The Effect of Indoor Humidity on Water Vapor Release in Homes

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ABSTRACT

With the introduction of moisture engineering and new design approaches for moisture control in buildings, it has become important to formulate a realistic design value for indoor humidity. The design value for indoor humidity is one of the most important parameters when determining the need for vapor retarders and other building envelope design features, especially in colder climates. Seasonal indoor humidity is primarily determined by a balance between moisture production rates and removal rates (by ventilation or dehumidification). However, experience has shown that a simple mass balance calculation tends to produce indoor humidity results that are too high for humid cool (coastal) climates and too low for dry climates. In these calculations, moisture sources are assumed to be constant and not a function of the ambient indoor humidity. In this paper we examine the most common sources of water vapor in homes and how they might vary with indoor humidity. Our review indicates that most of the sources, such as contributions from inhabitants and their activities, are virtually independent of humidity. However, moisture contributions from potted plants and from a wet foundation vary with indoor humidity levels. Both types of sources contribute less when the humidity is high and more when the humidity is low. This behavior is especially important because moisture from wet foundations overwhelms all other contributions. We show in this paper how taking the variability with humidity into account can lead to substantially lower estimates of indoor humidity, especially in airtight homes with low ventilation rates.

Given the importance of moisture from foundations, we believe much more measured data are needed, both on the quantity of water vapor contributed by foundations as well as on its variability with indoor humidity and temperatures, including the temperature of the foundation itself.

INTRODUCTION

With the introduction of moisture engineering, the advance of hygrothermal computer models for buildings, and new design approaches for moisture control in buildings, it has become important to formulate a realistic design value for indoor humidity. Indoor humidity is one of the most important parameters when determining the need for vapor retarders and other building envelope design features, especially in colder climates. Proposed *ASHRAE Standard 160, Design Criteria for Moisture Control in Buildings*[1] (ASHRAE n.d.), contains a methodology to calculate design indoor humidity. The basis for the methodology is described by TenWolde and Walker (2001). The method assumes that seasonal indoor humidity is primarily determined by a balance between moisture production rates and removal rates, either by ventilation or dehumidification, and ignores the effect of moisture storage in hygroscopic materials as well as the effect humidity may have on the moisture production rate. Field measurements by TenWolde (1988, 1994) and others have shown that moisture storage in wood-frame residences stabilizes the indoor humidity and that daily or even weekly averages can be used for the purpose of building moisture analysis and design. Over the last few years, the International Energy Agency (IEA) Annex 41

1. As a result of public review comments, the title of this standard is likely to change to *Criteria for Moisture-Control Design Analysis in Buildings*.

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has focused extensively on the moisture storage phenomenon, and a number of papers will be devoted to that at the 2007 Thermal Performance of the Exterior Envelopes of Whole Buildings X conference. This is one reason why this paper focuses exclusively on the effect of indoor humidity on moisture production. Another reason is that while moisture buffering can explain much of the shorter-term behavior of indoor humidity in wood-frame construction, it cannot explain some of the discrepancies in seasonal behavior that have been experienced. From anecdotal evidence we have often found that calculated seasonal indoor humidity at the extreme low and high ends deviates considerably from the measured data: calculated high humidity often exceeds measured humidity at the high end (e.g., in wet coastal climates) and is often too low at the low end (e.g., in cold winter climates). Moisture buffering is an unlikely explanation for this because the effect tends to be too short-term in wood-frame buildings to affect seasonal humidity.

BACKGROUND

Data on residential moisture generation reported in the literature vary widely. Measurements were taken under different conditions and climates and in different building construction types, and the studies may or may not include the effects of seasonal moisture storage. Hite and Bray (1949) conducted a study of common moisture sources in houses, and the data have been widely cited ever since (e.g., Angell and Olson 1988). Unfortunately, over time, errors due to unit conversions crept in, and some of the data cited (e.g., in Angell and Olson [1988] and Christian [1993]) are about 10% higher than the original data reported by Hite and Bray (1949). The most complete summary of data was published in a report of IEA Annex 14 (IEA 1991). The reported average total moisture production rate for one to two adults, based on multiple references, is on the order of 8.2 L/day (0.75 lb/h). These data can be augmented with data published by TenWolde (1988, 1994), who reported a measured average of 6.8 L/day (0.62 lb/h) for seven households without children. Based on these data, TenWolde and Walker (2001) proposed design residential moisture production rates based on the number of expected occupants, as shown in Table 1. The data in this table were adopted as default design values in the public review draft of Standard 160 (ASHRAE n.d.). The design values represent an estimated 32% exceedance level, i.e., 32% of homes in each category can be expected to have higher moisture production rates. This value is then combined with a 32nd percentile low ventilation rate to arrive at approximate 10th percentile indoor humidity values.

