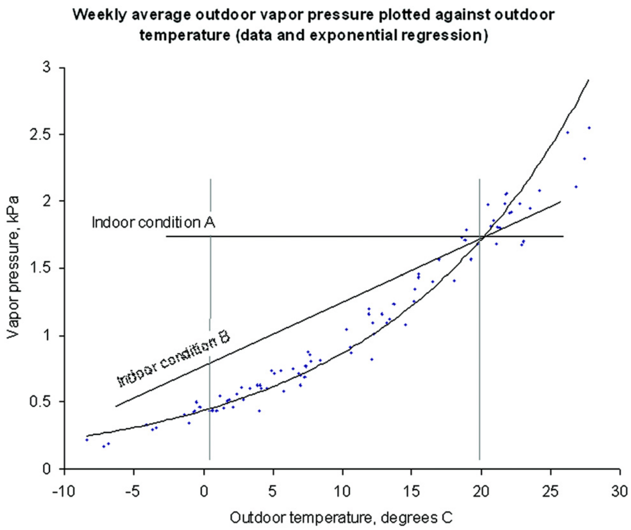

Figure 6 *Plot of weekly average outdoor vapor pressure against outdoor temperature, from Providence airport weekly average data for the study period. The chart shows two hypothetical indoor vapor pressure conditions: (A) constant indoor vapor pressure and (B) linearly increasing indoor vapor pressure as a function of outdoor temperature.*

- Regression of VPE data did tend toward a value of 0 Pa at outdoor temperature of 20°C.
- Regression between 0°C and 20°C was decreasing.
- VPE values below 0°C showed much scatter.
- There were few values for VPE above 20°C for most of the units.

CONCLUSIONS

Temperature and humidity measurements were taken in 71 dwelling units in the Providence, RI, region. The readings indicate that most of the units fall into indoor climate classes I and II. Indoor climate class I is defined as typical for storage areas; class II is defined as typical for offices. While classes III and IV are defined for residences, a minority of the results here fall into either of those two classes. Based on these data, the descriptor in the standard for indoor climate class III (low-occupancy dwellings) and climate class IV (high-occupancy dwellings) may not apply to the types and geographical location of North American buildings studied here.

In multifamily dwellings of the New England triple-decker type, vapor pressure tends to increase with height. This is likely due to thermal buoyancy during cold weather.

The basements of multifamily dwellings in this sample had lower vapor pressures than the living areas above. The basements of single-family dwellings had higher vapor pressures than the basements of multifamily dwellings.

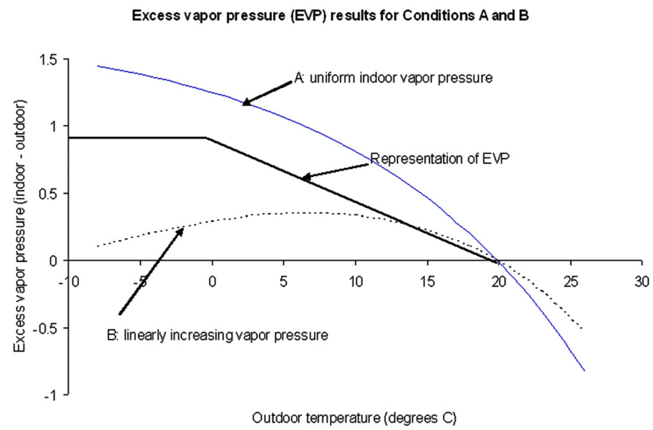

Figure 7 *Excess vapor pressure plots of conditions A and B from Figure 6, with a typical representation of EVP as used in* ISO Standard 13788.

Bedrooms showed higher vapor pressure than playroom areas, which were generally family rooms.

The methodology for representing vapor pressure excess found in *ISO Standard 13788* provides a useful means of characterizing the indoor wetness conditions using simple regression.

ACKNOWLEDGMENTS

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