In all indoor humidity calculations, the water vapor production rates are thought to be constant, regardless of indoor humidity level. However, it is reasonable to assume that if the temperature remains unchanged, evaporation into the air slows down at higher humidity levels, as the vapor pressure difference between the evaporating surface and the air becomes smaller. It is also reasonable to assume that water vapor added by human or animal respiration should diminish with increasing humidity, as the air that is taken into the lungs already has a higher vapor content. Searching the building science literature did not yield articles discussing this effect. We therefore also searched for this information in the fields of human, animal, and plant physiology.

SOURCES OF WATER VAPOR

We tried to determine which sources of indoor humidity might be affected by indoor humidity and which most likely are not. We assumed a constant indoor temperature of 21.1°C (70°F). We did not consider the effects of humidifiers, as they usually have some sort of humidistat control. Any humidification or dehumidification device with a humidistat control renders a humidity mass balance calculation unnecessary because the indoor humidity will likely be at or near the humidity setpoint. Air conditioning was also not considered. The effect of thermostat-controlled air conditioning on indoor humidity is complicated and depends, among other things, on the length of runtime cycles and, thus, on the proper sizing of the equipment (Shirey and Henderson 2004).

Many activities, such as showering and cooking, release bursts of water vapor in relatively short periods of time. However, it has been well demonstrated that this moisture is temporarily stored on surfaces and in hygroscopic materials and then is released soon after the event. Therefore, the amount released, not the momentary rate of release, is the most important for long-term indoor humidity calculations.

People

People and other animals add water vapor to the indoor air by respiration and transpiration. Hite and Bray (1949) report that a family of four contributes 0.20 kg/h (0.45 lb/h) at night and 0.21 kg/h (0.46 lb/h) during the day (three persons at home, a higher activity level) based on the ASHVE *Heating, Ventilating, Air-Conditioning Guide* (ASHVE 1946). Angell and Olson (1988) cite the exact same numbers, and the IEA Annex 14 *Sourcebook* (IEA 1991) quotes moisture release rates from 30 to 300 g/h (0.07 to 0.7 lb/h) per person, depending on level of activity. Sanders (1996) lists generally accepted rates for "respiration" as 0.9 to 1.25 kg/day (2 to 2.8 lb/day).

Table 1. Design Residential Moisture Generation Rates (TenWolde and Walker 2001)

Number of Bedrooms	Number of Occupants	Moisture Generation Rate		
		L/day	kg/s	lb/h
1	2	8	0.9×10^{-4}	0.7 lb/h
2	3	12	1.4×10^{-4}	1.1
3	4	14	1.6×10^{-4}	1.3
4	5	15	1.7×10^{-4}	1.4
Additional	+1 per bedroom	+1	$+0.1 \times 10^{-4}$	+0.1

The 1961 ASHRAE *Guide and Data Book: Fundamentals and Equipment* (ASHRAE 1961) provides data for "approximate loss in body weight by perspiration" for men at rest and at work when exposed to heat. According to this source, at 21.1°C (70°F), a man at rest loses about 90 g/h (0.2 lb/h) and at work loses 270 g/h (0.6 lb/h). Various sources seem to use *respiration* and *transpiration* interchangeably, even though they are very different mechanisms and are likely to respond differently to changing humidity conditions.

Respiration. McCutchan and Taylor (1951) present data on the effect of humidity on human respiration. They determined that with room temperature in the range of 20°C to 24°C (68°F to 75°F) the expired air is at 33.2°C (91.8°F) and 88.2% relative humidity (RH). The RH of the expired air drops slightly with a drop in indoor air humidity. The combined effect on water vapor added to the air by respiration is given by

$$W_e - W_i = A + Bt_i - 0.798W_i\,, \quad (1)$$

where

W_e = humidity ratio of expired air;

W_i = humidity ratio of indoor air;

t_i = indoor air temperature, °C (°F);

A = 0.02760 with the temperature in °C (0.02645 with the temperature in °F); and

B = 0.0000650 with the temperature in °C (0.0000361 with the temperature in °F).

The rate of respiration is in the order of 240 L/h per m^2 of body surface area (0.79 $ft^3/h{\cdot}ft^2$). With an average body surface area of an adult male around 1.8 m^2 (20 ft^2), Equation 1 gives the approximate moisture production from respiration for an adult at various room RHs, with the room temperature at 21.1°C (70°F). These rates are shown in Figure 1. When comparing these rates with the total rates quoted above, if these rates are correct, it is obvious that respiration only provides a minor portion of the total water vapor generated by people and that most of the release must be from transpiration.

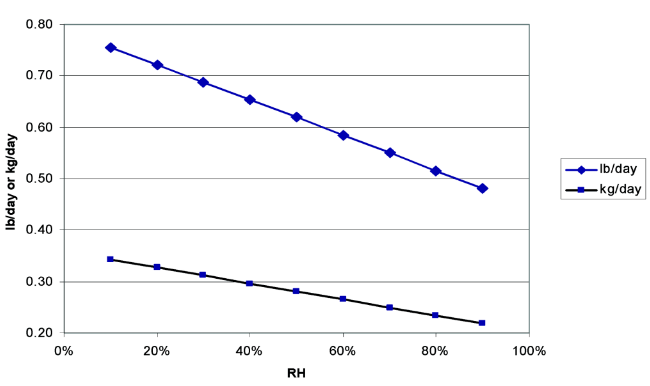

Figure 1 *Moisture production from respiration by an adult male at 21.1°C (70°F) room temperature.*

Transpiration. Ferguson and Martin (1991) provide measured transpiration rates from burn wounds, but, for comparison reasons, also provide transpiration rates from healthy skin, in terms of skin diffusion resistance (the diffusion resistance was defined in terms of absolute humidity gradient expressed in terms of weight per unit of volume). Taking a typical range of 2×10^3 to 6×10^3 s/m for the diffusion resistance of healthy skin at normal room temperatures, transpiration rates calculated for ambient conditions of 20°C (68°F) at 50% RH are in the range of 0.5 to 1.4 kg/day (1.1 to 3.1 lb/day) per adult person at rest, assuming a skin surface of 1.8 m^2 (20 ft^2) per adult person and a skin temperature of 30°C (86°F).

Total Moisture Generation. The sum of respiration and transpiration is in the range of 0.8 to 1.7 kg/day (1.8 to 3.7 lb/day) for an adult at rest, or approximately 30 to 70 g/h (0.06 to 0.15 lb/h). These calculated rates compare well with the IEA Annex 14 *Sourcebook* (IEA 1991) data and Sanders (1996) and are somewhat less than the 90 g/h reported in the *Guide and Data Book* (ASHRAE 1961). The variation is not remarkable because of the wide variation in metabolic rate. The total release rate is also commonly scaled to body weight, i.e., an infant weighing 10 kg (22 lb) roughly produces water vapor at 1/7 the rate of a 70 kg (154 lb) adult.

Variation with Humidity. Evaporation from the skin and vapor added by respiration both theoretically decrease with increased room humidity, but this assumes that the skin diffusion resistance does not change. However, it is widely accepted that moisture generation from people is a function of metabolic rate. At a given metabolic rate, the body cools by radiation, convection, and evaporative cooling. If ambient temperature is not changed, radiation and convective heat loss are not changed. This means that as evaporative heat loss from the lungs decreases with increased humidity, the body will compensate by increased sweating, effectively decreasing the skin diffusion resistance. If latent heat loss is diminished because of an increase in humidity, the body will have to adjust to maintain core temperature. It can do so with a slight increase in transpiration, by allowing slightly more liquid water (sweat) to the surface. Thus, assuming a constant metabolic rate, with an isothermal increase in humidity, the ratio of transpiration over respiration is likely to increase, but the total vapor release is likely to change little because the total demand for cooling has not changed. Thus, moisture release from humans is categorized as independent of humidity, and 50 g/h (0.11 lb/h) is used for an average adult at rest.

Pets

Moisture release from pets is likely to respond to changes in humidity in a manner similar to release from humans: transpiration is likely to compensate for any decrease or increase in respiration heat loss in response to changes in humidity. Thus we classify moisture release from pets as independent from humidity and treat it as a constant.

Cats. Bartorelli and Gerola (1963) report that the average respiration rate of 22 cats was 0.38 L/min (0.013 ft^3/min). If we assume a body temperature of 34°C (100°F) and 88% saturation, the absolute humidity of the exhaled air is 33.7 g/m^3 (0.0021 lb/ft^3). The absolute humidity of inhaled air at 20°C (68°F) is 8.7 g/m^3 (0.00054 lb/ft^3). Thus, the amount of vapor a cat contributes by respiration is in the order of 0.57 g/h (0.0012 lb/h) or 14 g/day (0.03 lb/day). Human respiration contributes about 20% to 40% of the total vapor release (see previous section). If we assume a similar ratio in pets, the total moisture release would be 1.4 to 2.8 g/h (0.003 to 0.006 lb/h).

Another proposed approach is to simply use the human moisture release rate of 30 to 70 g/h (0.06 to 0.15 lb/h) and adjust it for differences in weight. With a cat weighing 2.5 kg (5.5 lb) and a human adult weighing 70 kg (154 lb), this approach results in a moisture release rate of 1.1 to 2.5 g/h (0.002 to 0.006 lb/h), not very different from the range above. It appears that 2 g/h (0.004 lb/h) is a reasonable estimate for the water vapor contribution from a cat.

Other Pets. The calculations above demonstrate that the proportional approach based on weight is a reasonable approach. Based on the release rate and weight for humans, this leads to a rate of 0.43 to 0.86 g/h·kg (0.00043 to 0.00086 lb/h·lb). We propose an estimate of 0.7 g/h·kg (0.0007 lb/h·lb). Thus, a medium-size dog weighing 10 kg (22 lb) contributes about 7 g/h (0.015 lb/h).

Plants

Hite and Bray (1949) measured the vapor release from seven different houseplants at “normal winter indoor conditions” and reported release rates from 39 to 101 g/day (0.082 to 0.22 lb/day), with the amount primarily varying with the type and size of plant. The average release rate was about 2.5 g/h (0.055 lb/h) per houseplant. The authors state that most of this is from transpiration from the plant itself and very little is from evaporation from the soil, but no measurements or calculations are provided to substantiate this statement. The IEA Annex 14 *Sourcebook* (1991) lists the following release rates:

Potted flowers:	5–10 g/h (0.011–0.022 lb/h)
Potted plants:	7–15 g/h (0.015–0.033 lb/h)
Medium-size rubber plant:	10–20 g/h (0.022–0.044 lb/h)

These rates are much higher than the rates measured by Hite and Bray (1949) and seem high when compared with the vapor release from pets (e.g., 7 g/h [0.015 lb/h] from a medium-size dog).

Yik et al. (2004), in a more recent set of measurements, report a moisture release rate of 0.84 g/h (1.85 × 10^3 lb/h) per plant. This value is lower, but the measurements took place at relatively low temperatures (ambient conditions were 15°C [59°F] and 65% RH). If this rate is adjusted for room temperature, and we assume Hite and Bray (1949) measured at 21.1°C (70°F), the two rates would be very similar if the ambient humidity for Hite and Bray’s measurements was 30% RH, not unreasonable for the reported “normal winter indoor conditions” in Lafayette, Indiana.

Variation with Humidity. There is evidence that transpiration from plants varies with ambient humidity. In general, transpiration will increase with lower ambient humidities, all else being equal, but there is also evidence that plants are able to limit this response by closing the stomata. The relationship is therefore not a simple one and also appears to depend on the humidity history the plant or tree is exposed to (Franks et al. 1997). West and Gaff (1976) conclude that with standard atmospheric carbon dioxide levels, transpiration of seedling apple trees (*Malus sylvestris,* commonly known as *Granny Smith*) is unlikely to be regulated by the stomata until the leaf to air vapor density gradient exceeds 12 to 14 g/m^3 (0.00075 to 0.00087 lb/ft^3). With gradients up to 12 g/m^3 (0.00075 lb/ft^3), West and Gaff (1976) show that respiration increases roughly linearly with humidity gradient. With gradients above 12 g/m^3 (0.00075 lb/ft^3), transpiration remains constant or actually declines. If we assume that other plant species behave in a similar manner and that the plant surface and the air are both at the same temperature (21.1°C [70°F]), plant respiration increases linearly with decreasing RH until RH goes below 25% to 35%.

When determining the variability with humidity, it is of interest how much of the vapor contribution comes from plant transpiration and how much comes from evaporation from the soil. The authors of the present paper were unable to find published data on this ratio but attempted to calculate approximate release rates. Penman (1948) published data on natural evaporation from open water and soils, confirming the validity of the following by Rohwer (1931) for evaporation from open water (no wind):

$$E = A(p_{w,s} - p_w) \tag{2}$$

where

E	=	evaporation rate, kg/s·m^2 (lb/s·ft^2)
A	=	3.5×10^{-8} (SI) (2.4 x $\times 10^{-5}$ [I-P])
$p_{w,s}$	=	saturation vapor pressure of air, Pa (in. Hg)
p_w	=	vapor pressure of air, Pa (in. Hg)

The mass transfer coefficient (3.5×10^{-8} s/m [about 600 perms[2]]) corresponds reasonably well with data for vapor transfer coefficients from building surfaces (2.7×10^{-8} s/m [470 perms] without wind or temperature differences, [Hens 1993]), reported elsewhere in the literature. However, these measurements were carried out in the open air, with wind and sun possibly affecting the outcome. We therefore compared this equation with results from a more recent experiment by Pauker et al. (1993), who obtained formulas for water evaporation into still air from well-controlled experiments. They obtained very good results with a simple linear equation, although they found slightly better agreement with more complex equations:

$$J = B(C_w - C_a) \tag{3}$$

2. 1 perm = 1 grain/(h·ft^2·in. Hg).

where

J = evaporation rate, kg/h·m^2 (lb/h·ft^2)

B = 17.22 (SI) (2.202 [I-P])

C_w = absolute humidity at saturation, kg/m^3 (lb/ft^3)

C_a = absolute humidity of ambient air, kg/m^3 (lb/ft^3)

If we convert Equation 3 into the same units as Equation 2, we obtain the exact same equation.

Penman (1948) also measured differences between evaporation from soil versus open water and found that evaporation from wetted soil was generally 90% of that of open water. We therefore use a transfer coefficient of 3×10^{-8} s/m. For a 0.11 m (4.5 in.) diameter pot, the evaporation rate at 21.1°C (70°F), 50% RH is therefore 1.4 g/h (0.0031 lb/h). This rate decreases linearly with RH. Thus, we may assume that the total evaporation rate from plants decreases linearly with RH in the 30% to 100% RH range. Below 30% RH, we assume that the rate remains constant because the respiration rate may be decreasing with decreasing RH, while evaporation rates from the soil would be still be increasing. For our calculations we used an average total release rate of 2.5 g/h (0.0055 lb/h) per houseplant and assumed that this was measured at 21.1°C (70°F), 30% RH.

$$E_{plants} = 3.6(1 - \varphi) \text{ for } 0.3 < \varphi < 1$$

$$E_{plants} = 2.5 \text{ for } \varphi < 0.3$$

where

E_{plants} = total evaporation from plants at 21.1°C (70°F), g/h

φ = relative humidity

Showers and Bathing

Hite and Bray (1949) reported that an "average" shower contributes between 0.11 and 0.23 kg (0.25 and 0.5 lb) of water vapor, but they report great variability depending on a number of factors. They did not report the length of the shower, although later authors (Angell and Olson 1988) claim that this amount applies to a five-minute shower. The amount did not include condensation on walls, mirrors, or windows, nor the water evaporating after the shower from shower stall surfaces or from wet towels. Their measured rate for bathing in a bathtub was 1/4 of the rate for showering.

IEA Annex 14 (1991) reports that a three-minute shower releases 0.2 kg (0.44 lb) of vapor, and a 15-minute shower releases 0.8 kg (1.76 lb). The same source reports a release rate of 2.6 kg/h (5.7 lb/h) for showers and 0.7 kg/h (1.5 lb/h) for baths, which correlates reasonably well with the rates reported above. We therefore used 2.6 kg/h (5.7 lb/h) for showers and 0.7 kg/h (1.5 lb/h) for baths in our calculations. Of course, the presence and effectiveness of a bathroom fan greatly affects the effective contribution to the home. However, Yik et al. (2004) found that only about half the water vapor generated is removed by the fan, with the rest condensing on various surfaces.

The water temperature for showering and bathing is likely to be around 40°C (104°F). This would make the vapor release only a very weak function of ambient relative humidity. In addition, bathroom humidity is likely to rise rapidly during bathing, further obfuscating the net effect of indoor humidity. Any water deposited on various surfaces that is not drained will also evaporate. We therefore elect to treat water vapor release from bathing as a constant source.

Dishwashing, Cleaning, and Cooking

Dishwashing. Hite and Bray (1949) concluded that the vapor release from dishwashing for a family of four varies between 0.2 and 0.3 kg (0.5 and 0.75 lb). Yik et al. (2004) put the total at 3 g (0.0066 lb) per person per meal, plus 50 g (0.11 lb) per meal for drying, but dishwashing was done with cold water. Dishwashing now is done primarily with automatic dishwashers, and the vapor release is at temperatures of around 50°C to 70°C (120°F to 160°F) and therefore is not very humidity dependent. Moreover, water vapor release continues until all dishes are dry, and the amount released is therefore not a function of humidity. We used a constant 0.25 kg (0.55 lb) per load of dishes for our calculations.

Cleaning. Hite and Bray (1949) reported 0.15 kg/m^2 (0.03 lb/ft^2) for floor mopping, but the measurements by Yik et al. (2004) show a much lower amount, 0.005 kg/m^2 (0.001 lb/ft^2). The only areas that would likely be mopped are the bathroom and kitchen, and most likely no more than once a week. We therefore believe the moisture contribution from cleaning can be ignored.

Cooking. Yik et al. (2004) collected detailed data on cooking various dishes.

Rice for four persons:	55 g (0.12 lb)
Chicken wings:	37 g (0.081 lb)
Steaming:	283 g (0.624 lb)
Vegetable boiling or frying:	148 g (0.326 lb)
Noodles:	25 g (0.055 lb)
Soup boiling:	927 g (2.04 lb)

These are release rates from the food only and do not include water from combustion. Thus, a meal with rice, vegetables (boiled), and chicken wings releases on the order of 240 g (0.53 lb). We used 0.24 kg (0.53 lb) per meal in our calculations.

The same source lists water release from a gas burner as 450 g/h (1 lb/h) when turned on full, but the gas used was "town gas" with about half the energy content of natural gas. The combustion of natural gas, which is mostly methane, can add about 1.6 kg (0.1 lb) of water per m^3 (ft^3) of gas burned. Thus, a 3 kW (10,000 Btu) burner, on full, uses about 0.28 m^3/h (10 ft^3/h) of natural gas, adding around 0.45 kg/h (1 lb/h) of moisture from combustion, the same amount as reported by Yik et al. (2004).

Moisture release from cooking is not a strong function of indoor humidity. Water from gas combustion and boiling is independent of humidity, and most of the other release occurs at high temperatures. We therefore treat moisture release from cooking as independent of humidity.

Clothes Washing and Drying

Hite and Bray (1949) report that a load of laundry after wringing contained 11.9 kg (26.3 lb) of water. Angell and Olson (1988) cite a much lower number: 2.2 to 2.95 kg (4.9 to 6.5 lb) of water retained in a standard 3.6 kg (8 lb) load of laundry after dry spinning, indicating the advantages of spin dryers over wringers. However, laundry is rarely dried inside any more, as most households now use clothes dryers that are vented to the outside or laundry is dried outside. We therefore ignore the contribution from clothes.

Foundations

Moisture release from wet foundations can be a very important source of moisture. However, data are elusive, probably because the rates vary so greatly, and it is difficult to measure. The evaporation rate depends on the wetness of the soil but also on the amount of energy available for evaporation. Hite and Bray (1949) do not mention moisture release from the foundation, but a widely quoted publication (HHFA 1954) reports moisture transfer through a 0.1 m (4 in.) concrete slab over gravel over wet soil of about 0.09 kg/m^2·day (0.02 lb/ft^2·day). The report also showed that the evaporation could be reduced by up to a factor of 10 by installing various membranes under the concrete slab. However, these measurements were conducted at 26.7°C (80°F), 30% RH, and these rates are therefore too high considering that temperatures in foundations are more likely in the 10°C to 20°C (50°F to 70°F) range. If we correct for this temperature difference and assume the foundation temperature is 15.6°C (60°F), the rate would be about half, or 0.05 kg/m^2·day (0.01 lb/ft^2·day) at 20% RH of the ambient air. This translates into about 0.002 kg/m^2·h (0.0004 lb/ft^2·h).

Trethowen (1994) measured moisture release in crawlspaces in New Zealand and reported an average release rate of 0.4 kg/m^2·day (0.08 lb/ft^2·day) from bare soil. This translates into around 0.017 kg/m^2·h (0.0034 lb/ft^2·h). Trethowen also demonstrated the large effect of ground temperature on evaporation rates. This rate is considerably higher than the values reported by the The Housing and Home Finance Agency (HHFA) (HHFA 1954), but these rates were measured under very different conditions and different foundation types.

Using Equation 2 for evaporation from open water and assuming that evaporation from soil is 90% of that from water, we arrive at release rates as shown in Figure 2. The rates in Figure 2 represent very wet conditions in the foundation, a "worst case" scenario, with release rates of hundreds of kilograms of moisture per day, leading to disastrous moisture conditions in the home. It shows the potential of foundations to completely overwhelm all other moisture sources. Even if the rates seem much too high, the basic relationship with foundation temperature and indoor humidity should still be valid, as long as sufficient heat is available to evaporate the water. Figure 2 also shows that the foundation ceases to be a moisture source when the dew point of the indoor air reaches the temperature of the foundation soil or concrete. It could even be argued that at that point the foundation becomes a sink for water vapor and that any additional moisture generated elsewhere in the home is absorbed by the foundation. This would cap the indoor humidity at the dew point of the foundation. However, in our calculations we ignored this possible effect.

Given the large variation in moisture release rates, it was difficult to settle on a reasonable number for our calculations. It seemed to us that the HHFA (1954) release rates, as adjusted for foundation temperature and ambient conditions, may provide the most realistic average source rate. This rate is 0.002 kg/m^2·h (0.0005 lb/ft^2·h) with an assumed foundation temperature of 15.6°C (60°F) and indoor ambient air at 21.1°C (70°F) and is about 50 times lower than the rate shown in Figure 2 for those conditions. It gives a contribution of about 5 kg/day for a 100 m^2 home (12 lb/day for a 1000 ft^2 home), numbers that seem to agree reasonably well with practical experience. However, release rates could easily exceed this level, especially in homes built over a wet crawlspace.

For our calculations we assumed a "moist" foundation and applied the same temperature and relative humidity relationships as shown in Figure 3 to this reduced release rate. The values are given in Table 2.

Total Moisture Production

As an example, we calculated the water vapor production of a family of five (two adults, two children, one infant), living in a 200 m^2 (1986 ft^2) house as a function of indoor humidity. We assumed they cook with gas and that they own pets (a more complete description can be found in the Appendix). The indoor temperature is 21.1°C (70°F). The results are shown in Figure 3. The scenario results in a relatively modest rate of moisture production, between 6.6 and 10.2 kg/day (14.7 and 22.5 lb/day), which is unlikely to lead to very high

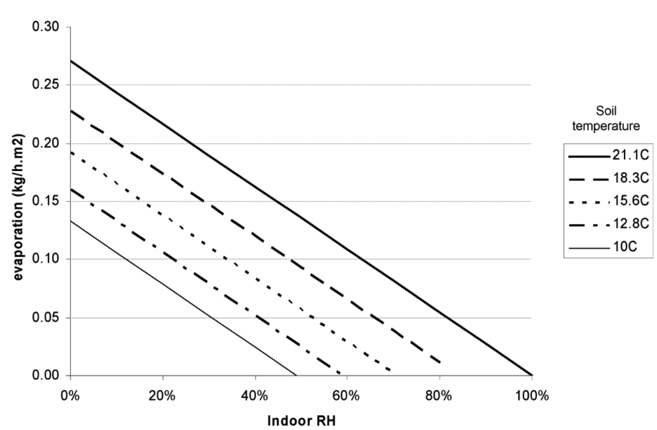

Figure 2 *Calculated evaporation rates from soil as a function of soil temperature and indoor air relative humidity at 21.1°C (70°F).*

winter humidity levels, even at low home ventilation rates (cold climates). The effect of using the variable release rates is minimal.

The moisture release in our scenario is much lower than the 15 kg/day (33 lb/day) proposed in the public review draft of Standard 160 (n.d. 2006) (see Table 1). This is not surprising because the design numbers in proposed Standard 160 are intentionally chosen to be more severe than average. Given the fact that moisture release from the foundation is by far the most variable and can dominate the overall moisture release rate, it is not unreasonable to assume that many homes that have very high moisture release rates would receive most of that moisture from a wet foundation. If that is the case, the effect of humidity on release rates and indoor humidity would be far greater. If we quadruple the foundation contribution for our example, leaving all else the same, the total release rates are between 6.7 and 20.3 kg/day (14.8 and 44.8 lb/day) (Figure 4). This is more in the range of the design values but also shows a much greater variability with humidity (Figure 4).

Effect of Variable Moisture Sources on Indoor Relative Humidity

We performed a whole-house moisture balance with the high values in Figure 4 to determine the possible effect of variable versus constant source rates on the design indoor humidity. The outdoor condition chosen was –8.5°C (16.7°F), 65.8% RH, which is the monthly average for January in Madison, Wisconsin (TenWolde and Colliver 2001). We did the calculation for a variety of ventilation conditions. For the constant rate we took the moisture release at 40% RH, 12.6 kg/day (27.7 lb/day), which is fairly close to the 15 kg/day (33 lb/day) design value proposed in the draft of Standard 160 (ASHRAE n.d.). Results are shown in Figure 5. Because of our choice for the constant rate, the lines for constant and variable release rates cross over at 40% RH. The results show that assuming a constant release rate can cause a substantially higher resulting RH for lower ventilation rates: at 0.1 ach ventilation, the variable rate calculation resulted in indoor humidity of around 55%, while the constant source produced about 75% RH. While these results depend on a number of assumptions, they do demonstrate that under certain conditions ignoring the effect of indoor humidity on moisture release rate may lead to substantially different and more severe conditions.

CONCLUSIONS AND RECOMMENDATIONS

Our literature review and calculations have shown that most of the moisture sources in a home can be considered independent of indoor humidity conditions. Moisture release from potted plants and moisture release from foundations are two

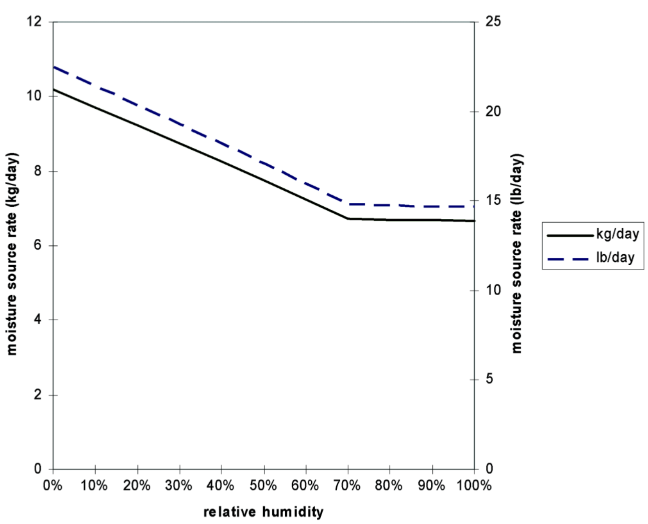

Figure 3 *Example moisture release from a family of five, with a medium contribution from the foundation.*

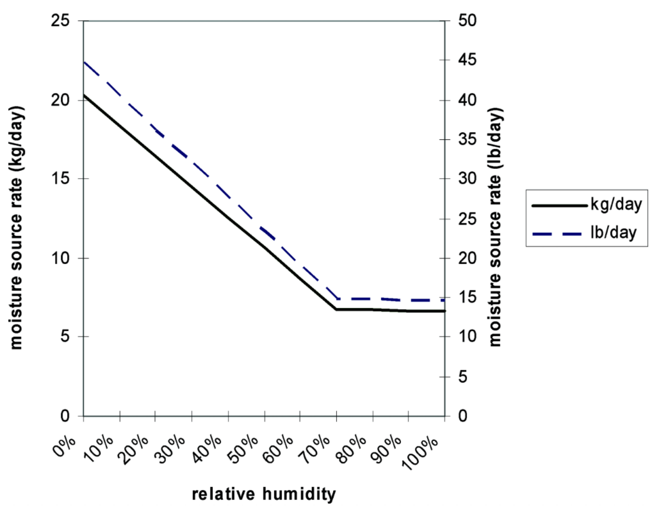

Figure 4 *Example moisture release from a family of five, with a high contribution from the foundation. Note: Foundation temperature is 15.6°C (60°F) and indoor air temperature is 21.1°C (70°F).*

Table 2. Contribution from a Foundation as a Function of Indoor Humidity

RH	10%	20%	30%	40%	50%	60%	70%
Source rate, kg/m²·h (lb/ft²·h)	0.0024 (0.0056)	0.002 (0.0047)	0.0016 (0.0038)	0.0012 (0.0028)	0.0008 (0.0019)	0.0004 (0.001)	0 (0)

Note: foundation temperature is 15.6°C (60°F) and indoor air temperature is 21.1°C (70°F).

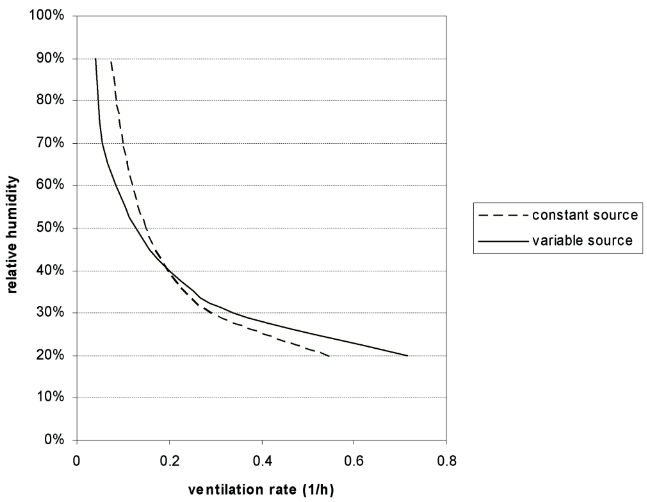

Figure 5 *Effect of variable versus constant moisture release on indoor relative humidity, for a family of five in Madison, WI.*

exceptions. The exact quantity released from foundations and how it varies with humidity is not known, but we do know that moisture from wet foundations can cause humidity and moisture problems during winter. The release from foundations is most likely higher with low indoor humidity than at high humidity. Taking this effect into account can lead to substantially lower estimates of indoor humidity, especially in airtight homes with low ventilation rates.

Given the importance of moisture from foundations, we believe much more measured data are needed, both on the quantity of water vapor contributed by foundations as well as its variability with indoor humidity and temperatures, including the temperature of the foundation itself.

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APPENDIX—MOISTURE RELEASE SCENARIO

Family of Five

Inhabitants: Mom, dad, two school-age children, one 10 kg (22 lb) baby, one 10 kg (22 lb) dog, one cat, three houseplants.

Both parents work during the day while two children are in school. The baby is taken to a day care center. Overall, three members of the family are home for 14 hours each day, while one adult and the baby are home for 15 hours each day. Three members of the family take 15-minute showers before leaving the house and one family member takes a 10-minute shower. Breakfast consists of cereal, toast, and yogurt, but coffee remains a staple. The whole family leaves the house around the same time—the children are dropped off at school and one parent takes the baby to day care. The house is vacant during the day except for the cat and dog. One parent picks up the baby and comes home around 4:30 p.m. After school, the school-age children spend some time at sports practice/friends' houses and come home around 5:30 p.m. The other parent is home at 5:30 p.m., just in time for dinner. After dinner, the dishes are placed into the dishwasher, a load of laundry is washed and dried, the dog is taken for a walk, and the baby is given a bath. The dishwasher kicks in around 11:00 p.m., once everyone is in bed.